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Welcome Message from the Committee

On behalf of the ENDE2019 organizing committee, I am honored to welcome you to the 24th International Workshop on Electromagnetic Nondestructive Evaluation in Chengdu, China. It has been an exciting year in our field and I’m sure we are all looking forward to discussing the remarkable research contributions that have been made within the NDT&E community, catching up with colleagues for both old and new, as well as promoting the area on a bigger stage.

The 24th workshop will focus on theoretical and applied research on Electromagnetic Nondestructive Evaluation methods, providing a wonderful opportunity to exchange ideas and updates on the latest developments. Papers will be presented in a single track and poster sessions. Apart from the traditional topics of ENDE measurement theory, there are emerging hot topics such as sensors, inversion problem, reconstruction and quantification imaging, signal and image processing as well as AI that we look forward to discussing in this workshop.

We are delighted to welcome two eminent scientists who will deliver keynote speeches. Satish Udga, the Executive Vice President of Michigan State University, will deliver a talk on Electromagnetic NDE Techniques for Inspecting Composite Materials and Additively Manufactured Components; Yong Nie, Deputy Chief Engineer from China Nuclear Power Operation Technology Corporation Ltd., CNNC, will provide a presentation in R&D of NDT Technologies for Nuclear Power Plant and Applications. We have also invited another four speakers from Imperial College, Iowa State University, Harbin Institute of Technology and King Mongkut’s University of Technology. In the meantime, 35 oral and 88 poster presentations are scheduled to present the latest developments in ENDE. Thank you for bringing novel ideas and results that have put ENDE2019 ahead of its time.

We would like to thank our sponsors and exhibitors. In particular we would like to appreciate our joint organizers, University of Electronic Science and Technology of China, Southwest Jiaotong University, Sichuan University, Newcastle University, UK and the National Natural Science Foundation of China; as well as countless other supporters.

The host city Chengdu is China’s 6th largest city with a population of over 16 million. It is the capital of Sichuan, one of the China’s largest provinces – historically it was the capital of Shu Han, one of the three warring states during China’s famous Three Kingdoms Era back in 220 AD. Aside from its illustrious history, it is also well known for being the home of the giant pandas, the friendliness of its people and the spiciness of its food. We would highly encourage you to soak in the unique and memorable experiences in this city and sincerely hope you enjoy a good time here.

A big thank to all authors and delegates for submitting papers to ENDE2019 and your continued support for this fantastic conference. Thanks also to the reviewers who spent valuable time and efforts to provide a comment. Finally, we would like to express our heartfelt gratitude to the conference International Steering Committee, staff and volunteers who have worked tirelessly to service ENDE2019.

We hope all of you will enjoy the conference and have a wonderful time sharing and discussing the research progress with colleagues. We also hope that you have a pleasant stay in the beautiful city of Chengdu.

Chair of ENDE2019
ENDE2019 Organizing Committee

**General Chairman:**

Guiyun Tian, University of Electronic Science and Technology of China, China/Newcastle University, UK

**Co-Chairs:**

Zhenmao Chen, Xi'an Jiaotong University, China
Xiaorong Gao, Southwest Jiaotong University, China
Junming Lin, Eddyson Electronic Corp, China
Tianpeng Gao, Special Equipment Safety Supervision Inspection Institute of Jiangsu Province, China

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Fang He, University of Electronic Science and Technology of China, China
Yong Li, Xi'an Jiaotong University, China
Qunying Liu, University of Electronic Science and Technology of China, China
Jianping Peng, Southwest Jiaotong University, China
Bo Tian, University of Electronic Science and Technology of China, China
Jianbo Wu, Sichuan University, China
Xiaoting Xiao, University of Electronic Science and Technology of China, China
Shejuan Xie, Xi'an Jiaotong University, China
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Qiuji Yi, Newcastle University, United Kingdom
Ying Yin, Special Equipment Safety Supervision Inspection Institute of Sichuan Province, China
Kun Zeng, University of Electronic Science and Technology of China, China
Yu Zhang, Southwest Jiaotong University, China
Hong Zhang, Fuzhou Branch of Fujian Normal University, China
Jincheng Zhao, Eddyson Electronic Corp, China
Kai Zheng, Special Equipment Safety Supervision Inspection Institute of Jiangsu Province, China
Deqiang Zhou, Jiangnan University, China
ENDE International Steering Committee

Christophe Reboud, CEALIST, France, ISC Chair

(Sorting order):
Sandor Bilicz, Budapest University of Technology and Economics, Hungary
Klara Capova, University of Zilina, Slovakia
Tomasz Chady, West Pomeranian University of Technology, Poland
Zhenmao Chen, Xi'an Jiaotong University, China
Yiming Deng, Michigan State University, USA
Fumio Kojima, Kobe University, Japan
Jinyi Lee, Chosun University, South Korea
Dominique Lesselier, CNRS-Centrale Supélec-Univ. Paris-Sud, France
Helena Geirinhhas Ramos, Instituto Superior Técnico Lisboa, Portugal
B. Purna Chandra Rao, Indira Gandhi Centre for Atomic Research, India
Joao Marcos Alcoforado Rebello, Federal University of Rio de Janeiro, Brazil
Artur Ribeiro, Instituto Superior Técnico Lisboa, Portugal
Guglielmo Rubinacci, Università di Napoli Federico II, Italy
Sung-Jin Song, Sungkyunkwan University, South Korea
Klaus Szzielsko, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (IZFP), Germany
Toshiyuki Takagi, Tohoku University, Japan
Antonello Tamburino, Università degli studi di Cassino, Italy
Theodoros Theodoulidis, University of Western Macedonia, Greece
Guiyun Tian, Newcastle University, UK/UESTC, China
Lalita Udpa, Michigan State University, USA
Satish S. Udpa, Michigan State University, USA
Noritaka Yusa, Tohoku University, Japan

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(Alphabetical order)
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Bin Gao, University of Electronic Science and Technology of China, China
Christophe Reboud, CEALIST Institute, France
Dominique Lesselier, CNRS-Centrale Supélec-Univ. Paris-Sud, France
Dong Liu, University of Electronic Science and Technology of China, China
Fasheng Qiu, NanChang Hangkong University, China
Frédéric Taillade, Électricité de France (EDF), France
Hai Zhang, University of Laval, Canada
Helena Geirinhhas Ramos, Instituto Superior Técnico Lisboa, Portugal
Jakob Juul Larsen, Aarhus University, Denmark
Jia Liu, University of Electronic Science and Technology of China, China
Jiangbo Wu, Sichuan University, China
Joerg Schotter, Austrian institute of technology, Austria
Junaid Ahmed, University of Electronic Science and Technology of China, China
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Libing Bai, University of Electronic Science and Technology of China, China
Louvalin Georadar, Austria Institute of Technology, Austria
Mengbao Fan, China University of Mining and Technology, China
Pan Hu, Nanjing University of Aeronautics and Astronautics, China
Qing Zhang, Nanjing University of Aeronautics and Astronautics, China
Sandor Bilicz, Budapest University of Technology and Economics, Hungary
Sébastien Lambot, FNRS Research Director Faculty of Bioscience Engineering & Earth and Life Institute, Belgium
Stefano Laureti, Università degli Studi di Perugia, Italy
Stephen Dankwa, University of Electronic Science and Technology of China, China
Sung-Jin Song, Sungkyunkwan University, South Korea
Toshiyuki Takagi, Tohoku University, Japan
Xavier Dérobert, Institut Français des Sciences et Technologies des Transports, de l’Aménagement et des Réseaux, France
Xiaoting Xiao, University of Electronic Science and Technology of China, China
Yan Yan, University of Electronic Science and Technology of China, China
Yong Li, Xi'an Jiaotong University, China
Yunze He, Hunan University, China
Zhichao Cai, East China Jiaotong University, China

Thank you to all the reviewers of the ENDE 2019 paper
ENDE2019 Keynote Speakers

**Satish Udpa**
IEEE Fellow  
Executive Vice President  
Professor  
Michigan State University

**Yong Nie**
Professor  
Deputy Chief Engineer, China Nuclear Power Operation Technology Corporation Ltd., CNNC

**Electromagnetic NDE Techniques for Inspecting Composite Materials and Additively Manufactured Components**

**ABSTRACT**
It is vitally important that as new manufacturing technologies and new types of materials emerge, we must have viable alternatives for inspecting the resulting product Non-destructively. New materials such as composites are increasingly finding their way into aerospace, energy and automotive industries. Likewise, additive manufacturing technologies are penetrating critically important sectors of our economy. This research explores the use of electromagnetic techniques for characterizing damage in composite materials and describes a process control tool that is capable of detecting defects in additively manufactured components. The presentation will first focus on an electromagnetic NDE technique that employs a multi-sensor probe for characterizing damage in components made of composites which are inherently anisotropic, have complex structural geometries, and are designed to operate in hostile environments. Second, we describe a multi-frequency EM sensor with a built-in calibration system and super-resolution capability for detecting defects in additively manufactured metal components during the manufacturing process.

**SPEAKER BIO**
Satish Udpa also serves as MSU’s Executive Vice President for Administration and is a University Distinguished Professor. He served as dean of the College of Engineering and chair of the Department of Electrical and Computer Engineering at MSU before his current appointment. Before joining MSU in 2001, Udpa was the Whitney Professor of Electrical and Computer Engineering at Iowa State University. He was on the faculty at Colorado State University prior to his time at Iowa State University. Udpa’s research interests span the broad area of materials characterization and Non-destructive evaluation. He has published extensively, holds several patents and serves as editor of several journals. Udpa is a Fellow of the Institute of Electrical and Electronics Engineers, the American Society for Non-destructive Testing, the Indian Society for Non-destructive Testing, and the Engineering Society of Detroit. He is a full member of the Academia NDT International. Udpa also served as the permanent secretary of the World Federation of NDE Centers from 1998 to 2003.

**R&D of NDT Technologies for Nuclear Power Plant and Applications**

**ABSTRACT**
To ensure the safe operation of the nuclear power plant (NPP), regular in-service inspection is a vital guarantee measure required by regulations. The NDT technologies used in in-service inspection of NPP mainly include ultrasonic testing, radiographic testing, eddy current (electromagnetic) testing (ECT), penetrant testing, magnetic particle testing, visual testing and leak detection technology et al. In addition to the general introduction of NDT technologies for NPP, the applications of the eddy current (electromagnetic) testing technique, such as the ECT of the steam generator tubes, the thimble tubes for neutron flux measurement and ECT of bolts and nuts will be emphasized in this invited lecture.

**SPEAKER BIO**
Yong Nie, Professor, Deputy Chief Engineer, China Nuclear Power Operation Technology Corporation Ltd., CNNC. He graduated from Sichuan University, majoring in metallic materials. For more than 30 years, he has been mainly engaged in research and development of NDT instrument and in-service inspection and maintenance technologies for key structures of nuclear power plants.
Adaptive Cross Approximations for Eddy Current Non-destructive Evaluations

ABSTRACT
Eddy current Non-destructive Evaluation (NDE) involves the detection of electromagnetic field irregularities due to non-conducting inhomogeneities in an electrically conducting material such as cracks, fasteners, sharp corners/edges, multi-layered structures, etc. The eddy-current problem is formulated by the Boundary Integral Equations (BIE) and discretized into matrix equations by the Method of Moments (MoM) or the Boundary Element Method (BEM). Computational tests are performed to demonstrate the accuracy and capability of the BIE method with a complex wave number for three-dimensional objects described by several triangular patches. Finally, our most recent research results on developing Adaptive Cross Approximation (ACA) to accelerate the impedance calculations for NDE applications will be presented.

SPEAKER BIO
Jiming Song received Ph.D. degree in Electrical Engineering from Michigan State University in 1993. From 1993 to 2000, he worked as a Postdoctoral Research Associate, a Research Scientist and Visiting Assistant Professor at the University of Illinois at Urbana-Champaign. From 1996 to 2000, he worked part-time as a Research Scientist at SAIC-DEMACO. Dr. Song was the principal author of the Fast Illinois Solver Code (FISC). He was a Principal Staff Engineer/Scientist at Semiconductor Products Sector of Motorola in Tempe, Arizona before he joined Department of Electrical and Computer Engineering at Iowa State University as an Assistant Professor in 2002.

Dr. Song currently is a Professor at Iowa State University’s Department of Electrical and Computer Engineering. His research has dealt with modelling and simulations of interconnects on lossy silicon and RF components, electromagnetic wave scattering using fast algorithms, the wave propagation in metamaterials, acoustic and elastic wave propagation and non-destructive evaluation, and transient electromagnetic field. He received the NSF Career Award in 2006 and is an IEEE Fellow and ACEB Fellow.

Translating Engineering to Healthcare

ABSTRACT
In healthcare applications, we have no choice but to be non-destructive! While commonly not considered in the same terms as ENDE, related techniques are used throughout medicine, taking advantage of the dielectric properties of biological tissues. This talk discusses Electromagnetic sensing and imaging from a biomedical perspective, from tracking surgical tools, medical robotics, implantable sensors, neuroscience, tomographic imaging and spectroscopy.

There are numerous challenges when transferring something from the bench to the bedside, some more prosaic such as cost, size and time restrictions, to the technical challenges of low SNR, poor contrast and ill-conditioned inversions. Overcoming these hurdles requires multidisciplinary development of instrumentation, signal processing and modelling. In this outline, the latest developments in these areas are discussed along with personal experience.

SPEAKER BIO
Dr. James Avery is a Research Associate in the Hamlyn Centre, Institute of Global Health Innovation and the Department of Surgery and Cancer, St Mary’s Hospital Imperial College UK. He received an MEng in Acoustical Engineering at the Institute of Sound and Vibration Research at the University of Southampton and completed his PhD in Biomedical Engineering at University College London in 2015. There he continued his work as an EPSRC Doctoral Research Fellow, developing Electrical Impedance Tomography methods for brain imaging as part of Prof. Holder’s Neurophysiology lab. Clinical studies during this time brought into sharp focus the benefits that good, open and reproducible engineering can have for patients and strengthened his desire to translate his work into clinical practice. Since 2018 he has worked as a postdoctoral researcher at the NIHR Imperial Biomedical Research Centre, seeking to develop new sensor technologies for surgery.
Flexible Tactile Sensors Based on Patterned Nanostructures of Graphene and 2D Materials

ABSTRACT

Flexible tactile sensors have been extensively investigated as a key component for emerging electronics applications such as artificial intelligence interface, robotics, wearable devices, computer hardware, and security systems. By exploiting atomically thick film of graphene and 2D semiconducting material, we develop highly sensitive and conformal pressure sensors for any curved surface using two dimensional (2D) nanomaterials. And we fabricate flexible electrical-skin devices for wearable health-monitoring devices and autonomous artificial intelligence systems such as robots using the array of functional microstructure (nanopyramid, patterned film etc.) of 2D materials. Furthermore, the self-powered piezotronic sensors made of these newly developed 2D piezoelectric film have been successfully used for real-time health monitoring, proving their suitability for the fabrication of flexible piezotronic devices due to their large piezoelectric responses and excellent mechanical durability.

SPEAKER BIO

Dr. PingAn Hu is a Professor at the School of Materials Science and Engineering in Harbin Institute of Technology (HIT). He obtained his Ph.D degree from Institute of Chemistry, Chinese Academy of Science in 2004, and then he worked as a JSPS research fellow at Waseda University, Japan, and a Research Associate in University of Cambridge. He got New Century Excellent Talents in University of China in 2010 and Longjiang Special Professorship in 2011. His current research interests are focused on 2D materials, bio-inspired skin electronics and nanoscale photoelectrometers. He published about 160 SCI papers in highly qualified international journals such as Physical Review Letter, Journal of American Chemical Society and Advanced Materials. His research has been introduced and commented by some international journals such as Nature Photonics, New Scientist.

Magnetic Property Changed by Interaction of Immuno-magnetic Nano-particle with Bacteria Cell

ABSTRACT

In foodborne detection, Immuno-magnetic nanoparticles (IMNPs) are generally able to concentrate the target bacteria in any solution without enrichment processes which can help to reduce the processing time and cost for conventional detection methods. In addition, the magnetic properties change of IMNPs should be focused by detecting the change when IMNPs captured the target bacterium. To convince the feasibility of the developed bacteria detection test kit based on the electro-magnetic responding sensing in next development research, all steps in the IMNPs preparation and capturing process should be studied for improve the test kid development. This research explored the realistic mechanism of IMNPs, which lead to the change of the magnetic properties in the bacteria detection process. The research hypothesis was determined that the variation of magnetic properties could be from an atom and electron condition in IMNPs molecule. The synchrotron XAS with high sensitivity and resolution could discover the information of the atomic structure and electronic transfer of IMNPs throughout three surface modifications and the bacteria capturing steps for observing the effects of each step. The change of magnetic properties was approved by the vibrating sample magnetometer (VSM).

SPEAKER BIO

Dr. Isaratat Phung-On is currently the Head of Maintenance Technology Center (MTC), Institute for Scientific and Technological Research and Services (ISTRS), at King Mongkut’s University of Technology Thonburi (KMUTT), Bangkok, Thailand, where he has joined since 1999. In education, he received a B. Eng in Production Engineering (1st class honor) from the KMUTT in 1999. He received his M.S. and Ph.D. in Welding Engineering from the Ohio State University in 2003 and 2007 respectively. His research interests are welding metallurgy, failure analysis, structural life assessment and Bioprocess equipment fabrication. Much of his work has been on improving the understanding, design, analysis and inspection of physical welding processes for various materials, mainly through the application of oil and gas, petrochemical and power plants industries. Asst. Prof. Isaratat has published researches and patents over 50 articles, including SCI journals. He also holds a diploma in the International Welding Engineering (IWE). There are also over ten patents filed under his invention related to his research interest.
# ENDE2019 Program Schedule

**ENDE2019**

## Program Schedule

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<td>Registration (lobby of longemont Hotel)</td>
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<td>15:00-17:00</td>
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<td>Welcome Reception &amp; Dinner (Skyline Freshly Brewery Bar)</td>
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<td>ISCE meeting (Daihai Hall, Long Yue Chinese Restaurant)</td>
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<tr>
<td>18:00-21:30</td>
<td>Welcome Reception &amp; Dinner (Skyline Freshly Brewery Bar)</td>
<td>18:30-20:00</td>
<td>ISCE meeting (Daihai Hall, Long Yue Chinese Restaurant)</td>
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<td>ISCE meeting (Daihai Hall, Long Yue Chinese Restaurant)</td>
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- Mr. Kun Zeng: +86-17780535710
Technical Schedule: Thursday, 12th September

**Opening Ceremony**
*Time:* 8:30-9:00  
*Room:* Dragon Ballroom III  
*Host:* Guiyun Tian  
*Location:* Pool of Conference Center

**Keynote**
*Time:* 9:20-10:50  
*Room:* Dragon Ballroom III  
*Session chairs:* Zhenmao Chen, Xiaorong Gao

09:20-10:05 **K01**
**Electromagnetic NDE Techniques for Inspecting Composite Materials and Additively Manufactured Components**  
*Satish Udpa, Michigan State University, USA*

10:05-10:50 **K02**
**R&D of NDT Technologies for Nuclear Power Plant and Applications**  
*Yong Nie, China Nuclear Power Operation Technology Corporation Ltd, China*

10:50-11:00  
Coffee Break

**Invited Talk**
*Time:* 11:00-12:00  
*Room:* Dragon Ballroom III  
*Session chairs:* Zhenmao Chen, Xiaorong Gao

11:00-11:30 **T01**
**Adaptive Cross Approximations for Eddy Current Non-destructive Evaluations**  
*Yang Bao, Department of Electrical and Computer Engineering, Iowa State University*  
*Zhiewei Liu, Department of Information Engineering, East China Jiaotong University*  
*Jiming Song, Department of Electrical and Computer Engineering, Iowa State University*

11:30-12:00 **T02**
**Translating Engineering to Healthcare**  
*James Avery, the Department of Surgery and Cancer, St Mary’s Hospital Imperial College UK*

**Poster Session 1**
*Time:* 13:20-14:50  
*Room:* Hong Kou Hall  
*Session chairs:* Christophe Reboud, Helena RAMOS, Nortaka Yusa

P1-1 **A0091**  
**Coplanar Capacitive-Inductive Dual Modality Imaging Sensor for NDE**  
*Xiaokang Yin, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China), Qingdao, China*  
*Jiaming Fu, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China), Qingdao, China*  
*Zhen Li, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China), Qingdao, China*  
*Wei Li, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China), Qingdao, China*  
*Guoming Chen, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China), Qingdao, China*

P1-2 **A0092**  
**A Novel Planar Eddy Current Probe Based on Taiji Graph**  
*Guoliang Chen, School of Mechanical and Electrical Engineering, Lanzhou University of Technology, Lanzhou, P. R. China*  
*Weimin Zhang, School of Mechanical Engineering, Beijing Institute of Technology, Beijing, P. R. China*  
*Wuyin Jin, School of Mechanical and Electrical Engineering, Lanzhou University of Technology, Lanzhou, P. R. China*  
*Kang Wang, School of Mechanical and Electrical Engineering, Lanzhou University of Technology, Lanzhou, P. R. China*  
*Zhibo Song, School of Mechanical and Electrical Engineering, Lanzhou University of Technology, Lanzhou, P. R. China*

P1-3 **A0094**  
**Research on Non-Destructive Examination of Superconducting Cables Based on the Method of Inversion of Electromagnetic Proper**  
*Xiaochun Liu, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China*  
*Wu Yu, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China*  
*Zhenmao Chen, XI’AN JIAOTONG University, XI’AN, China*  
*Shuangsong Du, Institute of Plasma Physics, Chinese Academy of Science, Hefei, China*  
*Yuanyuan Ma, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China*  
*Jinggang Qin, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China*

**Lunch**
*Time:* 12:00-13:20  
*Location:* Rayfont Dining Hall
P1-4 A0096 Prediction of the Hardness of X12m Using Barkhausen Noise and Chebyshev Polynomials Regression Methods

Shicheng Li, Beijing Jing Hang Research Institute of Computation and Communication, Beijing, 100074, China; The Classified Information Carrier Safety Management Engineering Technology Research Center of Beijing, 100074, China
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Cunfu He, College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, 100124, China
Yu Li, Faculty of Information Technology, Beijing University of Technology, Beijing, 100124, China
Kun Zhang, Faculty of Information Technology, Beijing University of Technology, Beijing, 100124, China
Xuicheng Liu, College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, 100124, China
Yanchao Cai, College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, 100124, China
Chu Wang, Beijing Jing Hang Research Institute of Computation and Communication, Beijing, 100074, China; The Classified Information Carrier Safety Management Engineering Technology Research Center of Beijing, 100074, China

P1-5 A0098 Inspection of Defect and Accumulated Sludge of Steam Generator Tube with EC-TMR Array Probe

Yu Tao, School of Information Science and Technology, Shanghai Tech University, Shanghai, China
Lei Peng, School of Information Science and Technology, Shanghai Tech University, Shanghai, China
ChaoFeng Ye, School of Information Science and Technology, Shanghai Tech University, Shanghai, China

P1-6 A0099 Mechanism Hybrid EMAT and Eddy Current Sensing Detection for Surface and Internal Defects NDT

Wei Guo, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China
Bin Gao, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China
Guijun Tian, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China; School of Electrical and Electronic Engineering, Newcastle University, UK
Dan Si, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China
Quping Ma, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China
Changrong Yang, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China

P1-7 A0100 Study on the Mechanism and Application of Applying Magnetic Barkhausen Noise to Evaluate Plastic Deformation

Xueliang Kang, School of Materials Science and Engineering, Shanghai University, Shanghai 200072, China; National Key Laboratory for Remanufacturing, Academy of Armored Forces Engineering, Beijing 100072, China
Shiyun Dong, National Key Laboratory for Remanufacturing, Academy of Armored Forces Engineering, Beijing 100072, China
Hongbin Wang, School of Materials Science and Engineering, Shanghai University, Shanghai 200072, China
Ping Men, National Key Laboratory for Remanufacturing, Academy of Armored Forces Engineering, Beijing 100072, China
Ruiyang Lv, National Key Laboratory for Remanufacturing, Academy of Armored Forces Engineering, Beijing 100072, China

P1-8 A0105 Three-Dimensional Simulation of Electromagnetic Acoustic Resonance Method Using CIVA Software

Hongjun Sun, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba, Sendai, Japan
Christophe Rerbourg, The French Alternative Energies and Atomic Energy Commission, CEA- LIST, Laboratory Methods for the Control, 91191 Gif-sur-Yvette, France
Pierre Calmon, The French Alternative Energies and Atomic Energy Commission, CEA- LIST, Laboratory Methods for the Control, 91191 Gif-sur-Yvette, France
Edouard Demaldent, The French Alternative Energies and Atomic Energy Commission, CEA- LIST, Laboratory Methods for the Control, 91191 Gif-sur-Yvette, France
Tetsuya Uchimoto, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba, Sendai, Japan; ElyTMax UMI 3757, CNRS – Université de Lyon – Tohoku University, International Joint Unit, Tohoku University, Sendai, Japan
Toshiyuki Takagi, Institute of Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba, Sendai, Japan; ElyTMax UMI 3757, CNRS – Université de Lyon – Tohoku University, International Joint Unit, Tohoku University, Sendai, Japan

P1-9 A0109 Study of New Features for Inclination Angle Characterization Using Eddy Current Pulsed Thermography
Feng Liu, School of Mechanical Engineering, Guizhou Institute of Technology, Guiyang, China; School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU
Junzhen Zhu, School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU
Guoyun Tian, School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU
Zhao Wang, School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU

P1-10 A0112 Development of Wireless Monitoring System for Distributed Ultrasonic Thickness Measurement
Gang Zhang, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China
Jun Tu, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China
Xuyuan Xu, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China
Xu Zhang, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China
Xiaochun Song, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China

P1-11 A0113 Study on Characteristic of the Common Electromagnetic Acoustic Coils for Thickness Measurement of Steel Plates
Xuyuan Xu, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China
Jun Tu, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China
Xu Zhang, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China
Donglin Li, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China
Xiaochun Song, School of Mechanical Engineering, Hubei University of Technology, Wuhan, China

P1-12 A0114 Numerical Investigation on Faults Diagnosis for AC Induction Machine by Magnetic Flux Distribution
Yating Yu, School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China; Institute of Electronic and Information Engineering of UESTC in Guangdong, 523808, Dongguan, China
Linfeng Li, School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China
Hong Qin, School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China

P1-13 A0128 Numerical Simulation on Stress Measurement with Eddy Current Thermography
Shuwen Deng, School of Manufacturing Science and Engineering, Sichuan University, Chengdu, China
Suxian Yang, School of Manufacturing Science and Engineering, Sichuan University, Chengdu, China

P1-14 A0130 Using Fusion Methods to Improve the 2D Eddy Current Image Around A Linear Crack
Artur Ribeiro, Instituto de Telecomunicações, Lisboa, Portugal; Instituto Superior Técnico, Universidade de Lisboa, Portugal
Dario Pasadas, Instituto de Telecomunicações, Lisboa, Portugal
Helena Ramos, Instituto de Telecomunicações, Lisboa, Portugal; Instituto Superior Técnico, Universidade de Lisboa, Portugal

P1-15 A0133 Inverse Analysis for Local Wall Thinning Based on Multi-Frequency Signal of Low Frequency Electromagnetic Monitoring Method
Haicheng Song, Graduate School of Engineering, Tohoku University, Sendai, Japan
Noritaka YUSA, Graduate School of Engineering, Tohoku University, Sendai, Japan

P1-16 A0134 Time Delay and Interface Roughness Estimation of Pavements Using Modified MUSIC: Experimental Results
Meng Sun, Information Engineering College, Shanghai Maritime University, Shanghai, China
Jingjing Pan, IETR, Polytech Nantes, Université de Nantes, Nantes, France
Yide Wang, IETR, Polytech Nantes, Université de Nantes, Nantes, France
P1-17 A0135 Detection of Impact Damages on CFRP Using Eddy Current Pulsed Thermography

A. Ba, Institute of Research in Electrical Energy of Nantes-Atlantique (IREENA), University of Nantes, 44602 Saint-Nazaire Cedex, France

Q. Yi, School of Engineering, Newcastle University, Newcastle Upon Tyne, NE1 7RU, United Kingdom

J. Zhu, School of Engineering, Newcastle University, Newcastle Upon Tyne, NE1 7RU, United Kingdom

H. K. Bui, Institute of Research in Electrical Energy of Nantes-Atlantique (IREENA), University of Nantes, 44602 Saint-Nazaire Cedex, France

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G. Wasseleync, Institute of Research in Electrical Energy of Nantes-Atlantique (IREENA), University of Nantes, 44602 Saint-Nazaire Cedex, France


Benli Wan, School of Automation Science and Electrical Engineering, Beihang University, Beijing, China

Bin Hu, China Special Equipment Inspection and Research Institute, Beijing, China

Yinzha Le, School of Automation Science and Electrical Engineering, Beihang University, Beijing, China

Yuntao Li, China Special Equipment Inspection and Research Institute, Beijing, China

Yuhong Zhu, China Special Equipment Inspection and Research Institute, Beijing, China

P1-19 A0143 Study on Detection of Subsurface and Far-surface Defects Based on PMFL

Zhou Fang, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

Peng Xu, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

Chenlu Zhu, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

Ping Wang, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

P1-20 A0148 Experimental Research on Parallel Wire Cable Tension Testing Based on the Permanent Magnetizer

Youwei Liu, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Xinjun Wu, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

P1-21 A0153 Nondestructive Evaluation of Troposphere Lower Layers Properties by Monitoring of Electromagnetic Energy Sources

Peter Fabo, Research Centre, University of Žilina, Žilina, Slovak Republic

Dagmar Faktorová, Faculty of Electrical Engineering and Information Technology, University of Žilina, Žilina, Slovak Republic

Adriana Savin, Nondestructive Testing Department, National Institute of R&D for Technical Physics, Iasi, Romania

P1-22 A0225 Sparsification of the DTN Operator and its Applications to Eddy Current Problems

Anton Efremov, University of Cassino and Southern Lazio, Cassino, Italy

Antea Perrotta, University of Cassino and Southern Lazio, Cassino, Italy

Salvatore Ventre, University of Cassino and Southern Lazio, Cassino, Italy

Lalita Udpa, Nondestructive Evaluation Lab, Michigan State University, East Lansing, MI 48824 USA

Antonello Tamburrino, Nondestructive Evaluation Lab, Michigan State University, East Lansing, MI 48824 USA/ University of Cassino and Southern Lazio, Cassino, Italy

P1-23 A0159 Reconstruction of Conductivity Distribution with Acousto-electrical Tomography Based on Neumann Boundary Condition

Kang An, Department of Electronic Engineering, Northwestern Polytechnical University, Xi’an, China

Changyou Li, Department of Electronic Engineering, Northwestern Polytechnical University, Xi’an, China

Kuisong Zheng, Department of Electronic Engineering, Northwestern Polytechnical University, Xi’an, China
P1-24 A0165 Research on Eddy Current Array Technique for Defect Detection of Aluminum Tubes

Heng Cao, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Tao Chen, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Hang Xu, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Linnan Huang, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Xiaqi Xiao, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China

P1-25 A0166 Nondestructive Evaluation of Circumferential Defects in Pipeline by Magnetic Measurement with Tunnel Magneto Resistor Sensor

Hang Xu, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Heng Cao, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Linnan Huang, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Donglin Li, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China

P1-26 A0179 Numerical Analysis and Interpretation of Eddy Current Magnetic Signature Micro-Magnetic Nondestructive Testing & Evaluation Method

Takamori Matsumoto, Graduate School of Engineering, Tohoku University, Japan
Benjamin Ducharme, Laboratoire de Génie Electrique et Ferroélectricité, France
Bhaawon Gupta, Laboratoire de Génie Electrique et Ferroélectricité, France/ Institute of fluid science IFS, Tohoku University, Japan/ ElyTMax UMI 3757, CNRS, Université de Lyon, Tohoku University, International Joint Unit, Tohoku University, Sendai, Japan
Gael Sebald, Laboratoire de Génie Electrique et Ferroélectricité, France/ Institute of fluid science IFS, Tohoku University, Japan/ ElyTMax UMI 3757, CNRS, Université de Lyon, Tohoku University, International Joint Unit, Tohoku University, Sendai, Japan
Tetsuya Uchimoto, Institute of fluid science IFS, Tohoku University, Japan/ ElyTMax UMI 3757, CNRS, Université de Lyon, Tohoku University, International Joint Unit, Tohoku University, Sendai, Japan

P1-27 A0168 Design of A Novel Magnetizing Probe for Eddy Current Testing of Small Defects in Ferromagnetic Steel Plates

Linnan Huang, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Chunhui Liao, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Tao Chen, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Heng Cao, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China
Hang Xu, School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China

P1-28 A0171 An Improved Multi-Frequency Eddy Current Excitation Method

Songke Li, School of Information Science and Engineering, Northeastern University, Shenyang 110819, China
Jinhai Liu, School of Information Science and Engineering, Northeastern University, Shenyang 110819, China

P1-29 A0260 Fast Sorting of Automobile Seat Parts by Heat-Treated States Based on Multi-Channel Eddy Current Testing Method

Junming Lin, Eddysun(Xiamen) Electronic Co., Ltd, Xiamen, 361008, China
Hanlin Li, School of Marine Engineering of Jimei University, Xiamen, 361021, China
Yaojin Luo, Eddysun(Xiamen) Electronic Co., Ltd, Xiamen, 361008, China
Weihua Lin, Eddysun(Xiamen) Electronic Co., Ltd, Xiamen, 361008, China
Kun Wang, Eddysun(Xiamen) Electronic Co., Ltd, Xiamen, 361008, China

P1-30 A0173 Evaluation of Tempering Induced Changes in The Mechanical Properties of 24crnimo Steel Using Magnetic Barkhausen Noise Analysis

Ruiyang Lv, Key laboratory of Nondestructive Testing of Ministry of Education, Nanchang Hangkong University, Nan Chang 330063, China/ National Key Laboratory for Remanufacturing, Academy of Armored Force, Beijing 100072, China
Shiyun Dong, Key laboratory of Nondestructive Testing of Ministry of Education, Nanchang Hangkong University, Nan Chang 330063, China
Kai Song, National Key Laboratory for Remanufacturing, Academy of Armored Force, Beijing 100072, China
Ping Men, National Key Laboratory for Remanufacturing, Academy of Armored Force, Beijing 100072, China
Xiaoting Liu, National Key Laboratory for Remanufacturing, Academy of Armored Force, Beijing 100072, China
Shixing Yan, National Key Laboratory for Remanufacturing, Academy of Armored Force, Beijing 100072, China
Xueliang Kang, National Key Laboratory for Remanufacturing, Academy of Armored Force, Beijing 100072, China

P1-31 A0176 Design of Power Grid Intelligent Patrol Operation and Maintenance System Based on Multi-Rotor UAV System
Qunying Liu, University of Electronic Science and Technology
Haifeng Zang, Guangzhou Polytechnic of Science and Trade
Shaojian Ni, University of Electronic Science and Technology
Bowen Li, University of Electronic Science and Technology
Jingsong Meng, University of Electronic Science and Technology
Yiguo Zhang, University of Electronic Science and Technology

P1-32 A0177 Design of Synchronous Motor Operation Control Platform Based on DSP
Qunying Liu, School of Automation and Engineering, University of Electronic Science and Technology of China
Junjie Dong, The Shenzhen Energy Storage Power Generation Co., Ltd. of China Southern Power Grid
Qian Peng, The Shenzhen Energy Storage Power Generation Co., Ltd. of China Southern Power Grid
Tao Yu, The Shenzhen Energy Storage Power Generation Co., Ltd. of China Southern Power Grid
Yeda Huang, The Shenzhen Energy Storage Power Generation Co., Ltd. of China Southern Power Grid
Jialiang Yu, The Shenzhen Energy Storage Power Generation Co., Ltd. of China Southern Power Grid

P1-33 A0178 Research on the Speed Regulation Strategy of Permanet Magnet Synchronous Motor based on Particle Optimization
Qunying Liu, School of Automation and Engineering, University of Electronic Science and Technology of China
Bowen Dou, School of Automation and Engineering, University of Electronic Science and Technology of China
Rufei He, School of Automation and Engineering, University of Electronic Science and Technology of China
Zhigiang Wang, School of Automation and Engineering, University of Electronic Science and Technology of China
Qing Li, School of Automation and Engineering, University of Electronic Science and Technology of China
Chuangjia Chen, School of Automation and Engineering, University of Electronic Science and Technology of China

P1-34 A0180 Data Augmentation and Artificial Neural Networks for Eddy Currents Testing
Romain Cornerais, Groupe Signal Image et Instrumentation, ESEO, Angers, France/Institut de Recherche en "Energie Electrique de Nantes Atlantique, Saint-Nazaire, France
Roberto Longo, Groupe Signal Image et Instrumentation, ESEO, Angers, France/Laboratoire d’Acoustique de l'Université du Mans - UMR CNRS 8613, Le Mans, France
Aroune Duclos, Laboratoire d'Acoustique de l'Université du Mans - UMR CNRS 8613, Le Mans, France
Guillaume Wasselynnck, Institut de Recherche en "Energie Electrique de Nantes Atlantique, Saint-Nazaire, France
Gérard Berthiau, Institut de Recherche en "Energie Electrique de Nantes Atlantique, Saint-Nazaire, France

P1-35 A0183 Development of a Signal Processing Method for Metal Pipe Inspection Using Multi-Mode Microwaves
Takuya Katagiri, Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Miyagi, Japan
Guannen Chen, Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Miyagi, Japan
Noritaka Yusa, Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Miyagi, Japan
Hidetoshi Hashizume, Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Tohoku University, Miyagi, Japan
P1-36 A0190 Multilayer CFRP Fiber Orientation Characterization Using FEM and Eddy Current Pulse Compression Thermography

Q. Yi, Department of Electrical and Electronic Engineering, Newcastle University, Merz Court, NE1 7RU, Newcastle upon Tyne, UK
G.Y. Tian, Department of Electrical and Electronic Engineering, Newcastle University, Merz Court, NE1 7RU, Newcastle upon Tyne, UK
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S. Laureti, Department of Engineering, University of Perugia, Polo Scientifico odiatico di Terni, Strada di Pentima 4, 05100 Terni, Italy
M. Ricci, Department of Informatics, Modeling, Electronics and System Engineering, University of Calabria, Rende, 87036, Italy

P1-37 A0185 Probabilistic Evaluation of the Detection Capability of Eddy Current Probes Against Corrosion Pits on Inner Surface Of Pressure Vessel

Takuma Tomizawa, Graduate School of Engineering, Tohoku University
Haicheng Song, Graduate School of Engineering, Tohoku University
Noritaka Yusa, Graduate School of Engineering, Tohoku University

P1-38 A0186 Eddy Current Testing as an Evaluation Method of the Phase Transition of Austenitic Stainless Steels by Hydrogen Charging

Sho Takeda, Institute of Fluid Science (IFS), Tohoku University, Sendai, Miyagi, Japan
Tetsuya Uchimoto, Institute of Fluid Science (IFS), Tohoku University, Sendai, Miyagi, Japan
Toshiyuki Takagi, Institute of Fluid Science (IFS), Tohoku University, Sendai, Miyagi, Japan
Hirotoshi Enoki, Graduate School of Engineering, Tohoku University, Sendai, Miyagi, Japan
Takashi Iijima, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, Japan

P1-39 A0253 Imaging Detection of Additive Manufactured parts Using Laser Ultrasonic

Yi Jiang, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, 210000, P. R. China
Haitao Wang, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics Nanjing, Jiangsu, 210000, P. R. China
Guliyun Tian, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics Nanjing, Jiangsu, 210000, P. R. China/School of Electrical and Electronic Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
Shuai Chen, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics Nanjing, Jiangsu, 210000, P. R. China

P1-40 A0254 Magnetic Measured Theory and Experiment Research of Three-Dimensional Residual Stress for Ferromagnetic Components Based on Piezomagnetic Effect

Wei Xin, China Special Equipment Inspection and Research Institute, China
Keqin Ding, China Special Equipment Inspection and Research Institute, China

P1-41 A0256 Microwave Sensor Based on Coplanar Waveguides for Dielectric Characterization

Haoran Sun, University of Electronic Science and Technology of China, China
Guohong Du, Chengdu University of Information Technology, China
Guliyun Tian, University of Electronic Science and Technology of China, China

P1-42 A0258 A Method to Distinguish Plastic Deformation and Stress State of Materials Based on the Combination of Magnetic Barkhausen Noise and Magnetic Parameters

Jidong Tan, China Special Equipment Inspection And Research Institute, China
Yang Zheng, China Special Equipment Inspection And Research Institute, China
Gongtian Shan, China Special Equipment Inspection And Research Institute, China
Jinjie Zhou, China Special Equipment Inspection And Research Institute, China
Zongjian Zhang, China Special Equipment Inspection And Research Institute, China
**P-143 A0263 Signal Modeling of Electromagnetic Flowmeter under Threevalue Trapezoidal Wave Excitation Using Numerical Fitting Method**

Liang Ge, College of Mechanical and Electronic Engineering, Southwest Petroleum University, Chengdu, 610500, China; Institute for Artificial Intelligence, Southwest Petroleum University, Chengdu, 610500, China

Junxian Chen, College of Mechanical and Electronic Engineering, Southwest Petroleum University, Chengdu, 610500, China; Institute for Artificial Intelligence, Southwest Petroleum University, Chengdu, 610500, China

Ze Hu, School of Electronic and Information Engineering, Southwest Petroleum University, Chengdu, 610500, China

Qing Yang, School of Electronic and Information Engineering, Southwest Petroleum University, Chengdu, 610500, China

Xin Lai, School of Engineering, Newcastle University, Newcastle, NE1 7RU, UK.

**P-144 A0261 Non-Linear Magnetization Effects in Transient Potential Drop Measurements for NDE of Steel**

M. yvind Persvik, Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

Zhiliang Zhang, Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

**P-145 A0264 Analytical Model for Velocity Induced Fields of Pulsed Eddy Current Testing at High-speed**

Qing Zhang, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Kaiyu Li, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Guiyun Tian, School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU

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**Oral Session 1.1**

**Time:** 14:50-16:10

**Oral session:** QNDE and AI in ENDE and systems

**Room:** Huang Pu Hall

**Session chairs:** Toshiyuki Takagi, Bin Gao

**14:50-15:10 A0136**

*Evaluation of Eddy Current Response Due to the Applied Stress on a Steel Plate Using Phase Diagram*

Sanjeema Bajracharya, Tokyo Institute of Technology, Japan

Eiichi Sasaki, Tokyo Institute of Technology, Japan

**15:10-15:30 A0088**

*Intelligent Recognition and Visual Evaluation Methods for Defects Using ACPM Technique*

Xinan Yuan, China University of Petroleum, China

Wei Li, China University of Petroleum, China

Xiaokang Yin, China University of Petroleum, China

Guoming Chen, China University of Petroleum, China

**15:30-15:50 A0108**

*Micromagnetic Quantitative Prediction of Multipolemechanical Properties of DP590 Steel Strip*

Xianxian Wang, Beijing University of Technology, China

Cunfu He, Beijing University of Technology, China

Xiucheng Liu, Beijing University of Technology, China

Bin Wu, Beijing University of Technology, China

**15:50-16:10 A0122**

*3D Defect Quantification Based on Chirp Excitation and High-resolution EC-TMR Sensor*

Yang Wang, Shanghai Tech University, Shanghai, China

Chaoqung Ye, Shanghai Tech University, Shanghai, China

Meiling Wang, Shanghai Tech University, Shanghai, China

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**Coffee Break**

**Time:** 14:30-14:50

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**Coffee Break**

**Time:** 16:10-16:20
Oral Session 1.2

Time: 16:20-17:40
Oral session: QNDE and AI in ENDE and systems
Room: Huang Pu Hall
Session chairs: Toshiyuki Takagi, Bin Gao

16:20-16:40 A0124
Comparison of Neural Network and System Invariant Analysis Technology Applied to Eddy Current Testing
Xinwu Zhou, Tohoku University, Japan
Tetsuya Uchimoto, Tohoku University, Japan
Shichao Cai, Tohoku University, Japan
Tomoya Some, NEC Corporation, Japan
Toshiyuki Takagi, Tohoku University, Japan

16:40-17:00 A0131
Quantitative Assessment of Stress Corrosion Cracks Using Distribution of Magnetic Flux Density Based on Eddy Current Testing
Cherdpong Jomdecha, Xi'an Jiaotong University, China
Wenlu Cai, Xi'an Jiaotong University, China
Xudong Li, Xi'an Jiaotong University, China
Shujuan Xie, Xi'an Jiaotong University, China
Zhenmao Chen, Xi'an Jiaotong University, China
Tetsuya Uchimoto, Tohoku University, Japan
Toshiyuki Takagi, Tohoku University, Japan

17:00-17:20 A0209
Using Eddy Current Testing to Assess Damage on Carbon Fiber Reinforced Polymer
Dario Pasadas, Instituto de Telecomunicações, Portugal
Bo Feng, Instituto de Telecomunicações, Lisboa, Portugal
Artur Ribeiro, Universidade de Lisboa, Portugal
Helena Ramos, Universidade de Lisboa, Portugal

17:20-17:40 A0093
Micromagnetic Non-Destructive Testing on High Chromium Creep Test Samples: Characterization, Modelling and Physical Interpretation
Bhaawan Gupta, Tohoku University, Japan
Benjamin Ducharn, Univ. Lyon, France
Tetsuya Uchimoto, Tohoku University, Japan
Gael Sebald, Tohoku University, Japan

Dinner
Time: 18:30-20:00
Location: Royfont Dining Hall

ISC Meeting (Invited Only)
Time: 18:30-20:20
Location: Dubai Hall, Long Yue Chinese Restaurant, 2F, Longemont Hotel
Chair: Christophe Reboud
## Technical Schedule: Friday, 13th September

### Oral Session 2

**Time:** 8:00-10:10  
**Oral session:** ENDE sensors and numerical modeling  
**Room:** Huang Pu Hall  
**Session chairs:** Lalita Udpa, Zhiwei Zeng

#### 8:00-8:30 T03

**Flexible Tactile Sensors Based on Patterned Nanostructures of Graphene and 2D Materials (Invited Talk)**

- Pingan Hu, Harbin Institute of Technology, China  
- Guiyun Tian, Newcastle University, UK  
- Jia Zhang, Harbin Institute of Technology, China  
- Mingjin Dai, Harbin Institute of Technology, China  
- Wei Feng, Harbin Institute of Technology, China

#### 8:30-8:50 A0104

**Influence of Fatigue Damage on NDE of Plastic Strains in RAFM Steel Using Electromagnetic NDE Methods**

- Manru He, Xi’an Jiaotong University, China  
- Hong-En Chen, Xi’an Jiaotong University, China  
- Shejuan Xie, Xi’an Jiaotong University, China  
- Zhenmao Chen, Xi’an Jiaotong University, China  
- Tetsuya Uchimoto, Tohoku University, Japan  
- Toshiyuki Takagi, Tohoku University, Japan

#### 8:50-9:10 A0193

**Modeling of the Transduction of Electromagnetic Acoustic Transducers Operating on Ferromagnetic Materials Based on Equivalent Surface Force**

- Xu Ding, Wuhan University of Science and Technology, China  
- Xinjun Wu, Huazhong University of Science and Technology, China

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### 9:10-9:30 A0216

**Efficient Calculation of Transient Eddy Current Response from Cylindrical Conductive Media**

- Theodoros Theodoulidis, University of Western Macedonia, Greece  
- Anastasios Skarlatos, CEA Saclay, France

#### 9:30-9:50 A0222

**Efficient Numerical Model Solution of Electromagnetic Scattering Problems Based on the Dirichlet-to-Neumann Map**

- Antonello Tamburrino, University of Cassino and Southern Lazio, Italy  
- Antea Perrotta, University of Cassino and Southern Lazio, Italy  
- Anton Efremov, Michigan State University, USA  
- Antonio Maffucci, National Institute of Nuclear Physics, Italy  
- Lalita Udpa, Michigan State University, USA  
- Salvatore Ventre, University of Cassino and Southern Lazio, Italy

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### 9:50-10:10 A0101

**Corrosion Evaluation Of Steel Rebar In Concrete Using Electromagnetic Method**

- Dongfeng He, Research Center for Structural Materials, National Institute for Materials Science, Tsukuba, Japan

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**Coffee Break**

**Time:** 10:10-10:20
Oral Session 3

Time: 10:20-12:00

Oral session: Analytical and numerical modeling
Room: Huang Pu Hall
Session chairs: Sandor Bilićz, Mengbao Fan

10:20-10:40 A0103

Probabilistic Analysis of The Capability of EMAR For Monitoring Wall Thinning

Noritaka Yusa, Tohoku University, Japan
Haicheng Song, Tohoku University, Japan
Daiki Iwata, Tohoku University, Japan
Tetsuya Uchimoto, Tohoku University, Japan
Toshiyuki Takagi, Tohoku University, Japan
Makoto Moroi, Tohoku Electric Power Co., Inc., Japan

10:40-11:00 A0121

Effect of Electric Anisotropy on Skin Depth of Induced EM Fields in CFRP Due to Eddy Current Sensors

Jun Cheng, Nanjing Normal University, China
Shuai Xu, Nanjing University of Aeronautics and Astronautics, China
Jiquan Yang, Nanjing Normal University, China
Jinhao Qiu, Nanjing University of Aeronautics and Astronautics, China
Toshiyuki Takagi, Tohoku University, Japan

11:00-11:20 A0123

A Mixed Strategy for Efficient Acousto-Electric Tomography Based on Complete Electrode Model

Changyou Li, Northwestern Polytechnical University, China
Kang An, Northwestern Polytechnical University, China
Kuisong Zheng, Northwestern Polytechnical University, China
Dominique Lesselier, Univ. Paris-Saclay, France

11:20-11:40 A0167


Zongfei Tong, Xi'an Jiaotong University, China
Shejuan Xie, Xi'an Jiaotong University, China
Xudong Li, Xi'an Jiaotong University, China
Cuixiang Pei, Xi'an Jiaotong University, China
Zhenmao Chen, Xi'an Jiaotong University, China
Yunze He, Hunan University, China

11:40-12:00 A0181

Optimal Design of Remote Field Eddy Current Testing Using Shielding Plate and Ferromagnetic Ring for Ferromagnetic Pipeline Inspection

Salbo She, Hunan University, China
Yunze He, Hunan University, China

Lunch

Time: 12:00-13:20
Location: Rayfont Dining Hall
Poster Session 2

Time: 13:20-14:50
Room: Hong Kou Hall
Session chairs: Christophe Reboud, Artur Lopes Ribeiro, Yiming Deng

P2-1 A0187 The Automatic Inspection of Photovoltaic Cell Based on CNN and the Registration of E1 And ET Images

Baoyuan Deng, College of Electrical and Information Engineering, Hunan University, Changsha, China
Yunze He, College of Electrical and Information Engineering, Hunan University, Changsha, China
Yuan Yang, College of Electrical and Information Engineering, Hunan University, Changsha, China

P2-2 A0188 Application of Artificial Neural Networks in Fault Detection and Diagnosis: The Case of Artificial Intelligence in Monitoring Mechanical Structures

Stephen Dankwa, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China
Wenfeng Zheng, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China
Bin Gao, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China

P2-3 A0184 Thickness Evaluation of Coiled Tubing Using Pulsed Uniform Electromagnetic Field

Jianming Zhao, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China) Qingdao, China
Wei Li, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China) Qingdao, China
Xin’an Yuan, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China) Qingdao, China
Xiaokang Yin, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China) Qingdao, China
Guoming Chen, Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China) Qingdao, China

P2-4 A0192 Robot-aided Micromagnetic Testing System for Complex Automobile Body Components

Cunfu He, College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, China
Haijiang Dong, College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, China

Xiucheng Liu, College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing, China

Wang Li, College of Science, Xi’an University of Posts and Telecommunications, Xi’an, 710121, China
Zhenmao Chen, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Center of NDT and Structural Integrity Evaluation, Xi’an Jiaotong University, Xi’an, 710049, China

Qingze Tian, School of Aerospace Engineering, Xiamen University, Xiamen, China
Zhiwei Zeng, School of Aerospace Engineering, Xiamen University, Xiamen, China

Fan Li, School of Aerospace Engineering, Xiamen University, Xiamen, China
Zhiwei Zeng, School of Aerospace Engineering, Xiamen University, Xiamen, China
Xiaohua Liu, School of Aerospace Engineering, Xiamen University, Xiamen, China
Junming Lin, Work Station of Academicians, Fujian Province (Eddyson), Xiamen, China
Yonghong Dai, Work Station of Academicians, Fujian Province (Eddyson), Xiamen, China

P2-5 A0186 Crack Shape Reconstruction Using an Adaptive Genetic Algorithm from Multi-Frequency Eddy Current Testing Signals

P2-6 A0187 Hybrid Formulation Domain Decomposition Finite Element Method for Simulating Eddy Current Testing

P2-7 A0198 Remote Field Eddy Current Testing of Fiber Fracture in Unidirectional CFRP

Yanfei Liao, School of Aerospace Engineering, Xiamen University, Xiamen, China
Zhiwei Zeng, School of Aerospace Engineering, Xiamen University, Xiamen, China
Xiaohua Liu, School of Aerospace Engineering, Xiamen University, Xiamen, China
Junming Lin, Work Station of Academicians, Fujian Province (Eddyson), Xiamen, China
Yonghong Dai, Work Station of Academicians, Fujian Province (Eddyson), Xiamen, China

P2-8 A0199 Rail Damage Imaging Method with Multi-objective High Resolution Autonomous Focusing Based on Time Reverse Operator Decomposition

Xin Li, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
Gulyun Tian, School of Electrical, Electronic and Computer Engineering, Newcastle University, Newcastle NE1 7RU, China
Haitao Wang, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
Zeyu Dong, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
Yi Jiang, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
<table>
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<tr>
<th>Paper</th>
<th>Title</th>
<th>Authors</th>
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| P2-9 | A0200 Analysis of Magnetic Flux Leakage In-line Inspection Data Based on Multi-sensor Data Fusion Technology | Weilin Shao, Pressure Pipeline Division, China Special Equipment Inspection and Research Institute, Beijing, China  
Jinzong Chen, Pressure Pipeline Division, China Special Equipment Inspection and Research Institute, Beijing, China |
| P2-10 | A0205 Tensor Based Finite Element Model for the Calculation of Leakage Field in Magnetic Flux Leakage Testing | Alimey Fred John, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China  
Libing Bai, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China  
Yuhua Cheng, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China |
| P2-11 | A0206 Eddy Current Pulsed Thermography for Metal Additive Manufactured Part Defect Detection | Yunlai Gao, COMAC Beijing Aeronautical Science and Technology Research Institute, Beijing, China  
Jiazheng Zhang, COMAC Beijing Aeronautical Science and Technology Research Institute, Beijing, China  
Bin Gao, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China  
Gulyun Tian, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China |
| P2-12 | A0207 Stress Corrosion Cracking Comparative Analysis of Electrical Steels Using Needle Probes Technique | Y. A. Tana Daffo, Faculty of Engineering and Technology of the University of Buea, CAMEROON  
P. Tsafack, Faculty of Engineering and Technology of the University of Buea, CAMEROON  
B. Gupta, Laboratoire de Génie Electrique et Ferroélectricité, INSA Lyon, FRANCE  
B. Ducharme, Laboratoire de Génie Electrique et Ferroélectricité, INSA Lyon, FRANCE/ School of Engineering Technology, Purdue University, USA |
| P2-13 | A0211 A Self-Sensing Woven Hybrid Fiber Composite with Chipless RFID Sensing Enabled Structure | Adi Mahmud Jaya MARINDRA, School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU  
Gulyun Tian, School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU |
| P2-14 | A0212 A Phase Measurement Based Structured Light Sensor for the Inspection of Internal Corrosion of Metal Pipes | Mohand Alzuhrif, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, USA  
Zonglin Li, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, USA  
Yiming Deng, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, USA |
| P2-15 | A0213 Thermography Detection for Hidden Surface Cracks in Metals under Polymer Coatings | Yongheng Wang, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China  
Xiaorong Gao, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China  
Jianping Peng, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China  
Netzelmann Udo, Fraunhofer Institute for Nondestructive Testing IZFP, Dept. Components and Assemblies, Campus E3 1, 66123 Saarbrücken, Germany |
| P2-16 | A0214 Comparison and Fusion of Multi-Sensors Eddy Current Images by Exploiting Hermite-Gaussian Pattern Analysis | H. Chebbi, Laboratoire Simulation et Modélisation, CEA LIST, GIF-sur-Yvette, 91191, France  
Z. Chen, School of Electrical and Electronic Engineering, University of Manchester, Manchester, M13 9PL, UK  
L. Ferrigno, DIEI Dept., Università degli Studi di Cassino e dellaLazioMeridionale, Cassino (FR), 03043, Italy  
M. Laracca, DIEI Dept., Università degli Studi di Cassino e dellaLazioMeridionale, Cassino (FR), 03043, Italy  
H. Malekmammadi, Dept. of Engineering, University of Perugia, Perugia, Italy  
D. Premel, Laboratoire Simulation et Modelisation, CEA LIST, GIF-sur-Yvette, 91191, France  
M. Ricci, DIMES Dept., University of Calabria, Rende (CS), Italy  
G.Y. Tian, School of Engineering, Newcastle University, Newcastle, NE1 7RU, UK  
Q. Yi, School of Engineering, Newcastle University, Newcastle, NE1 7RU, UK  
W. Yin, School of Electrical and Electronic Engineering, University of Manchester, Manchester, M13 9PL, UK |
P2-17 A0215 Numerical Analysis of the Effect of Varying Thickness on Transduction Efficiency of Lamb Waves

Gongzhe Qiu, Huazhong University of Science and Technology, China

P2-18 A0219 Research on Stress Detection of DC01 Steel via Barkhausen Noise

Xiang Zhang, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China
Jianping Peng, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China
Xiaorong Gao, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China
Jie Bai, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China

P2-19 A0220 Research on Microcrack Algorithm Based on Eddy Current Pulsed Thermography

Lingfan Feng, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China
Jianping Peng, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China
Xiaorong Gao, Photoelectric Engineering Institute, Southwest Jiaotong University, Chengdu, China

P2-20 A0221 Imaging via Monotonicity: From Two-Phase to Graded Materials

Antonello Tamburrino, DIEI, University of Cassino and Southern Lazio, Cassino, Italy; ECE, Michigan State University, East Lansing, USA
Guglielmo Rubinacci, DIETI, University of Naples “Federico ii”, Napoli, Italy
Salvatore Ventre, DIEI, University of Cassino and Southern Lazio, Cassino, Italy

P2-21 A0223 Multidirectional Alternating Current Potential Drop Technique for Classifying Defects on Inner Surface of Pipeline

Wenyang Li, School of Manufacturing Science and Engineering, Sichuan University, Chengdu 610065, China
Fangji Gan, School of Manufacturing Science and Engineering, Sichuan University, Chengdu 610065, China
Shiping Zhao, School of Manufacturing Science and Engineering, Sichuan University, Chengdu 610065, China
Yongjie Zhou, College of physics and electronic information engineering, Qinghai Normal University, Xining 810016, China


Dagmar Faktorova, Faculty of Electrical Engineering and Information Technology, University of Žilina, Slovak Republic
Rozina Steigmann, Nondestructive Testing Department, National Institute of R&D for Technical Physics, Iasi, Romania
Nicoleta Iftimie, Nondestructive Testing Department, National Institute of R&D for Technical Physics, Iasi, Romania
Mariana Dominca Stanclu, Faculty of Mechanical Engineering, Transilvania University, Brasov, Romania
Peter Fabo, Research Centre, University of Žilina, Slovak Republic
Adriana Savin, Nondestructive Testing Department, National Institute of R&D for Technical Physics, Iasi, Romania

P2-23 A0226 Data Fusion of Holistic NDE for Boiler Inspection

Xiaodong Shi, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA
Xuhui Huang, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA
Claron Hamilton, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA
Fares T. Alharbi, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA
Lalita Udpa, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA
Yiming Deng, Nondestructive Evaluation Laboratory, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA

P2-24 A0228 Model Based Probe Optimization for Pulsed Eddy Current Testing Inspections of Tubes

Roberto Miorelli, CEA, LIST, Gif-sur-Yvette, France
Chiara Zorni, EDF, Direction Industrielle, Département END Automatisés, 2 rue Ampère, Saint Denis, France
Natalia Sergeeva-chollet, CEA, LIST, Gif-sur-Yvette, France
Christophe Reboud, CEA, LIST, Gif-sur-Yvette, France

P2-25 A0230 Parameter Optimization Design of Eddy Current Sensor Based on Finite Element Analysis
Minghui Hu, Key Laboratory of Pressure Systems and Safety, MOE, East China University of Science and Technology, Shanghai, 200237, China

Ziyue Yuan, Key Laboratory of Pressure Systems and Safety, MOE, East China University of Science and Technology, Shanghai, 200237, China

Shandong Tu, Key Laboratory of Pressure Systems and Safety, MOE, East China University of Science and Technology, Shanghai, 200237, China

P2-26 A0231 Material Toughness Critical Value Determination for the Pipeline Submitted Under Medium Pressure

Darko Bajic, Faculty of Mechanical Engineering, University of Montenegro, Podgorica, Montenegro

Srećan Culafic, Faculty of Mechanical Engineering, University of Montenegro, Podgorica, Montenegro

P2-27 A0232 Edge Detection of Metal Thickness of Electromagnetic Acoustic Transducer Based on Super-Heterodyne Phase-Sensitive Detector

Zhichao Cai, School of Electrical and Automation Engineering, East China Jiaotong University

Zhenyong Zhao, School of Electrical and Automation Engineering, East China Jiaotong University

Lan Chen, School of Electrical and Automation Engineering, East China Jiaotong University

Gulyun Tian, School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU

P2-28 A0233 Multi-source Effect in Electric Current Perturbation Testing for Ferromagnetic conductor

Zhiyang Deng, Key Lab of Digital Manufacturing Equipment & Technology, Huazhong University of Science and Technology

Yihua Kang, Key Lab of Digital Manufacturing Equipment & Technology, Huazhong University of Science and Technology

Xiaochun Song, School of Mechanical Engineering, Hubei University of Technology Wuhan China

P2-29 A0236 Hybrid Hysteresis Models Based on a Regressor Approach for the Characterisation of Soft Steels

Anastassios Skarlatos, CEA, LIST, CEA Saclay, 91191 Gif-sur-Yvette, France

Ane Martinez-De-Guerenu, CEIT, Manuel Lardizabal 15, 20018 Donostia / San Sebastián, Spain/ Universidad de Navarra, Tecnun, Manuel Lardizabal 15, 20018 Donostia / San Sebastián, Spain

Roberto Miorelli, CEA, LIST, CEA Saclay, 91191 Gif-sur-Yvette, France

Christophe Rebound, CEA, LIST, CEA Saclay, 91191 Gif-sur-Yvette, France


Yali Du, Shanxi Engineering Research Center for NDT and Structural Integrity Evaluation, State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi’an Jiaotong University, Xi’an, 710049, China/ Department of Applied Physics, School of Science, Xi’an Polytechnic University, Xi’an 710048, China

Shejuan Xie, Shanxi Engineering Research Center for NDT and Structural Integrity Evaluation, State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi’an Jiaotong University, Xi’an, 710049, China

Xudong Li, Shanxi Engineering Research Center for NDT and Structural Integrity Evaluation, State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi’an Jiaotong University, Xi’an, 710049, China

Zhennao Chen, Shanxi Engineering Research Center for NDT and Structural Integrity Evaluation, State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi’an Jiaotong University, Xi’an, 710049, China

P2-31 A0238 Efficient Analytical Model for Pulsed Eddy Current Evaluation of Tubes

Zhian Xue, School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, P.R. China

Mengbao Fan, School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, P.R. China

Binghua Cao, School of Information and Control Engineering, China University of Mining and Technology, Xuzhou, P.R. China

P2-32 A0240 Fast Localization of Impact Damage on Woven CFRP based on Sparse Microwave Imaging

Ruslee Suthaweekvil, Department of Electrical and Computer Engineering, Faculty of Engineering, King Mongkut’s University of Technology North Bangkok, Thailand, 10800

Gulyun Tian, School of Engineering, Newcastle University, Newcastle, UK, NE1 7RU

P2-33 A0241 Natural Crack Evaluation Based on Novel Yoke Structured Electromagnetic Thermography

Zewei Liu, School of Automation Engineering, University of Electronic Science and Technology of China, China

Bin Gao, School of Automation Engineering, University of Electronic Science and Technology of China, China

Xiaofeng Li, School of Automation Engineering, University of Electronic Science and Technology of China, China

Gulyun Tian, School of Automation Engineering, University of Electronic Science and Technology of China, China/ School of Engineering, Newcastle University, England, UK
P2-34 A0242 The Effect of Grain and Grain Boundary Microstructure on Domain Wall Motion and Magnetic Barkhausen Noise under Tensile Stress

Jia Liu, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China
Guilyun Tian, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, China

P2-35 A0245 Reconstructing The 3-D Sizes of Defects with Magnetic Flux Leakage Testing Signal

Hongmei Li, Nondestructive Testing and Structural Reliability Evaluation Laboratory, North Minzu University, Yinchuan 750021 China
Ranran Huang, Nondestructive Testing and Structural Reliability Evaluation Laboratory, North Minzu University, Yinchuan 750021 China
Jia Yan, Nondestructive Testing and Structural Reliability Evaluation Laboratory, North Minzu University, Yinchuan 750021 China

P2-36 A0246 Quantitative Evaluation and Imaging of Localised Thickness Loss in GFRP with Ka-Band Microwave Open Ended Waveguides

Jinhua Hu, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Centre of NDT and Structural Integrity Evaluation, School of Aerospace Engineering, Xi'an Jiaotong University, ShaanXi, Xi'an 710049, China
Yong Li, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Centre of NDT and Structural Integrity Evaluation, School of Aerospace Engineering, Xi'an Jiaotong University, ShaanXi, Xi'an 710049, China
Jianguo Tan, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Centre of NDT and Structural Integrity Evaluation, School of Aerospace Engineering, Xi'an Jiaotong University, ShaanXi, Xi'an 710049, China
Wenjia Li, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Centre of NDT and Structural Integrity Evaluation, School of Aerospace Engineering, Xi'an Jiaotong University, ShaanXi, Xi'an 710049, China
Zhenmao Chen, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Centre of NDT and Structural Integrity Evaluation, School of Aerospace Engineering, Xi'an Jiaotong University, ShaanXi, Xi'an 710049, China

P2-37 A0248 Eddy Current Testing of the Lightning Strike Protection Layer in Aerospace Composite Structures

Bo Feng, Instituto de Telecomunicaciones, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
Dario J. Pasadas, Instituto de Telecomunicaciones, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
Artur L. Ribeiro, Instituto de Telecomunicações, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
Helena G. Ramos, Instituto de Telecomunicações, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

P2-38 A0249 Quantitative Evaluation of Conductivity Distribution inside Stress Corrosion Crack with Electromagnetic NDE Methods

Wenlu Cai, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Center of NDT and Structural Integrity Evaluation, Xi'an Jiaotong University, Xi'an 710049, China
Cherdpong Jomdecha, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Center of NDT and Structural Integrity Evaluation, Xi'an Jiaotong University, Xi'an 710049, China
Li Wang, College of Science, Xi'an University of Posts and Telecommunications, Xi'an 710121, China
Zhenmao Chen, State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Engineering Research Center of NDT and Structural Integrity Evaluation, Xi'an Jiaotong University, Xi'an 710049, China

P2-39 A0250 Electromagnetic NDT Methods for Evaluation of Steel Specimens after Tensile Testing

Tomasz Chady, West Pomeranian University of Technology, Szczecin, Faculty of Electrical Engineering, Sikorski St. 37, 70-313 Szczecin, Poland
Piotr GLOGOWSKI, West Pomeranian University of Technology, Szczecin, Faculty of Electrical Engineering, Sikorski St. 37, 70-313 Szczecin, Poland

P2-40 A0252 An Electromagnetic Acoustic Transducer for Generating and Receiving Torsional Mode Guided Waves

Chen Huang, Science and Technology on Electromagnetic Compatibility Laboratory, China Ship Development and Design Center, Wuhan, 430054, P.R. China
Jiang Xu, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, 430074, P.R. China

P2-41 A0255 Development of an Omni-Directional PPM EMAT for Plate Inspection

Zenghua Liu, Beijing University of Technology, China
Aili Li, Beijing University of Technology, China

P2-42 A0257 A Method to Distinguish Plastic Deformation and Stress State of Materials based on the Combination of Magnetic Barkhausen Noise and Magnetic Parameters
Yang Zheng, China Special Equipment Inspection And Research Institute, China

Jidong Tan, China Special Equipment Inspection And Research Institute, China

Gongtian Shen, China Special Equipment Inspection And Research Institute, China

Bin Gao, University of Electronic Science and Technology of China, China

Zongjian Zhang, China Special Equipment Inspection And Research Institute, China

P2-43 A0259 Irregular Eddy Current Testing of Micro-Cracks on Relay Contacts

Junming Lin, Eddysun(Xiamen) Electronic Co., Ltd, Xiamen, Fujian, 361008, P. R. China

Hanlin Li, School of Marine Engineering of Jimei University, Xiamen, Fujian, 361021, P. R. China

Weihua Lin, Eddysun(Xiamen) Electronic Co., Ltd, Xiamen, Fujian, 361008, P. R. China

Yaojin Luo, Eddysun(Xiamen) Electronic Co., Ltd, Xiamen, Fujian, 361008, P. R. China

Yonghong Dai, Eddysun(Xiamen) Electronic Co., Ltd, Xiamen, Fujian, 361008, P. R. China

P2-44 A0261 Magnetic Field and Stress-induced Magnetic Domain Reorientation and Its Correlation with Barkhausen Noise

Fasheng Qiu, Key Laboratory of Nondestructive Testing (Nanchang Hang Kong University), Ministry of Education, Nanchang 330063, P.R China

Matic Jovičević Klug, Institute for Materials Science, Kiel University, Kiel 24143, Germany

Jeffrey McCrod, Institute for Materials Science, Kiel University, Kiel 24143, Germany

Guiyun Tian, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu 611731, People’s Republic of China

P2-45 A0265 Multi-Channel IoT-based Ensemble-Features Fault Diagnosis for Machine Condition Monitoring

Shang Gao, the school of mechanical engineer, Nanjing University of Science and Technology, China

Cuicui Du, the school of mechanical engineer, Nanjing University of Science and Technology, China

Deren Kong, the school of mechanical engineer, Nanjing University of Science and Technology, China

Fei Shang, Corresponding author, the school of mechanical engineer, Nanjing University of Science and Technology, China

Coffee Break

Time: 14:30-14:50

Oral Session 4

Time: 14:50-16:10

Oral session: ENDE application

Room: Huang Pu Hall

Session chairs: Tomasz Chady, Yunze He

14:50-15:10 A0116

Improved Design of A Side-Incident Microwave Probe for Non-Destructive Inspection of Metallic Pipes

Guanren Chen, Tohoku University, Japan

Takuya Katagiri, Tohoku University, Japan

Noritaka Yusa, Tohoku University, Japan

Hidetoshi Hashizume, Tohoku University, Japan

15:10-15:30 A0129

Evaluation of Detectability of Differential Type Probe with Directional Eddy Current for Detection of Fiber Misalignment in CFRP

Hiroyuki Kosukewaga, Tohoku University, Japan

Yuta Kiso, Tohoku University, Japan

Mitsuo Hashimoto, Tohoku University, Japan

Toshiyuki Takagi, Tohoku University, Japan

11:20-11:40 A0224

Nondestructive Evaluation of Surface Corrosion in Weakly Magnetic Stainless Steel Plates Using Discriminative and Generative Classifiers

Prashanth Baskaran, Universidade de Lisboa, Portugal

Helena Ramos, Universidade de Lisboa, Portugal

Artur Ribeiro, Universidade de Lisboa, Portugal

Jorge Pereira, Universidade de Lisboa, Portugal

15:50-16:10 A0119

Study of Closed Crack Detection by Vibro-Acoustic Modulation under Electromagnetic Loading

Chuang Zhang, Hebei University of Technology, China

Longlong He, Hebei University of Technology, China

Suizhen Liu, Hebei University of Technology, China

Coffee Break

Time: 16:10-16:20
Technical Schedule: Saturday, 14th September

Oral Session 5
Time: 16:20-17:40
Oral session: ENDE application for high speed railway
Room: Huang Pu Hall
Session chairs: Jinyi Lee, Jianping Peng

16:20-16:40 A0095
Flaw Detection near the TSP of A CuNi Test Specimen Using Frequency Characteristics of A Cylinder-Type Magnetic Camera
Hoyong Lee, Gwangju University, Republic of Korea
Sejin Kim, Chosun University, Republic of Korea
Heejong Lee, Chosun University, Republic of Korea
Jinly Lee, Chosun University, Republic of Korea

16:40-17:00 A0182
Evaluation of Local Wall Thinning of Carbon Steel Pipe Based on Multi-Frequency Electromagnetic Field
Shanshan Sun, Jiangnan University, China
Deqiang Zhou, The Key Laboratory for Advanced Food Manufacturing Equipment Technology of Jiangsu, China
Noritaka Yusa, The Key Laboratory for Advanced Food Manufacturing Equipment Technology of Jiangsu, China

17:00-17:20 A0210
Wireless Power Transfer Based Eddy Current for Characterization of Crack Orientation
Lawal Umar Daura, Newcastle University, UK
Guliyun Tian, Newcastle University, UK

17:20-17:40 A0099
The Highspeed Railway Inspection Technologies and Non-Destructive Technichal Properties Measurement Technologies Develooped in the Key Laboratory of Non-Destructive Testing and Monitoring Technology for High-Speed Transport Facilities of The Ministry of Industry and Information Technology
Ping Wang, Nanjing University of Aeronautics and Astronautics, China

Oral Session 6
Time: 8:00-10:10
Oral session: Material characterization
Room: Huang Pu Hall
Session chairs: Marco Ricci, Shejuan Xie

8:00-8:30 T04
Magnetic Property Changed by Interaction of Immuno-Magnetic Nano-Particle with Bacteria Cell (Invited talk)
Isaratat Phung-On, King Monuk’s University of Technology Thonburi, Thailand

8:30-8:50 A0106
Magnetic Barkhausen Noise Mapping System for Laser-quenched Zone in Steel Shaft
ChuanDong Zhang, Beijing University of Technology, China
Cunfu He, Beijing University of Technology, China
Xiucheng Liu, Beijing University of Technology, China

8:50-9:10 A0174
Fast 3D Model Dedicated to Thermographic Inspections of Planar Composite Structures
Anpion Ratsakou, CEA, LIST, France
Christophe Reboud, CEA, LIST, France
Anastassios Skaltsos, CEA, LIST, France
Dominique Lesselier, Laboratoire des Signaux et Systèmes, France

9:10-9:30 A0175
Dependence of Corecivity and MBN Signal on Martensitic Stainless Steel With and Without Quench
Hiroaki Kikuchi, Iwate University, Japan
Kohei Sugai, Iwate University, Japan
Keilichi Matsumura, INFINITECH Co., Ltd., Yokohama, Japan

Gala dinner and award ceremony
Time: 18:30-21:00 Location: Phoneix Ballroom III
Smart Coating based on Frequency Selective Surface for Position Insensitive Crack Monitoring

Bingsheng Zhang, Guangdong University of Technology, China
Kun Wang, Guangdong University of Technology, China
Yao Li, Guangdong University of Technology, China
Chutian Huang, Guangdong University of Technology, China
Jun Zhang, Guangdong University of Technology, China
Guiyun Tian, Newcastle University, UK

Characterization of Bearing Rings Using Pulsed Eddy Current Evaluation

Mengbao Fan, China University of Mining and Technology, China
Jingwei Sha, China University of Mining and Technology, China
Binghua Cao, China University of Mining and Technology, China

Oral Session 7

Time: 10:20-12:00
Oral session: Inverse problems and signal processing
Room: Huang Pu Hall
Session chairs: Antonello Tamburrino, Yong Li

Sensitivity Analysis for The Inverse Problems of Electromagnetic Nondestructive Evaluation

Sándor Bilicz, Budapest University of Technology and Economics, Hungary

A Signal Processing Method for Steel Plate Thickness Measurement Using EMATS

Chao Jiang, Huazhong University of Science and Technology, China
Wencai Liu, CNPC Research Institute of Safety and Environment Technology, China
Xinjun Wu, Huazhong University of Science and Technology, China

Comparison of Different Approaches to Mitigate Diffusion Effects on Time-Analysis of Eddy Current Signals

M. Ricci, University of Calabria, Italy
H. Malekmohammadi, University of Perugia, Italy
Q. Yi, Newcastle University, UK
G. Y. Tian, Newcastle University, UK
De Marchi, University of Bologna "Alma Mater", Italy
M. Malatesta, University of Bologna "Alma Mater", Italy
L. Ferrigno, University of Cassino and Southern Lazio, Italy
M. Laracca, DIEI Dept., University of Cassino and Southern Lazio, Cassino, 03043, Italy
L. Udpa, Michigan State University, USA
A. Tamburrino, Michigan State University, USA/University of Cassino and Southern Lazio, Italy

Coffee Break

Time: 10:10-10:20
15:30-15:50 A0234
Capacitive Imaging Based Sensitivity Distribution Study for Adhesion Assessment

Xuhui Huang, Michigan State University, USA
Claron Hamilton, Michigan State University, USA
Zonglin Li, Michigan State University, USA
Lalita Udpa, Michigan State University, USA
Satish S. Udpa, Michigan State University, USA
Yiming Deng, Michigan State University, USA

Closing ceremony

Time: 11:40-12:00  Room: Huang Pu Hall  Host: Suixin Yang

Lunch

Time: 12:00-13:20  Location: Rayfont Dining Hall

Lab Visit

Time: 14:00-17:30  Location: Qingshuihe Campus, UESTC
Host: Yuhua Cheng

ENDE2019
Social Events
General Information
Social Events

- **CHINESE EM NDT BOARD MEETING**
  
  **Location:** Huang Pu Hall  
  **Time:** Wednesday, September 11, 15:00 – 17:30

- **ISC MEETING**
  
  **Location:** Dubai Hall, Long Yue Chinese Restaurant  
  **Time:** Thursday, September 12, 18:30 – 20:00  
  The ISC meeting session will take place on Friday, September 12, in the Dubai hall, Long Yue Chinese Restaurant, Longemont Hotel. All ISC members are invited to attend.

- **WELCOME RECEPTION**
  
  **Location:** Skyline Freshly Brewery Bar (42F, Longemont Hotel)  
  **Time:** Wednesday, September 11, 18:00 – 21:30  
  The Welcome Reception for ENDE 2019 will take place on Wednesday, September 11 in the Longemont Hotel. All attendees that are registered for the conference are welcome to join.

- **GALA DINNER**
  
  **Location:** Phoenix Ballroom, Longemont Hotel  
  **Time:** Friday, September 13, 18:30 – 21:00  
  The Gala dinner for ENDE 2019 will take place on Thursday, September 13, in the Longemont Hotel. All attendees are welcome to participate. Best Poster Award and Travel Award will be announced during this time. Meanwhile, performance with local Sichuan characteristic will be held.

- **CLOSING CEREMONY**
  
  **Location:** Huang Pu Hall  
  **Time:** Saturday, September 14, 11:40-12:00  
  The closing ceremony will take place on Saturday, September 14, in the Huang Pu Hall. Best Oral Presentation Award will be announced during this time.

- **LAB VISIT**
  
  **Location:** Qingshuihe campus, UESTC  
  **Time:** Saturday, September 14, 14:00-17:00  
  The lab visit to University of Electronic Science and Technology of China will take place in Saturday, September 14. Shuttle buses will be arranged.
Instruction for Presentation

Oral Presentation

The duration of a presentation slot is 20 minutes. Please make sure your lecture limited within 15 minutes so that audience can have 5 mins for the questions. Presentations MUST be uploaded at the speakers’ room at least 20 minutes before the session starts. Please bring a paper printed with your short bio (200 words at most) to the session room and then give it to the session chair prior to your presentation.

Poster Presentation

Poster Format:
The size of poster board is 90cm (W)* 120cm (H). Posters will be in portrait format. Layout of poster is provided as an example template for editing your poster.

Submission Instructions:
Poster(s) can be printed by yourself. For the convenience of authors, we provide the poster printing service, authors can click the "Print Poster" button on the Quick Links of the main page, then upload a poster and make payment ($15 for each poster). Please note that the poster printing service will end on 8th September 2019.

Notice:
Each poster board will be labelled with a specific “Board Number “, which corresponds to a dedicated poster. Please refer to the conference program to find your poster board on-site. You are required to stand at your poster for the duration of the poster session. It is essential to present your work to anyone interested in it and to make sure that your presence is verified by one of the session chairs. Before the start of each poster session, our staff will provide necessary assistance for on-site installation of individual posters. After poster session, you are required to remove your poster.

Tips:
The template is only a guideline. The authors are responsible to make sure the final posters are in good visual and technical quality for poster awards.
ENDE2019 will have three types of conference awards to reward and support researchers in the field of ENDE. All conference awards will be judged by members of ISC and session chairs.

**Best Oral Presentation Awards**

The Best Oral Presentation Awards will be offered to up to two best oral presentation papers of high overall quality and level of innovation. The winners will receive a certificate and rewards. All oral presented papers will be eligible for nomination for best oral presentation awards provided they meet the requirement: it is required that an author of the paper must be fully registered, and in attendance to present details and answer questions during the designated oral presentation session.

**Best Poster Awards**

The Best Poster Awards will be given to up to four best posters presented at the conference. The posters will be evaluated in terms of design and layout, novelty, key points, balance of text visuals, and overall evaluation. The winners will receive a certificate and other rewards. The posters will be eligible for nomination for Best Poster Awards provided they meet the following requirements:

- It is required that an author of the poster must be fully registered, and in attendance to present details and answer questions during the designated poster presentation session.
- The first author must be a student or young researcher (no more than 35 years old before December 31, 2019), including MSc/PhD students and Research Associates.
- The poster should consist of well-prepared visual materials about the work, posted on a designated board.

**Travel Awards**

The Travel Awards will be presented to up to three attendees in order to encourage researchers to participate in the conference from a distance. Selection criteria include the novelty of the research, quality of the paper, and clarity of the presentation. The winners will receive a certificate and financial support. The attendees will be eligible for nomination for Travel Awards provided they meet the following requirements:

- It is required that the attendee must complete conference registration, and in attendance to present details and answer questions during the designated oral/poster presentation session.
- The attendee currently not residing in the hosting country of the conference, regardless of nationality.

Please note that there is no need to apply for the above awards, the evaluation will take place during the conference. Nobody is able to receive awards in duplicate.
Venue Map

1F Dragon ballroom layout: Opening ceremony

2F Session venue layout
ENDE History

The first ENDE was held in London in 1995, and the following list contains histories of the ENDE conferences:

1st ENDE, London, UK, 1995, Roy Collins;
2nd ENDE, Tokyo, Japan, 1996, Kenzo Miya;
3rd ENDE, Reggio Calabria, Italy, 1997, Raffaele Albanese;
4th ENDE, Chatou, France, 1998, D. Lesselier & A. Razek;
5th ENDE, Des Moines, United States, 1999, S.S. Udpa;
6th ENDE, Budapest, Hungary, 2000, J. Pávó & G. Vértesy;
7th ENDE, Kobe, Japan, 2001, Fumio Kojima;
8th ENDE, Saarbrücken, Germany, 2002, Gerd Dobmann;
9th ENDE, Saclay, France, 2003, D. Prémel & T. Sollier;
10th ENDE, East Lansing, United States, 2004, L. Udpa & N. Bowler;
11th ENDE, Iwate, Japan, 2006, Seiki Takahashi;
12th ENDE, Cardiff, United Kingdom, 2007, David C. Jiles;
13th ENDE, Seoul, Republic of Korea, 2008, Sung-Jin Song;
14th ENDE, Dayton, United States, 2009, J. Knopp & K. Jata;
15th ENDE, Szczecin, Poland, 2010, Tomasz Chady;
16th ENDE, Chennai, India, 2011, T. Jayakumar;
17th ENDE, Rio de Janeiro, Brazil, 2012, João M. A. Rebello;
18th ENDE, Bratislava, Slovak Republic, 2013, 2013, Klara Capova;
19th ENDE, X’ian, China, 2014, Zhenmao Chen;
20th ENDE, Sendai, Japan, 2015, Noritaka Yusa;
21st ENDE, Lisbon, Portugal, 2016, Artur Lopes Ribeiro & Helena Geirinhas Ramos;
22nd ENDE, Saclay, France, 2017, Lesselier Dominique & Christophe Reboud;
23rd ENDE, Detroit, United States, 2018, Yiming Deng.
University of Electronic Science and Technology of China (UESTC) is situated at Chengdu. Fifty years’ efforts and cultivations have witnessed the University’s process from sole dependence on electronic information engineering to all-around programs in electronic disciplines, and the University now turns out to be a key multidisciplinary university with electronic science and technology as its nucleus, engineering as its major field and featured the harmonious integration of science, engineering, management and liberal arts, well prepared at the call of the history to come up as a high-level research-oriented university.

Southwest Jiaotong University (SWJTU) was founded in 1896 and known as the cradle of China’s railway engineers. SWJTU is a premier engineering university and is on the list of China’s first batch of 211 Project universities. By making use of its disciplinary advantage and substantiating its aim to serve national interest and regional development, the University plays a leading role in China’s construction of a new Silk Road and a traffic hub in the west. Currently, SWJTU is committed to the implementation of “Three Major Strategies”, to enhance the strength of the University by means of talent nurturing, internationalization and big data.

Sichuan University (SCU) is one of China's top universities, attached to the Ministry of Education, which is located in Chengdu, a famous historical and cultural capital city of Sichuan Province, known as the land of abundance. The university campuses, with their favorable environment and beautiful landscape, make a wonderful place for learning and research. Sichuan University has a comprehensive range of disciplines covering 12 categories: humanities, science, engineering, medicine, economy, management, law, history, philosophy, agriculture, education and art. It consists of 34 colleges, including a postgraduate college and an overseas education college. A total of 46 disciplines have been authorized by the state to grant doctoral degrees.
University of Electronic Science and Technology of China (UESTC) is situated at Chengdu (the city of over a thousand-year-old cultural history in “the land of abundance”). Sichuan, P.R. China. UESTC was admitted into “Project 211” and the nation’s Project 985, receiving special support for developing world-class universities and world-famous research-oriented universities.

Research Center of Non-destructive Evaluation and Structural Health Monitoring is one of outstanding teams in school of Automation Engineering, UESTC. The research interests include multimodality nondestructive testing, intellectualization and popularization of new sensors/arrays and measurement instrument; signal processing and machine learning strategy, research and application of key technologies for on-line monitoring of high-voltage electrical appliances as well as smart grid. The team received more than 25 million research funding from diversity parts (including National Natural Science Foundation of China, Sichuan Science and Technology Department, AVIC Chengdu Aircraft Industrial, China National Petroleum Corporation, etc.). In the past five years, more than 60 papers on the top international journals and conferences in the field of NDT&E have published with high citation. The team has significant world-class track records in Sensors, NDT&E, SHM, Signal Processing, Machine Learning and their applications.

Southwest Jiaotong University (SWJTU) was founded in 1896 and known as the cradle of China’s railway engineers. SWJTU is a premier engineering university and is on the list of China’s first batch of 211 Project universities. By making use of its disciplinary advantage and substantiating its aim to serve national interest and regional development, the university plays a leading role in China’s construction of a new Silk Road and a traffic hub in the west. Currently, SWJTU is committed to the implementation of “Three Major Strategies”, to enhance the strength of the university by means of talent nurturing, internationalization and big data.

Photonic Engineering Institute & Nondestructive Testing Research Center of SWJTU comprised of academic research leaders, engineering managers and technical experts, including 3 professors, 6 associate professors and 12 senior scientific researchers. The institute has already accomplished 11 national projects, and 9 science and technology development projects of the Ministry of Railway and hundreds of projects cooperation with railway bureaus. Joint Laboratory of Olympus NDT is mostly engaged in theoretical and applicable technology research on Nondestructive Testing. The testing equipment of the Laboratory are provided by Olympus NDT Incorporation, Chengdu SCLEAD Science & Technology Co., Ltd and SWJTU.
Sichuan University (SCU) is one of China’s top universities, attached to the Ministry of Education, which is located in Chengdu, a famous historical and cultural capital city of Sichuan Province, known as the land of abundance. It consists of three campuses: Wangjiang, Huaxi, and Jiang'an, covering an area of 470 hectares and boasting 2.515 million square meters of floor space. The university campuses, with their favorable environment and beautiful landscape, make a wonderful place for learning and research.

History of Sichuan University

Sichuan University has a comprehensive range of disciplines covering 12 categories: humanities, science, engineering, medicine, economy, management, law, history, philosophy, agriculture, education and art. It consists of 34 colleges, including a postgraduate college and an overseas education college. A total of 45 disciplines have been authorized by the state to grant doctoral degrees. Altogether, the university offers 354 doctoral programs, 438 master programs, 32 professional master’s programs, 138 undergraduate programs, and 37 post-doctoral research stations. It also has 48 national key disciplines and 4 national key cultivated disciplines.

Sichuan University has established contacts and cooperative relationships with over 260 renowned colleges and universities as well as research institutes from 34 countries and regions. It has established well-rounded joint education programs at different levels and in various forms with 214 famous universities from over 33 countries, including United States, Australia and some European countries.
The Key Laboratory of Non-Destructive Testing and Monitoring Technology for High-Speed Transport Facilities of the Ministry of Industry and Information Technology

The key laboratory of non-destructive testing and monitoring technology for high-speed transport facilities was approved for establishment by the Ministry of Industry and Information Technology in 2017. The lab relies on the instrumentation science subject of Nanjing University of Aeronautics and Astronautics (NUAA). NUAA is a comprehensive university especially featured with Aerospace Engineering. The main focus of research in the instrumentation science area is non-destructive testing (NDT) and structural health monitoring (SHM). The key lab directors of Academic Commission include prominent Professors and Academicians comprising Prof. Qinghai Dai from Tsinghua University, Prof. Gongtian Shen from China Special Equipment Inspection and Research Institute, and Prof. Guiyun Tian from Newcastle University. The current director of the lab is Prof. Ping Wang from NUAA.

The key laboratory has established a complete laboratory system which integrates scientific research and personnel training. The main focus of the lab is on innovation and application of NDT and SHM for quality assurance and manufacturing in high-speed transportation facilities including high-speed trains and aeronautic and astronomic facilities. The key laboratory assists and undertakes the development of high quality and reliable equipment and components for major projects in China, including National Key R&D Program "Manufacturing Basic Technology and Key Components" Project, "Key Technologies and Demonstration of Internet of Things and Smart City" Project, "Major Scientific Instruments" Project of Ministry of Science and Technology and National Scientific Foundation of China, as well as the key projects of China Railway Corporation.

Applications:

- The core equipment of CHINA RAILWAY’s new domestic high-speed rail defect inspection train GTC-80.
- On-line Automatic Mechanical Features and Quality Testing System for Cold Rolling Steel Plate Processing Performance of China Bao Steel Group, the largest cold rolling factory of the world.
- Health monitoring systems for CRTS-II Track Plate of Beijing-Shanghai High-speed RailwayK75+431 bridge of Guiyang-Guangzhou High-speed Railway, Nanjing, Shenzhen, and Wuhu Metro.

Eddysun (Xiamen) Electronic Co., Ltd.

Eddysun (Xiamen) Electronic Co., Ltd. is one of the well-known National High-tech Enterprises specializing in Non-destructive Testing (NDT) from 1993. With strong support of R&D capacity, management system and experienced staff, Eddysun is engaged in research, production and business on various NDT products, such as multi-frequency eddy current testing instruments, high-resolution/high-penetrating ultrasonic testing instruments, metal magnetic memory instruments, acoustic pulse instruments, acoustic instruments, variable array eddy current instruments, super-aped eddy current instruments, multi-channel ultrasonic testing instruments, integrated and cloud NDT systems, and electromechanical integration systems.

Eddysun is the only designated ECT manufacturer of Chinese air force, navy and army. It is also recognized as "qualified supplier" by Daya Bay Nuclear Power Plant. Its Products have been sold to dozens of countries and regions in the world. Many scientific achievements achieved by Eddysun filled the gap of NDT industry in Asia and even in the world. Eddysun has more than 250 patents and is responsible for or participated in drafting and revising of more than 150 national and industry standards. In 2010, Eddysun established an academician expert workstation approved by the Fujian Provincial Government and won the honorary title of National demonstration workstation in 2016.

LeuchTek GmbH

Since over 10 years, LeuchTek GmbH has been serving the European market as a professional lighting company with innovative, high-quality, energy-saving lighting products. LeuchTek located in Hamburg Germany, it integrates capabilities of development, design and sales in-house. Leading by Dr. Chunlei Yang, our team is made up of experts with experience in various industries and on the international market. Our product range extends from modern office lighting, outdoor lighting to special plant assimilation lighting and industry lighting. We are also enthusiastic about public activities, we are supporter and sponsor for football team FC St. Pauli., supporter for Children Magazine “ErsteHilfe für Kinder” (First aid for Children) ect. in Germany.
Guangzhou Doppler Electronic Technology Co., Ltd. was established in 2008 to provide high-level solutions for the non-destructive testing industry. Relying on the intensive research of high-end technology and an in-depth understanding of industry development trends, the company has gradually created a brand image of high-end customized equipment developer and provider.

At present, the company’s products cover ultrasonic equipment, transducers, scanners, and automated detection systems. After ten years of intensive cultivation, the company has initially completed the perfect transformation from system supporting to system integration. Differentiated development also makes it stand out in the fierce market competition. The company has built an international advanced transducer production line, which can provide thousands of industrial detection probes and medical ultrasonic probes for customers. With its strong technical strength and foresight, the company has obvious advantages in composite wafers and high-performance composite probes development. A series of special high-end probes, such as immersion probes, 2D array, ring array, high frequency, TOFD, have reached the international advanced level and have strong international competitiveness.

In terms of the ultrasonic system, Doppler produced the first portable phased array ultrasonic detector in China, which was rated as a national key product. After six years of market test, it became stable and reliable, with excellent performance. In order to further improve the ability to solve the problem of non-destructive testing, the company gradually develops its product line, from single supporting equipment to diversified equipment development of scanners, automatic crawlers and even automated detection platforms. The company’s system integration capability is constantly rising with the keen focus on their goals and mission statement as: “With innovation as the driving force and quality as the guarantee, we will continue to develop and bring new concepts of providing high-level solutions, continue to meet market demand, and strive for the first line of ultrasonic testing.

- SDK available for Re develop
- Raw data extraction, reprocess
- Powerful phased array imaging technology
SCLEAD SCIENCE & TECHNOLOGY CO., LTD.
Safety Assurance | Ultrasonic Inspection | Image Processing

SCLEAD was established in 2000 to provide solutions for wheelset ultrasonic testing and wayside train condition monitoring systems in railway industry. The products cover a full range of wheel and axle flaw detection solutions at wayside, light and heavy maintenance with advanced ultrasonic and image process technologies. SCLEAD offers automatic solutions of wheel profile, crack, surface inspection, bearing failure diagnosis, pantograph and train key components integrity monitoring at the wayside of depot entrance and main line.

Based on various of advanced NDT, optical imaging, machine vision, data processing and managing technologies, SCLEAD has provided hundreds of reliable systems for periodic wheelset flaw ultrasonic testing and daily train wayside condition monitoring in high-speed train, locomotive, rolling stock and metro application.

SCLEAD is willing to offer advanced technologies and products with open mind to the global market.

Web: http://www.sclead.com  Mail: info@sclead.com
Intelligent recognition and visual evaluation methods for defects using ACFM technique

Xin'an Yuan, Wei Li*, Xiaokang Yin and Guoming Chen

Center for Offshore Engineering and Safety Technology, China University of Petroleum (East China), Qingdao, China

Abstract

The traditional alternating current field measurement (ACFM) technique identify the defects by the butterfly plot, which is easily disturbed by the lift-off variations of the probe. The size of the defect is evaluated by the characteristic signal of $B_x$ and $B_z$, which cannot offer the visual morphology of the defect. This paper presents a novel intelligent recognition and visual evaluation methods for defects using the ACFM technique. Firstly, the defect surface profile imaging inversion algorithm based on the $B_z$ image gradient field is presented to reconstruct the surface profile image of the defect. As shown in Fig. 1, the surface profile images of the crack, irregular crack and corrosion defect are reconstructed by the Bz signal.

Fig. 1. The surface profile images of the defect. (a)-(c) $B_z$ of the crack, irregular crack and corrosion.(d)-(f) Surface profile images of the crack, irregular crack and corrosion.

Secondly, the defect surface profile image database is developed by simulations and experiments. The convolutional neural networks (CNN) deep learning algorithm is proposed to achieve intelligent classification recognition of different kinds of defects. The recognition results of the defects are shown in Fig. 2. The results show that all the defects can be identified and classified accurately.

Fig. 1. The recognition results of defects by CNN deep learning algorithm.

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Based on the classification results, the two-step interpolation and segmentation interpolation algorithms are presented to achieve visual evaluation of the length, depth and 2D profile for the crack, as shown in Fig. 3.

![Figure 3](image1.png)

Figure 3. Visual evaluation of the crack. (a) Profile of crack in the specimen. (b) $B_x$. (c) Calculated results. (d) Visual profile of the crack.

The bidirectional gradient fusion algorithm is proposed to achieve visual evaluation of the arbitrary directional irregular crack surface profile, as shown in Fig. 4.

![Figure 4](image2.png)

Figure 4. Visual evaluation of the irregular crack. (a) Surface profile of irregular crack in the specimen. (b) $B_x$. (c) Visual profile of the irregular crack. (d) Calculated results.

As the characteristic signal $B_x$ is sensitive to the lift-off, the 3D morphology reconstruction algorithm based on the image segmentation technique is presented for the 3D morphology and arbitrary section visual evaluation of the corrosion defect, as shown in Fig. 5.

![Figure 5](image3.png)

Figure 5. Visual evaluation of the corrosion. (a) $B_x$. (b) 3D morphology of corrosion. (c) Visual profile of the section.

The results show that the intelligent recognition and visual evaluation methods based on the ACFM technique proposed in this paper can recognize and classify the surface profile image accurately. The crack, irregular crack and corrosion defects can be evaluated visually.

References


Acknowledgments
This work was funded by the Special national key research and development plan (No. 2017YFC0804503), the National Natural Science Foundation of China (No.51574276 and No.51675536), the Major National Science and Technology Program (2016ZX05028-001-05).
The high speed railway inspection technologies and non-destructive mechanical properties measurement technologies developed in the key laboratory of non-destructive testing and monitoring technology for high-speed transport facilities of the Ministry of Industry and Information Technology

Ping Wang, Jia Yinliang, Xu peng, Shi yu, Ji Kailun, Sheng Hongwei
Nanjing university of aeronautics and astronautics, Nanjing 211100, China

The key laboratory of non-destructive testing and monitoring technology for high-speed transport facilities was approved for establishment by the Ministry of Industry and Information Technology in 2017. The main focus of the lab is on innovation and application of NDT and SHM for quality assurance and manufacturing in high-speed transportation facilities including high-speed trains and aeronautic and astronomic facilities.

The lab undertakes tasks related to rail detection such as the major scientific instrument development project of the National Natural Science Foundation, the development of major scientific instruments by the Ministry of Science and Technology and the major projects of China State Railway Group Co., Ltd. (CHINA RAILWAY). We have studied the defect characteristics of ferromagnetic materials and the influence of using environment to overcome the speed bottleneck of dynamic magnetization and eddy current under the condition of high-speed movement. Under the conditions of high-speed and heavy-haul railways, the relationship between rail defect characteristics and electromagnetic response signal is analyzed, and the relationship model between rail defects and three-dimensional electromagnetic field response signal under different detection speed and electromagnetic excitation conditions is established. We have solved the problems of selection of excitation parameters, elimination and application of eddy current effect and compensation of velocity effect.

A rapid patrol inspection method has been realized using electromagnetic, eddy current, ultrasonic techniques, magnetic memory and Alternating Current Field Measurement to detect the defects in the top surface, sub top surface and a certain depth of the serving rails. In the lab, the defects detection and fault warning of rail at 350 km/h high speed have been realized for the first time in China. The speed level is the fastest in the world. On this basis, the lab has successfully developed high-speed and low-speed rail defect detection trains. Both trains have rail-driving capability and can quickly acquire relevant the data of rail defect morphology parameters to distinguish damage degree, the whole range playback by playback software and carry out rail fault early warning and life evaluation. The high-speed trains are generally used for the detection of the railways, especially the high-speed railways and the latest one is GTC-80. The maximum detection
speed of GTC-80 is 80km/h and it has already gone into service. The speed of low-speed trains ranges from 20 to 30km/h and they are generally used for the detection of urban rails, especially for the subway rails.

Another main topic of research in Lab is the non-destructive measurement of the mechanical properties of metal material which determine the range of use and service life of metal materials. Since the change of the mechanical properties is usually related with the change of microstructure of the material caused by various microscopic stress concentrations, and the microscopic properties of materials are related to the mechanism of electromagnetic signal coupling, micro-electromagnetic measurement can be used for non-destructive testing of metal materials. The micro-electromagnetic detection methods used in the study are: Barkhausen, pulsed eddy current, magnetic Incremental permeability, electromagnetic ultrasound.

The characteristic values extracted by various methods can be effectively obtained by the parameter optimization and data fusion. Experiments show that the absolute value of Barkhausen, magnetic incremental permeability, electromagnetic ultrasonic method for material yield strength, tensile strength, and elongation prediction relative error is within 10%. The relative error of the impulse eddy current method for estimating the yield strength is within 6%.

The various eigenvalues obtained by several methods are analyzed and modeled by statistical and modern optimization methods, and are applied in an online detection system of a steel coil production line. Real-time detection of mechanical properties of different steel grades is achieved and have been applied in BAOSTEEL, the largest manufacturer of cold rolling steel sheet.
COPLANAR CAPACITIVE-INDUCTIVE DUAL MODALITY IMAGING SENSOR FOR NDE

Xiaokang YIN\textsuperscript{1*}, Jiaming FU\textsuperscript{1}, Zhen LI\textsuperscript{1}, Wei LI\textsuperscript{1} and Guoming CHEN\textsuperscript{1}

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Abstract
In the field of electromagnetic nondestructive testing, inductive (eddy current) imaging technique is primarily used for the inspection of conductors\textsuperscript{[1,2]}, while capacitive imaging technique is mainly used on non-conductors\textsuperscript{[3,4]}. This paper proposed a novel capacitive/inductive dual modality sensor, which can detect defects both in insulation materials and on conducting surfaces. The information of defects on the conducting surface and in the non-conducting layer of the tested specimen can be obtained simultaneously by the proposed sensor with its mode controlled by electronic switches, the sensor geometry is shown in Fig. 1.

![Figure 1: Dual Modality Imaging Sensor Geometry](image)

Finite Element models constructed in COMSOL were constructed to obtain the Measurement Sensitivity Distributions (MSD) for the sensor in the capacitive and inductive mode. The MSD, which are effectively the point spread functions of the sensor in both modes, can be used as a tool for probe design and performance prediction.

![Figure 2: (a) Geometry of Specimen I and Defects, (b) Capacitive Image, and (c) Inductive Image](image)

The first specimen is an aluminium-glass fibre hybrid structure. The 280 mm by 90 mm aluminium plate is with four 5 mm deep flat-bottomed circular holes. The diameters of the holes are shown in Fig. 2 (a). A 2 mm thick glass fibre plate with three holes with the same diameters and different depths was placed on top of the aluminium plate, and the two shallower holes are hidden if seen from the top, as shown in Fig.2(a).

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The probe was scanned over a 30 mm by 140 mm at a 0.5 mm lift-off. Two images, namely capacitive image and inductive image, were obtained after a single scan, as shown in Fig.2(b) and Fig.2(c) respectively.

It can be seen from the capacitive image all the holes, both on the aluminium plate and in the glass-fibre plate, were detected. This is due to the probing field is sensitive to features in both non-conducting materials and on the conducting surface in the capacitive imaging mode. In the inductive image, only the four holes on the aluminium plate surface were detected and the sizes of holes can be inferred from the indications in the image. It can be inferred that the defect is located on the aluminum plate or the fiberglass plate.

![Image](a) ![Image](b) ![Image](c)

Figure 3: (a) Geometry of Specimen II and Defects, (b) Capacitive Image, and (c) Inductive Image

The second specimen is also an aluminium-glass fibre hybrid structure. The glass fibre board is with two sets of holes. The aluminium plate is with a narrow crack in this case. The size of the specimen and the size of defects are shown in fig.3 (a). The probe shown was scanned over a 90 mm by 100 mm at a 0.5 mm lift-off.

The capacitive image and inductive image were obtained after a single scan, as shown in Fig.3(b) and Fig.3(c) respectively. Both the through holes and hidden hole in the glass fibre board were appeared as indications in the capacitive image, but the crack can not be seen in the capacitive image, because the imaging sensitivity of the capacitive mode depends on the size of the probe. In the inductive image, the crack is clearly seen but the features in the glass fibre board are absent.

The above results show that the dual modality imaging sensors can be used to identify defects in the insulation layer and the conducting surface under the insulation, which makes it promising to be used to target the corrosion under insulation problem in practice.

References

Acknowledgments
This work was funded by the Special national key research and development plan (No. 2017YFC0804503), the National Natural Science Foundation of China (No.51675536 and No. 51574276), the Major National Science and Technology Program (2016ZX05028-001-05).
A NOVEL PLANAR EDDY CURRENT PROBE BASED ON TAIJI GRAPH

GUOLONG-CHEN\textsuperscript{1*}, WEIMIN ZHANG\textsuperscript{2}, WUYIN-JIN\textsuperscript{1}, KANG-WANG\textsuperscript{1} and ZHIBO-SONG\textsuperscript{1}

\textsuperscript{1} School of Mechanical and Electrical Engineering, Lanzhou University of Technology, Lanzhou, P. R. China
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Abstract

Planar eddy current sensor is an important kind of eddy current sensors. However, traditional planar eddy current sensors using the circular, rectangular exciting coils have a low sensitivity for some direction defect. Thus, TaiJi graph from classical Chinese philosophy was proposed to be an exciting coil of a planar eddy current sensor. In order to simplify the exciting coil, the TaiJi graph was simplified, shown in Fig.1. Then, to suppress the lift-off noise, the sensor was designed to be differential mode. On one hand, the TaiJi exciting coils adopted the parallel topology structure, shown in Figure 2; on the other hand, the pick-up coil elected one winding of circular coils. Then, to effectively get the disturbance signal of eddy current induced by the central exciting line, one circular coil cut out some area of pick-up coil was be studied, too.

To verify the validity of proposed probe, three types of sensors are designed. As shown in Figure 3, the three sensors are Double D-circular, TaiJi-circular, and TaiJi-circular cut out some area. FEMs and experiment of the three types sensors were conducted. In the experiment, the finite length defect and the different length short defect will be detected. Then the result will be analyzed.

\textbf{Figure 1.} The simplified TaiJi graph

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Figure 2. The exciting coils with parallel topology based on TaiJi graph

Figure 3. The three types of eddy current sensors: (a) Double D-circular, (b) TaiJi-circular, (c) TaiJi-circular cut out some area

Acknowledgments
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Abstract

Creep phenomenon is an important feature to assess in high temperature applications, although the correlations with microstructure and magnetic behaviour remain unclear. In this work, 12%Cr-Mo-W-V creep test samples (used in thermal power plants) are investigated using three electromagnetic inspection techniques. Magnetic parameters based on the results are then evaluated in comparison to the microstructure. Additionally, a modified Jiles-Atherton model has been used to numerically reproduce experimental results from Magnetic Incremental Permeability (MIP), Magnetic Barkhausen Noise (MBN) and standard B(H) measurements. All the three techniques exhibit different responses in understanding creep and the modelling parameters derived from the adapted Jiles-Atherton Model parameters are then correlated to the microstructure information.

Coupling between the stress and magnetic field is the main and important feature of the ferromagnetic materials consisting of various small magnetic domains in its microstructure [1][2]. Conventional Eddy current testing has been extensively used for the ferromagnetic materials characterization but when it comes to creep damage detection, it becomes difficult to distinguish between the changes caused by the actual creep damage and from the signals generated by other sources like, cracks, surface roughness, hardness etc. In this research three different electromagnetic techniques are applied to the 12 different samples from three different categories with different temperature and stress treatments. Magnetic Incremental Permeability (MIP) is used to investigate samples as it is highly sensitive to stress. On the other hand, Magnetic Barkhausen Noise being sensitive to the mechanical changes in the materials, is also used to analyse the samples in addition to standard B(H) curve measurements. Finally, ferromagnetic hysteresis models such as dry friction quasi static model [3], Preisach model [4], Jiles-Atherton model [5], which are based on magnetic induction B versus applied magnetic field strength H, are implemented to get the simulated data based on experiments. All these models will be presented along with their limitations which are majorly the accommodation and the congruency issue (particularly in the case of MIP). For instance, MIP technique is related to the dynamic permeability of the material when applying a bias excitation field, and the resulting ferromagnetic minor loop modelling requires advanced modelling techniques. Having a physical interpretation, the J-A model [6] is modified to derive modelling parameters which are then evaluated against the microstructure of the test samples. Finally, experimental data obtained using different techniques applied to creep samples are presented, and the relevant ferromagnetic model is given. It is shown that using appropriate model, it is possible to assess model parameters directly from the magnetic signals. The objectives of these simulations are to improve magnetic signatures interpretations in co-relation to microstructure. Using Jiles-Atherton model, it is shown that 3 out of 5 parameters can be obtained from the magnetic curves. Their correlation to microstructure information is discussed. Such parameters are foreseen to

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constitute indicators of damaging independent of the experimental setup. Experimental results based on three techniques will be presented in detail and how the models are adapted to a particular method will also be presented. While fitting to the experimental data, the 5 J-A parameters can be used as degrees of freedom in the simulation process. Fig. 1(a) below shows evolution of one of the J-A parameters ‘K’ vs. Precipitation number for differently treated samples. It is quite evident that the energy required (K) to break the pinning site is larger in case of higher number of precipitates.

After the determination of these parameters, Pearson correlation coefficient is evaluated against different mechanical and microstructural parameters as shown in Fig. 1(b). The graphs shown here correspond to MBN technique results.

References

Acknowledgements
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RESEARCH ON NON-DESTRUCTIVE EXAMINATION OF SUPERCONDUCTING CABLES BASED ON THE METHOD OF INVERSION OF ELECTROMAGNETIC PROPER

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Abstract

The cable-in-conduit conductors (CICC) is a kind of preferred conductor for the large-scale superconducting magnets, such as fusion reactors, high magnetic fields, and accelerators [1]. It consists of jacket and thousands of superconducting cables which is illustrated in Figure 1. Most cables also integrate copper strands and/or cores. The cables finally are inserted into a steel jacket to become the CICCs [2]-[4]. At present, Nb3Sn / Nb-Ti strands are successfully applied to the CICC.

Superconducting cable is the core component of CICC conductor which carries tens of thousands of amps of current under extreme operating conditions. Once operated, they cannot be repaired and replaced for life. Its quality directly affects the performance of the conductor and even affects the safety of the superconducting Tokamak device. Due to the multi-level composite structure, it is easy to cause partial damage or even strand breakage of the superconducting cable in the complex deformation mode as shown in Figure 2. The extreme operating conditions of low temperature, high current and strong magnetic field will further aggravate the damage of the strand, which affects the current carrying capacity of the cable. Therefore, it is vital to inspect superconducting cables on-line during the manufacture and operation process.

At present, the inspection method is mainly destructive tests and lacks effective means for online detection. In order to develop an effective non-destructive testing method and solve the problem of online detection of superconducting cables, this paper proposes a method based on magnetic field signal inversion. Through the combination of theoretical model and experimental research, the correlation between damage signal and magnetic flux leakage signal of superconducting cable is explored. Meanwhile, the wavelet transform is used to extract characteristics and reduce noise for strands signal, and then extract defect signal, which realizes the effectiveness of the new evaluation method in complex environment.

This work of this paper is exploratory study for the large-scale application of superconducting cables in the future fusion reactor and the realization of high parameter operation of the fusion reactor.

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Figure 1. Cross section of CICC (left) and disassembled cable sample (right).

References


Acknowledgments

The authors would like to thank Arnaud Devred from IO for the useful advice and encouragement of this work. The authors also appreciate Dr. Cai from Xi’an Jiaotong University for the strong support.
FLAW DETECTION NEAR THE TSP OF A CuNi TEST SPECIMEN USING FREQUENCY CHARACTERISTICS OF A CYLINDER-TYPE MAGNETIC CAMERA

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² IT-based Real Time NDT Center, Chosun University, Gwangju, Republic of Korea

Abstract

The main condenser of the nuclear power plant condenses and recovers the steam that passes through the low pressure turbine (LPT) into the system for reuse. The steam discharged from the lower part of the LPT flows into the condenser and circulates around the heat exchanger tubes. At this time, cooling water passes through the inside of the tube and condenses hot steam outside the tube.

Heat exchanger tubes used for nuclear power plant condensers are composed of a variety of materials depending on the characteristics of the plant and the requirements of the supplied coolant. These materials include titanium alloy (ASME SB388 grade 2), austenitic stainless steels (AL-6X, SAE 304/304L/316/316L), ferritic stainless steels (NuMonit, AL 29-4C, SEACURE®), duplex stainless steels, cupronickel alloys (CuNi 95/5, 90/10, 70/30), aluminum alloys, and admiralty brasses. As cooling water for the condenser, fresh water, seawater, salt water, and reclaimed water are used. [1] A CuNi alloy heat exchanger tube is used for fresh water, and the inlet and the outlet of the tube are mechanically expanded and sealed to the tube sheets. Typical damage modes that can occur in heat exchanger tubes composed of CuNi alloys include abrasion, steam erosion, stress corrosion crack (SCC), and ammonia corrosion.

As a technical standard for eddy current testing of a CuNi condenser tube in a nuclear power plant, the ASME Section V SE-243 (“Standard practice for electromagnetic examination of copper and copper-alloy tubes”) is used. [2] This means that the eddy current test of the condenser tubes is performed using a bobbin probe during the planned outage of a power plant. However, detecting defects near the tube support plates (TSPs) is difficult due to the large signal from the TSP material (carbon steel) during inspection.

In this study, a novel method to detect SCC and corrosion near the TSP using a cylinder-type magnetic camera is presented. The cylinder-type magnetic camera is composed of a long cylinder-type bobbin coil and a magnetic sensor matrix. [3] When an alternating current is applied to the bobbin coil, as shown in Fig. 1, an induced current is generated in the specimen. At this time, if the specimen has a flaw, the induced current is distorted near the flaw, and the time varying magnetic flux density distribution changes in the radial direction of the specimen. By measuring these magnetic flux density distribution changes with sensors that are sensitive to magnetic flux density in the radial direction, we can determine the presence of defects and their shape. Unlike conventional bobbin type probes such as an X-probe or motorized rotating pancake coil (MRPC), cylinder-type magnetic cameras can measure the eddy current distribution of the test specimen without mechanical scanning. In addition, measuring, analyzing, and visualizing the amplitude and phase angle distribution based on frequency changes in real time is possible.

Fig. 2 shows the results of identifying the location of the TSP and the existence of defects under TSP using a cylinder-type magnetic camera with changing excitation currents. Fig. 2(a) shows the TSP placed on a sound test specimen, and Fig. 2(b) shows the TSP placed on a groove. The groove was machined to the outside of the specimen to represent ammonia corrosion. If

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the amplitude and phase angle distribution changes of the time varying magnetic field are observed while the frequency changes continuously at 6, 15, 30, and 50 kHz, the shape of the outer diameter groove from which the TSP signal is removed can be recognized. More detailed experimental results using a Cu-Ni specimen having artificial flaws that represent ammonia corrosion and SCC will be presented at the conference.

Figure 1. Components and measurement principle of a cylinder-type magnetic camera

Figure 2. Test results of TSP (a) on a sound specimen, (b) on a grooved specimen

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Acknowledgements
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A0096 PREDICTION OF THE HARDNESS OF X12M USING BARKHAUSEN NOISE AND CHEBYSHEV POLYNOMIALS REGRESSION METHODS

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Abstract
Barkhausen noise (BN) is a popular non-destructive evaluation (NDE) signal that could be used to predict the properties of materials such as hardness, residual stress and carbon content. The challenge of BN signal is the pseudo-random trait because BN signal is generated by the stochastic movements of domain walls. To overcome this challenge, the focus points of the relevant analysis include the suitable feature extraction and the design of prediction model. In this paper, to evaluate the hardness of Cr12MoV (i.e. x12m), the prediction model is our topic and two self-designed multi-variable regression tools were firstly employed in NDE.

The conventional prediction models employed in NDE contain the linear-like regression model and neural network (NN). However, these models share the limitation that models could not keep the balance between accuracy and efficiency of the nonlinear problem. As shown by the contribution proposed by Y. Zhang[1], Chebyshev polynomials (CP) \( U_n(x) \) was combined with Bernstein polynomials to build the multi-variable non-linear regression tool (i.e. Multi-variable Chebyshev polynomials regression (MCPR)). The approximation of multi-variable function \( g(y), y \in [0,1] \) using Bernstein polynomials \( B_n(y) \) is defined as: (CP is employed to approximate the \( p_n(x,y) \))

\[
g(y) = \sum_{n=0}^{\infty} \sum_{j=0}^{\infty} g(S_n, \ldots, S_y) \prod_{d=1}^{n} p_{n,d}(y_d) + e
\]

However, the limitation of MCPR is prone to causing the coefficient explosion phenomenon (i.e. the number of regression coefficients \( b_{n_1,\ldots,n_d} \) is exponential to the number of input variable \( r \)). To further enhance the efficiency of MCPR, we had proposed two ideas[2], including cascaded regression and feature selection. On one hand, by combining CP and partial least square regression[3] (PLSR), conventional multi-variable CP-based regression model is decomposed as the accumulation of single-variable regression models. On the other hand, the intention of feature selection method is to reduce the number of input variable. In this paper, our models are employed to enhance the prediction accuracy of material properties.

In the experimental part, the performance of our regression tools is evaluated by predicting the hardness of x12m material. As the input of the regression tools, the features generated from the envelope of BN signal are listed in Table I, including the shape information, statistics results, frequency domain parameters. Moreover, as shown by Fig.1, the left-(right-)sub-peak value is firstly introduced as the auxiliary feature of main peak value. The experimental results were presented as Fig.2 and Table II. To show the performance of our methods, three models (i.e. Back propagation neural network (BP), PLSR and random forests (RF)) were adopted. In details, BP is a typical neural-network-based nonlinear regression tool.
and PLSR is the popular nonlinear-like regression tool. As shown by Fig. 2(a-b), the scatter points generated from the typical model are far away from the baseline. As shown by Fig.2(c-d), the points generated from the CP-based methods are closer to the baseline than the former models. According to the results, more accurate performance is achieved by our regression models among different regression models. The high performance could be ascribed to two aspects: Firstly, given a proper order, any nonlinear model could be approximated by an orthogonal polynomials; Secondly, compared with the NN-based model, a more specific mathematical equation could be deducted by the polynomials-based model. Based on our idea, our proposed mathematical regression model could be treated as a potential regression model choice in the future NDE works.

Fig. 1 Two half-period BN samples labeled with Peak information.

Table I. The selected features in our study

<table>
<thead>
<tr>
<th>Peak value</th>
<th>Peak Position</th>
<th>Mean value of BN profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left sub-peak value</td>
<td>Harmonic information</td>
<td>Right sub-peak value</td>
</tr>
<tr>
<td>75% bandwidth</td>
<td>Intercep of tangential magnetic field</td>
<td>Half bandwidth</td>
</tr>
</tbody>
</table>

Fig. 2 Scatterplot of predicted output and the measured output with different algorithms based on x12m. (a) RBF (b) PLSR (c) Random Forests (d) Feature-selection-based CP regression method (FCPR) (e) Cascaded-based CP regression method (CCPR)

Table II. The regression accuracy

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>BP</th>
<th>PLSR</th>
<th>RF</th>
<th>FCPR</th>
<th>CCPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>0.5548</td>
<td>0.5331</td>
<td>0.5151</td>
<td>0.3629</td>
<td>0.4144</td>
</tr>
</tbody>
</table>

References


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**INSPECTION OF DEFECT AND ACCUMULATED SLUDGE OF STEAM GENERATOR TUBE WITH EC-TMR ARRAY PROBE**

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**Abstract**

Steam generators are heat exchangers connecting primary and secondary loops of nuclear power plant. It has an important safety role because they constitute one of the primary barriers between the radioactive and non-radioactive sides of the plant as the primary coolant becomes radioactive from its exposure to the core. For this reason, the safety of steam generator should be treated seriously.[1]. As the core component of steam generator, heat exchange tubes often degrade over time under mechanical vibration and chemical action.[2] In addition, the accumulated sludge outside the tube wall may reduce the heat exchange efficiency and lead to serious defects such as corrosion during long-term operation. Therefore, during scheduled maintenance outages or shutdowns, inspections is necessary to detect and characterize degradation in a timely manner, which is a key factor in ensuring the safe operation of nuclear power plants.

In this paper, an eddy current probe with array tunnel magnetoresistance (TMR) sensors is proposed for inspection of defects and sludge of steam generator tube in nuclear power plants. TMR sensor is a kind of high sensitive magnetoresistance sensor based on quantum tunnel effect.[3]. Compared with conventional magnetic sensor, e.g. hall sensor and anisotropic magnetoresistance (AMR) sensor, it has higher magnetic field measurement sensitivity, lower power consumption and wider linearity range.[4]. It is small and can be integrated in system making it is suitable for fabrication of large-scale, high-density sensor array. During inspection, the tube under test is excited electromagnetically by an excitation coil, which induces eddy current in the tube wall. The magnetic field associated with the eddy current is monitored by the TMR array sensors resulting in high resolution, high sensitivity magnetic field imaging. The existing of defect or sludge will disturb the distribution of the eddy current. So they can be detected by analysing the magnetic field image.

Firstly, the operating principle of the probe is mimicked numerically using a finite element method (FEM) model. The governing equations of the model is based on reduced magnetic vector potential equations,[5] as shown in equations (1) and (2). Using these equations eliminate the need of re-meshing for different coil positions, so the resultant system matrix remains unchanged during probe scan. The images of different defects will be predicted based on this model. Furthermore, the influence of defect orientation and lift-off of the probe on the output result will be studied numerically. It is proved that when the probe moves in defect-free area, the change of lift-off between the probe and the tube wall does not affect the output, which is of great significance to remain good signal to noise ratio in practical inspection.

\[
\nabla \times \nabla \times A + j \omega \sigma A = \nabla \times H - \nabla \times vH - j \omega \sigma A
\]

\[
\nabla \cdot (j \omega \sigma A + \sigma \nabla V) = -\nabla \cdot j \omega \sigma A
\]

Subsequently, a porotype probe composed of excitation coil, TMR sensor array and data acquisition system is developed and tested. The TMR sensor array integrates 32 TMR sensor elements, each of which has size 0.45mm*0.45mm*0.45mm. The sensor elements are bonded and encapsulated on a circular printed circuit board (PCB), as shown in Figure 1. The sensitive axis of the TMR sensor is placed along the radial direction of the PCB board to

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measure the radial component of the magnetic field. A bobbin excitation coil is wound outside of the circular PCB. Then the PCB and the coil are placed inside a 3D printed plastic structure, as shown in Figure 2.

Finally, the feasibility of the proposed probe is validated experimentally. A steam generator tube sample (Inconel alloy 690) is tested by the prototype probe. The inner and outer radii of the tube are 16.86 mm and 19.04 mm respectively. There are 9 axial notches machined on the tube wall. The interval between each two adjacent defects are 20mm. All of the 9 defects are 2.540mm in length and 0.127mm in width, among which #1 to #4 are inner diameter (ID) notches with the depth of 20%, 40%, 60%, 80% of thickness of the tube wall, #5 is a through wall notch and #6 to #9 are outer diameter (OD) notches with the depth of 80%, 60%, 40%, 20% thickness. Preliminary experimental results are shown in Figure 3.

The TMR sensor array has high sensitivity in wide frequency range. Consequently, the probe can work with low frequency excitation for inspection of sludge located outside of the tube wall. More studies with details will be presented in future submission.

References
Mechanism Hybrid EMAT and Eddy Current Sensing Detection for Surface and Internal Defects NDT

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Abstract: Fast and efficient comprehensive inspection of oil and gas pipelines is a critical and challenging task. This paper proposes a novel mechanism hybrid non-destructive testing (NDT) method of Electromagnetic Acoustic Transducer (EMAT) and Pulsed Eddy Current Testing (PECT) for detecting surface and internal defects. This transceiver-integrated sensor simultaneously excites pulsed eddy current and ultrasonic waves and picks up composite signals. In particular, the ultrasound detects deep defects, and the eddy current detects surface defects. Numerical simulation and experiments have been carried out on the detection of hybrid defects. The feasibility, efficiency and reliability of the proposed method were verified.

Keywords: Non-destructive testing, Mechanism composite, Electromagnetic acoustic transducer, Pulsed eddy current testing, hybrid defects.

1 Introduction

Different non-destructive testing (NDT) techniques have their own strengths and weaknesses, and multiphysic NDT can balance the limitations of each detection method. Therefore, the combination of different NDT technologies can improve the reliability and efficiency of the inspection [6]. The EMAT with bulk waves shows that it is possible to detect deep cracks rather than that near the surface. In contrast, PECT can effectively detect defects in surface areas, but negative to deep defects. In addition, EMAT and PECT are based on the principle of electromagnetic induction. Besides, these two detection techniques are non-contact, non-destructive testing methods that do not require coupling agents. In terms of the scope of defect detection and the principle of detection techniques, the combination of these two detection technologies may be fully complementary.

There are two ways to combine EMAT with PECT: system composite and mechanism composite. System composite refers to the detection of the specimen by using separate EMAT sensor and PECT sensor, which are separately excited and received. The mechanism composite can be carried out through the electromagnetic physical process between different detection methods. There have been many studies on the system composite. H. Willems presented a wall thickness measurement sensor for pipeline by using EMAT technique. Eddy current (ECT) and the magnetic flux leakage (MFL) are combined with EMAT for detecting metal loss[7]. H. Willems developed a composite detection device based on PECT, MFL and EMAT technology for in-line inspection of pipes[8]. Edwards RS et al. combined the one-transmitting-receiving mode surface wave EMAT with the eddy current probe, and evaluated the defects by using data fusion method[9]. Ryoichi Urayama et al. proposed a novel dual sensor structure with combining an EMAT and EC probe to monitoring of piping wall thinning in a high temperature environment[10]. Tetsuya Uchimoto et al. developed an EMAT-EC dual probe to assess wall thinning with compatible EMAT and EC operating modes. Thus, this leads to the capability of sizing width and depth of wall thinning in quantitatively way[11]. There are less reports of the mechanism fusion of EMAT and ECT. Huang F et al. presented a new testing method combining EMAT and ECT by using one probe to transmit and receive the signal simultaneously. The empirical procedure of the method is separately treated and finally the results analysis are synthesized[12]. Shejuan Xie proposed a hybrid method combining with PECT and EMAT by using filter strategies to separate the detected signals[13].

In order to realize the comprehensive inspection of pipelines, improve reliability and inspection speed, it is of research and application significance to study the new method of combining EMAT with PECT mechanism layer to solve the above problems. Based on the common principle of electromagnetic ultrasound and pulsed eddy current, a new detection method of mechanism layer is proposed. In particular, the new sensor structure can stimulate the ultrasonic longitudinal wave with obvious directivity to detect internal defects while the surface defects can be detected by receiving the eddy current excited by the EMAT coil. This directly realize the physic coupling mechanism of EMAT and PECT.

2 Methodology

2.1 The basic principle of EMAT/PECT
Fig.1 The basic principle of EMAT and PECT

The principle of pulsed eddy current and electromagnetic ultrasonic bulk waves composite is shown in Fig.1. When a high-frequency alternating pulse current is applied to the coil, an alternating magnetic field is generated around the coil, and a pulse eddy current is excited on the surface of the specimen. According to Maxwell’s equations, the pulsed eddy current dynamic magnetic field corresponds to the following equation:

\[ \frac{1}{\mu} \nabla^2 A - \sigma \frac{\partial A}{\partial t} = -J_s \]  

(1)

where \( \mu \) is the magnetic permeability, \( A \) is the magnetic vector potential, \( \sigma \) is the electrical conductivity of the material and \( J_s \) is the source current density of the coil.

Considering the influences of skin effect and proximity effects of the coil, the total current density in the coil is:

\[ J_e = J_s + J_e \]  

(2)

\[ J_e = -\sigma \frac{\partial A}{\partial t} \]  

(3)

\[ i = \int_S J_e \, ds \]  

(4)

where \( J_e \) is the pulsed eddy current density in the specimen, \( i \) is the actual current in the coil, \( S \) is the cross-sectional area of the coil. As shown in Equation 2, assuming that the \( J_s \) is constant, the vary of \( J_e \) will be reflected in the coil current \( i \).

When there are surface defects, the distribution and intensity of the pulsed eddy current change. By detecting the change of voltage in the coil, the existence of defects in the conductor can be found.

In the static bias magnetic field, the pulsed eddy currents in the conductor produce Lorentz force that alternates in direction. The force conducts in the solid and changes to generate ultrasonic wave. Besides Lorentz force, there exists Magnetostriction force and Magnetization force in ferromagnetic materials. The expressions of Lorentz force is expressed as follows:

\[ f_e = B_0 \times J_e \]  

(5)

where \( B_0 \) denotes magnetic induction of the static bias magnetic field.

Assuming that the sample is isotropic and meets the assumption of linear elasticity and continuity, the sample will undergo elastic deformation under the action of Lorentz force with alternating directions. Thus, the motion equation of the specimen is expressed as:

\[ GV^2 u + (G + \kappa)V(V \cdot u) + f_e = \rho \frac{\partial^2 u}{\partial t^2} \]  

(6)

where \( G \) and \( \kappa \) is the Lame constants, \( u \) is the displacement matrix of the particle, \( \rho \) is the density of the specimen.

According to the relationship between the mass displacement and the force of the Eqn(6), the ultrasonic field can be calculated. The receiving process of EMAT is just the opposite of the excitation process. When the ultrasonic wave in the specimen propagates to the receiving coil of EMAT, the moving charged particles in the specimen will generate dynamic current under the action of external bias magnetic field, and the current density can be calculated as:

\[ J_s = \sigma \nu \times B_0 \]  

(7)

where \( \nu \) is the vibration velocity of particle in echo.

The dynamic current density in the specimen generates a dynamic magnetic field inside and around the specimen, and the EMAT receiving coil in this dynamic magnetic field will generate a dynamic induced electromotive force, which is the received signal of the coil.

3 Numerical simulation

In order to verify the detection capabilities of the EMAT and PECT combinations, a simulation study was performed. The finite element simulation software COMSOL Mutiphysics is used for simulation studies. all of simulation results are on the basis of 2D modeling. The electromagnetic field module and the solid mechanics module are used in the simulation, in which the electromagnetic field module calculates the static magnetic field of the permanent magnet and the dynamic magnetic field generated by the coil. In addition, the solid mechanics module calculates the sound field generated by the pulse eddy in the aluminum plate.

3.1 Analysis of the pulsed eddy current

The simulations set different sizes of surface defects to study the response of pulsed eddy currents. The defect of varying width is from 1mm to 6mm, with the depth 2mm; the defect of varying depth is from 1mm to 6mm, with the width 2mm. The difference between the defective response and the non-defective response of the pulsed eddy current with different widths and depths is shown in Fig.2(a) and Fig.3(a), respectively. Fig.2(b) and Fig.3(b) illustrates the relationship between the peak value of the pulsed eddy current differential signal and the defect size, respectively.

It can be seen that as the length of the defect increases, the difference amplitude between the defect and the non-defect is also larger. There is a perfect linear relationship can be observed in Fig.2(b). While the change in defect depth has less effect on the signal. In Fig.3(b), it illustrates when the defect depth exceeds 2mm, the voltage amplitude of the pulse eddy current no longer increases. This is because the skin effect of pulsed eddy current is more obvious at high excitation frequencies. When the depth of the defect exceeds 2 mm, the pulsed eddy current is hardly generated at the bottom of the defect, so the signal amplitude no longer increases as the depth of the defect increases.

![Fig.2 Surface defect with varying width (a). the differential](image-url)
validation experiments are implemented. The proposed experimental platform is generated as shown in Fig.6. The composite sensor consists of a spiral coil and a NdFeB permanent magnet. The RITEC-5000 provides excitation and processes EMAT signal. The excitation frequency is 2MHz. Both signals are collected into the computer for further analysis.

Specimen of non-ferromagnetic aluminum is used for experimental verification. The schematic model of the specimen is shown in Fig.7. The thickness is 20mm. The artificial surface defects with different width, depth and angle are setted. All surface defects are 20mm in length, with different widths from 1mm to 6mm, different depths from 1mm to 6mm, and different angles from 15° to 75°. On the reverse side of the specimen, there are four bottom thinning defects of different thicknesses, from 18mm to 12mm.

3.2 Analysis of ultrasonic wave

While the pulsed eddy current is generated, the ultrasound shear wave is also excited by it under the static bias magnetic field in the aluminum plate. Fig.4 shows the sound field displacement at different times in the aluminum plate and the propagation process of ultrasonic wave is clearly expressed. The propagation velocity of the shear wave can be calculated from the time difference between the two shear waves and the thickness of the aluminum.

The ultrasonic echo signal with non-defect and different thinning defect is shown in Fig.5. It can be seen that the ultrasonic echo with thinning defect is advanced as compared with that with non-defect. And the bottom thinning information can be obtained by calculating the time difference of the echo signals.

4 Experimental validation

4.1 Experimental platform and specimen defects

In order to verify the above simulation studies,
location.

4.3 Analysis of the ultrasonic wave

While the pulsed eddy current signal is obtained, the ultrasonic signal is collected simultaneously. Fig. 11 shows the ultrasonic echo signals at different thicknesses in aluminum. It can be seen that as the thickness decreases, the time of the first echo is also advanced. The propagation time of the ultrasonic wave can be acquired by calculating the time difference between the second echo and the first echo, that is, the time of flight. Information about the thickness of specimen can be obtained by the product of the measured ultrasonic velocity and the measured time of flight. Fig. 12 demonstrates the three-dimensional thickness image of three sets of scan points data in aluminum. The position and size of the thickness variation of the specimen can be seen from it.

![Fig. 11 ultrasonic echo signals of different thicknesses](image1)

![Fig. 12 three-dimensional imaging of thickness](image2)
5 Conclusion

This paper proposes a novel EMAT and PECT composite non-destructive testing method for simultaneous detection of surface and internal defects. This transceiver-integrated fused sensor has detection capabilities that increase detection range, reliability and efficiency. The principle of EMAT and PECT mechanism fusion strategy is investigated by finite element simulation, and the ability is verified to detect hybrid defects. It is evidenced that all works have a excellent reaction among the response and surface defects of different width, depth, orientation and multivariable internal defects.

References

Study on the mechanism and application of applying magnetic Barkhausen noise to evaluate plastic deformation

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Abstract: Seven specimens of 45 steel with different residual strains were prepared by homogeneous plastic tensile test. The microstructure of the specimens was observed by scanning electron microscopy and the texture characteristics of the specimens were studied by X-ray diffraction. The results showed that plastic deformation mainly leads to dislocation increment in the microstructure rather than obvious deformed grain morphology, texture and residual stress. Then the dislocation density of each sample was calculated by X-ray diffraction method. The MBN signals of the samples were tested by magnetic Barkhausen noise method and the corresponding RMS (root mean square) values were calculated. The results showed that the dislocation density increases and the RMS value decreases with the increase of plastic deformation magnitude, the phenomenon was explained deeply. By establishing the correlation between dislocation density and RMS value, it was found that there was a good linear relationship between dislocation density and RMS value. According to the formula provided by the fitting curve, the dislocation density can be predicted by measuring the RMS value of any degree of plastic deformation.

Keywords: magnetic Barkhausen noise; dislocation density; plastic deformation; quantitative evaluation

1. Introduction

Magnetic Barkhausen noise (MBN) is a nondestructive testing technology that is widely used in detection of thickness of carburization layer[¹] and film[²], grain size[³], phase content⁴⁻⁵, stress⁶⁻⁷, etc. This phenomenon is due to the interactions of domain walls with defects like grain boundaries, dislocations, inclusions and second phases, so the MBN is sensitive to microstructural changes of ferromagnetic materials. During plastic deformation, microstructure of the material will change significantly, so the MBN method can be used for characterizing plastic deformation.

Pedro P. de C. Antonio et al studied the variation of MBN signal under small plastic deformation, he attributed the change of MBN signal to the influence of many factors⁸. Martin J. Sablik et al tried to model the stress-strain curve with a modified theory, he thought that the 90° domain wall would also cause the change of MBN signal, but no further discussion was given⁹. The research in this field is rare, and the experiment is basically carried out under the action of coaxial external force, so the influence of external force is introduced¹⁰⁻¹¹. In order to study the influence of dislocation density on MBN signal separately, a special design and demonstration was carried out in this study.

Dislocation is a common type of lattice defect in crystal materials, which is strongly related to mechanical properties of metals, the four theories of strength for materials are all based on dislocation theory. Dislocation has always been a hot topic in the research of metallic materials. The microscopic
mechanism of plastic deformation can be explained by dislocation theory\textsuperscript{[12,13]}, Dislocation density determines the process of recovery and recrystallization\textsuperscript{[14-17]}. Dislocation density plays a key role in work-hardening of materials\textsuperscript{[18,20]}. In a word, dislocation provides an important characterization method for material science research.

Dislocation density is the main parameter for characterizing dislocation. There are several commonly used methods of calculating dislocation density, among them TEM and X-ray diffraction line profile analysis are the most widely used techniques to quantify the dislocation density. Each analytical method has its characteristics, application range and limitations. TEM technique can give an in-situ observation of dislocation morphology\textsuperscript{[21,22]}, however it is time consuming for a TEM sample preparation, and obtained information is from small area. Besides, for a sample with large number of dislocations, it is difficult to distinguish one from another, so TEM is mainly used for low density dislocation research. XRD reveals the average data over a relatively large area and it can be used for high density dislocation research, however, the sample preparation and observation is complex as well.

Detection of dislocation density by non-destructive method is free of the complicated sample preparation process, which is facilitate for life prediction\textsuperscript{[23]} and damage assessment\textsuperscript{[24]}.

2. Materials and methods

2.1 Material preparations

Tensile specimens of the same size were prepared with 45 steel. The samples were annealed to eliminate residual stress. In order to obtain different dislocation density, the tensile method was adopted. Three specimens were stretched to break, and the stress-strain curves were obtained. The mean maximum strain was about 21\%. Then 7 specimens with different residual strains were obtained by tensile method (Fig.1), the residual strains were 1\%, 4\%, 8\%, 12\%, 14\%, 16\%, and 18\% respectively, the specimens were named as #1, #2, #3, #4, #5, #6, #7 correspondingly.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{tensileSpecimens.png}
\caption{Tensile specimens with different plastic deformation}
\end{figure}

2.2 MBN measurements

MBN measurement was performed using the experimental system developed in the authors’ laboratory. The test system is schematically shown in fig. 2.
The U-shaped yoke placed on the surface of the sample is used to provide a magnetic field. A sinusoidal signal provided by the function generator is applied to the excitation coil. The pick-up coil used to detect the MBN signals is mounted in the middle between the legs of the U-core. The original signal is amplified and filtered. To minimize undesirable effect of eddy current in the induction process, in the experiment the excitation frequency was set to 10 Hz, the sampling frequency was set to 200 kHz.

The morphology of one MBN signal is shown in figure 3. The MBN signal is composed of many pulses of different intensities. In order to quantitatively describe one MBN signal, the RMS (root mean square) is used as the eigenvalue. The RMS voltage of the MBN signal is computed using the expression

$$V_{\text{RMS}} = \sqrt{\frac{\sum V_i^2}{n}}$$

Where $V_i$ is voltage intensity and $n$ is the number of voltage pulses.

2.3 Microstructure characterization and X-ray Diffraction Measurements

The microstructure of the specimen was characterized by scanning electron microscope (SEM). The specimens were prepared according to the standard procedure, etched with Nitric acid alcohol solution (4% HNO3, 96% alcohol) after grinding and polishing. A PANalytical X-Pert system with Cu – kα radiation ($\lambda =0.154$nm) was used for XRD measurement. The X-ray tube was operated at 40 kV and 40 mA. The diffraction lines were recorded from $2\theta =10^\circ$ to $90^\circ$ with a step of $0.02^\circ$ to cover the
main diffraction angles of the samples. The (110), (200) and (211) pole figures were measured and the orientation distribution function (ODF) was calculated for texture analysis.

3. Results and discussion

3.1 Microstructure analysis

The samples for MBN and XRD measurement were free from external influences (Force, temperature and magnetic field), the microstructure completely determines the MBN and XRD signals. The influence of microstructure can be divided into different factors, such as dislocation, residual stress, grain size, texture and so on. The external force was uniformly and slowly applied to the cross section of the specimen during tensile test, resulting in uniform plastic deformation in the material, no macroscopic residual stress was generated in the specimens. Texture is another important factor affecting the detection signal. Texture may be formed during plastic deformation, Textural structure with specific orientation distribution results in anisotropy of the detection signals. Plastic deformation can also cause grain shape changes, the size of which depends on the composition of the material, the type of microstructure and the degree of plastic deformation. The morphology and size of the grains will also cause changes in the detection signals. The microstructure and texture of the specimens were observed.

(a)SEM figure; (b) ODF figure

Figure 4. Microstructure and texture observation of the #7 specimen

The corresponding result of the #7 specimen was given in figure 4. As shown in Fig.4 (a), the ferrite (black in color) and pearlite (white in color) is uniformly distributed, no obvious deformed structures or bands were observed. Fig.4 (b) shows the orientation density map at different directions. According to the color scale, the orientation density is uniformly distributed in all directions, and there is no orientation concentration in the material. The deformation of the #7 specimen is the largest, and there was no deformed microstructure and texture produced during tensile deformation. The test results of other samples with smaller deformation are similar. In summary, tensile deformation process mainly results in changes of dislocation density of the specimens.

3.2 Dislocation density measured by X-ray diffraction method

The dislocation density was measured according to the XRD profile analysis method. The modified Williamson-Hall method (m-WH) is a widely used method to evaluate the dislocation density[25,26]. The dislocation density measured by X-ray diffraction experiment can be described by the following
equation [27]:

\[(\Delta K)^2 = \left(\frac{\alpha}{d}\right)^2 + \beta K^2 C + O(K^2 C^2)\]  \hspace{1cm} (2)

\[\Delta K = \frac{2W \cos \theta}{\lambda}\]  \hspace{1cm} (3)

\[K = \frac{2 \sin \theta}{\lambda}\]  \hspace{1cm} (4)

\[\beta = \frac{\pi M^2 b^2}{2} \rho\]  \hspace{1cm} (5)

In which, \(\alpha\) is shape factor, \(d\) is the average grain size, \(\theta\) is diffraction angle, \(W\) is the full-width-half-maximum (FWHM) of the XRD diffraction peak, \(\rho\) is the dislocation density, \(\lambda\) is X-ray wave length, \(K\) is the magnitude of diffraction vector, \(M\) is a constant parameter depending on the effective outer cutoff radius of dislocation, in deformed materials \(M\) varies in between 1 and 2, for most instance \(M\) was selected as 2[28,29], \(O\) indicates non-interpreted higher order terms, \(b\) is the magnitude of the Burgers vector. \(C\) is the so called dislocation contrast factor, which is determined by the elastic anisotropy and the dislocation type of the material

\[C = C'_{h00} (1 - qH^2)\]  \hspace{1cm} (6)

\(C'_{h00}\) is a constant (0.258). In a similar manner, the \(q\) parameter was determined as 1.977. \(H^2\) can be expressed as the fourth-order invariant function of the Miller indices (hkl):

\[H^2 = \frac{h^2k^2 + k^2l^2 + l^2h^2}{(h^2 + k^2 + l^2)^2}\]  \hspace{1cm} (7)

According to Eq. (2), the \(\Delta K\) for each (hkl) plane was plotted as a function of \(K^2 C^2\), after linear fitting, the slope \(\beta\) was calculated and the dislocation density \(\rho\) can be obtained according to Eq. (5).

In this research, \(b=0.284[31]\), \(\alpha\) is given as 0.9 under assumption of spherical crystals with cubic symmetry[32], the results of X-ray diffraction was given in figure 5.

![Figure 5. XRD diffraction peaks of the specimens](image-url)

As shown in figure 5, 3 distinct diffraction peaks ((110), (200) and (211)) were detected in each sample. The diffraction peaks have obvious broadening characteristics. FWHM values of the (110), (200) and (211) X-ray diffraction peaks were obtained from the original diffraction data. However for (h00) plane, the value of \(H^2\) in Eq. (7) is zero. In such a case Eq. (2) cannot be applied[33], so only diffraction data from (110) and (211) was used. The relationship between \((\Delta K)^2\) and \(K^2 C\) was given
in Figure 6. After linear fitting, it can be seen clearly in Figure 6 that with the increase of plastic deformation, the slope of fitting curve is increasing. The $\beta$ value of each sample was obtained through fitting and the corresponding dislocation density was calculated according to Eq. (4), as shown in table 1, the dislocation density increases with the increase of plastic deformation.

![Figure 6: Peak broadening analysis using the modified Williamson–Hall plot](image)

**Table 1. Summary of the Coefficient of the Fitting Curve in the Modified Williamson-Hall Plot**

<table>
<thead>
<tr>
<th>specimen</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual strain (%)</td>
<td>1</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.113</td>
<td>0.143</td>
<td>0.172</td>
<td>0.228</td>
<td>0.25</td>
<td>0.328</td>
<td>0.341</td>
</tr>
<tr>
<td>$\rho$ ($\times 10^{15}$/m$^2$)</td>
<td>2.2</td>
<td>2.8</td>
<td>3.4</td>
<td>4.5</td>
<td>4.9</td>
<td>6.5</td>
<td>6.7</td>
</tr>
</tbody>
</table>

### 3.3 Dislocation density evaluated by MBN

After the XRD test, the MBN signals of each sample were tested at the same location. All tests were carried out under the same condition. Figure 7 shows the morphology of 3 MBN signals obtained from each sample. As can be seen clearly, the morphology of each MBN signal is spindle shaped, large in the middle, and small in the two ends. The distribution area of MBN signal corresponding to the plastic deformation of 1% is the largest, indicating that the MBN signal intensity is the strongest of the 7 specimens, whereas the distribution area of MBN signal corresponding to the plastic deformation of 18% is the smallest, indicating the weakest intensity of MBN signals. It looks as if the difference of MBN signal morphology is not obvious between the two specimens with similar degree of plastic deformation, on the whole, the MBN signal morphology of the 7 samples is quite different. The MBN signal intensity of specimens from the smallest plastic deformation to the largest plastic deformation is gradually decreasing. In order to assess this difference quantitatively, RMS of each sample was calculated. Because the overall appearance of MBN signals obtained from the same sample is different. The RMS value of each sample is averaged over ten MBN signals to minimize the effect of signal morphological differences.
From macroscopic view, the difference of MBN signals in different samples is caused by plastic deformation. In fact it is the difference of dislocation density that results in the different intensity of MBN signals. Fig. 8 shows the relationship between plastic deformation, dislocation density and MBN signal among different specimens. As can be seen clearly, with the increase of plastic deformation degree, the basic rule is the increase of dislocation density and the decrease of MBN signal intensity.

3.4 Relationship between dislocation density and MBN signal

The value of the dislocation density $\rho$ can be calculated from the average values of the crystallite size $D$ and microstrain $\varepsilon$ by relationship[34]

$$\rho = \frac{3\sqrt{\pi \langle \varepsilon^2 \rangle^{1/2}}}{D_b}$$  \hspace{1cm} (8)
where \( \mathbf{b} \) is the Burgers vector.

According to Eq. (8), the dislocation density increases with the increase of plastic strain, the research in this paper has also reached the same conclusion. The dislocation multiplication can be well explained by the Frank-Read source model, which is usually used to characterize dislocation generation in the bulk of a crystalline material[35].

The MBN signal intensity decreases with the increase of dislocation density, this is determined by magnetic domain dynamics. The MBN signal is generated when the magnetic domain moves. Any factor that hinders the movement of magnetic domains will affect the MBN signal. Dislocations hinder the movement of magnetic domain walls. Each dislocation will have a critical value of the pinning force per unite length, the domain wall can move only when the external force is greater than the pinning force provided by all the dislocations. The critical field is defined as[36]

\[
H_{\text{crit}} = \frac{\gamma \cos \theta_{\text{crit}}}{\mu_0 M_s L (\cos \Omega_1 - \cos \Omega_2)}
\]  

(9)

Where \( L \) is the distance between two adjacent pinning sites. Under the same test conditions, the other parameters are the same. According to Eq. (9), the critical strength \( H_{\text{crit}} \) for MBN activity decreases as the spacing \( L \) increases. According to the model of Nes and Marthinsen[37,38], the slip length of dislocations reduced due to the formation of cell structures and sub-boundaries during deformation. As the degree of deformation increases, the dislocation density increases, the value of \( L \) decreases, the critical field strength required for magnetic domain wall motion increases, and the number of magnetic domains that can be moved decreases, eventually the value of MBN signal decreases.

3.5 Correlation between dislocation density and MBN signal

According to the above analysis, the law that the MBN signal decreases with increasing dislocation density is very clear. This makes it possible to quantitatively evaluate the dislocation density using the magnetic Barkhausen noise method, and the relationship diagram was drawn, in which, dislocation density is abscissa and RMS is ordinate, as shown in figure 9. The seven data points show a good linear relationship. According to the regression analysis, the relationship between RMS and Dislocation density can be expressed as:

\[
D = \frac{R-3.58}{0.36}
\]  

(10)

Where \( R \) indicates RMS intensity, \( D \) indicates dislocation density. In order to verify the reliability of the method, three tensile specimens were prepared using the same material and method. The residual strain of the samples was 15% after tensile deformation. The mean RMS value of the three samples is 1.57, substitute it into Eq. (10), the calculated dislocation density value is \( 5.58 \times 10^{15}/m^2 \). The mean dislocation density of the three specimens tested by the m-WH method was \( 5.32 \times 10^{15}/m^2 \), the relative error of this method is 4.9%. The results show that the MBN method has high accuracy in measuring dislocation density.
4. Conclusions

The mainly change of the microstructure of the specimens during tensile deformation is the dislocation multiplication. With the increase of plastic deformation degree, the dislocation density increases and the MBN signal intensity decreases. There are remarkable negative linear relevant relations between RMS and dislocation density. According to the regression function, the dislocation density can be forecasted, and the prediction value is of high precision. This study confirms that it is feasible to quantitatively evaluate dislocation density using MBN method.

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References


CORROSION EVALUATION OF STEEL REBAR IN CONCRETE USING ELECTROMAGNETIC METHOD

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Abstract

Corrosion of steel reinforcing bar (rebar) in concrete reduces the strength capacity of concrete, and also causes the crack of concrete due to the volume increase of the corrosion products. Detection of corrosion at the early stage is important for the safety evaluation and repairing of the concrete structures. Electromagnetic induction (AC field) method [1], Microwave radar system [2], and thermography technology [3] have been used to evaluate the break, the location, or the corrosion of the steel rebar in concrete. Compared with other methods, the low frequency electromagnetic induction method has the advantages of low cost and easy operation. And the moisture of concrete also has less influence to the detection results.

We developed an electromagnetic method to evaluate the corrosion of steel rebar. Fig. 1(a) shows the experimental setup. AC magnetic field was produced by the excitation coil when AC current flow in it. Then, eddy current was induced in the surface of the steel rebar. The detection coil was used to measure the magnetic field produced by the eddy current. The signal after the amplifier was sent to a lock-in amplifier. From the lock-in amplifier, two signals were obtained: X signal (the same phase signal with the excitation current) and Y signal (90 degree phase difference signal with the excitation current). From the slope of the plotted X-Y graph using the X and Y signals, the corrosion of the steel rebar can be judged. In our experiments, the size of the excitation coil was 3 cm. The frequency was 80 kHz and the current was about 20 mA.

We had four samples of steel rebars with different corrosion levels. The diameters of the all steel rebars were 16 mm. The steel rebar “a” had no corrosion; steel rebar “b” had a little corrosion, there are some corroded dots on the surface the steel rebar; steel rebar “c” had big corrosion, the thickness of the corroded layer was about 0.1 mm and steel rebar “d” had severe corrosion with the thickness of the corrosion layer of about 1 mm.

We scanned the steel rebar using the electromagnetic system. Fig. 1(b) shows the signals of steel rebar when the covering depth was 5 cm. X-Y graphs were plotted using the X and Y output signals of the lock-in amplifier. The slopes were different for the steel rebars with different corrosion levels. The absolute value of $\Delta Y/\Delta X$ increased with the corrosion level.

(a)                                                                                (b)

Fig. 1(a). Experimental setup for the corrosion evaluation of steel rebar using electromagnetic method. (b). The X-Y graph of the X, Y signals of steel rebars with different corrosion levels. Sample a: no corrosion; sample b: a little bit corrosion, some corroded dot on the surface; sample c: big corrosion, 0.1 mm corrosion thickness; sample d: severe corrosion, 1 mm corrosion thickness.

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Using this system, we also monitored the corrosion progress of steel rebar in concrete. Using 5kg/m³ salt water alternating immersion to accelerate the corrosion of steel rebar. Fig. 2(a) shows the sample. We measured the absolute values of $\Delta Y/\Delta X$ four times: Fig. 2(b) shows the results. We can see the absolute values of $\Delta Y/\Delta X$ increased with the corrosion progress.

As a summery, we developed electromagnetic method to evaluate the corrosion of steel rebar in concrete. And it can also be used to monitor the corrosion progress of steel rebar in concrete.

References
PROBABILISTIC ANALYSIS OF THE CAPABILITY OF EMAR FOR MONITORING WALL THINNING

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Abstract
Maintaining the integrity of piping systems is one of the most important issues to maintain the safety of large structures such as chemical and power plants as the rupture of pipes, especially those carrying high-pressure fluids, would lead to serious accidents [1,2]. Whereas many studies have been performed to evaluate effect of factors affecting pipe wall thinning [3,4], it is difficult to predict pipe wall thinning quantitatively and thus periodic non-destructive inspections to evaluate pipe wall thicknesses are indispensable. In contrast, usually advanced and post preparations, rather than measuring signals, occupy major part of the costs and resources needed for performing non-destructive inspections practically. This implies the effectiveness of situating sensors to monitor wall thickness if one needs to evaluate the wall thickness frequently.

Electromagnetic acoustic resonance (EMAR)[5,6] would be one of most promising non-destructive inspection methods for monitoring pipe wall thickness because of its high accuracy in evaluating the thickness of target and no need to use couplant. Several earlier studies have demonstrated the effectiveness of the method[7,8]; however they used mechanically introduced flaws for their validation, or compared the results not with actual wall thickness but with results of conventional ultrasonic tests. Furthermore, the complicated profile of actual wall thinning implies that it would not be reasonable to discuss the capability of EMAR deterministically.

On the basis of this background, this study attempted to evaluate the practical applicability of EMAR to monitoring pipe wall thinning probabilistically. Approximately 60 carbon steel plates made from S50C were soaked into iron(III)-chloride-based corrosive solution to introduce various artificial corrosion. Subsequent experiments to measure EMAR signals were performed using a pulsar-receiver (RITEC, RPR-4000) and an EMAR probe consisting of two samarium-cobalt magnets measuring 10x20x20 mm and one race track coil attached at the bottom of the magnets. The resonance frequencies were evaluated using the superposition of the nth compression technique[8], and then the thickness of the target was calculated using the fundamental resonance frequency and the velocity of speed evaluated in advance. The probabilistic analyses of the capability of EMAR were performed based on the concept of probability-of-detection (POD)[9].

Figure 1 shows the surface profile of two of the corroded plates observed using a laser microscope (Keyence, VK-X1000). The figure confirms that the corrosion has a complicated uneven surface that conventional mechanical machining cannot realize. The result of POD analysis is presented in Fig. 2, which indicates that local wall thinning with a depth of 0.161 mm is detectable with a probability of 50% if EMAR probe is situated properly.

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Figure 1. Surface profile of corrosion

Figure 2. Probability of detection curve

References

INFLUENCE OF FATIGUE DAMAGE ON NDE OF PLASTIC STRAINS IN RAFM STEEL USING ELECTROMAGNETIC NDE METHODS

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Abstract

The ITER program nowadays under progress is for the peace application of nuclear fusion energy that is regarded as a promising clear and sustainable energy for future human society. Plastic deformation inevitably occurs in in-vessel components of a fusion reactor during operation due to giant unexpected load which has significant impact on the structural safety. Thus, finding a reliable Non-Destructive Evaluation (NDE) technique for the structural material of fusion reactors is of great importance. Reduced-Activation Ferritic /Martensite (RAFM) steel [1] which is considered as one of the important candidate structural materials for ITER test blanket module because its low activation, excellent mechanical property and good micro-structural stability. In previous works of authors, the validity of three typical NDE techniques, i.e., the Magnetic Barkhausen Noise (MBN), the Magnetic Incremental Permeability (MIP) and the Magnetic Flux Leakage (MFL) method for evaluation the plastic deformation in the RAFM steel has been demonstrated [2]. Since the operation of ITER is of pulsed mode which may cause fatigue damage in in-vessel structures, to clarify the influence of fatigue damage on the NDE of plastic deformation in in-vessel components is necessary in order to apply the magnetic NDE methods in practice.

In this study, the relationship between fatigue damage and NDE experimental signals on samples with different residual plastic deformations is studied experimentally. Four samples of RAFM steel was firstly fabricated and dealt with proper heat treatment in order to ensure a free strain state of the material. Then, different levels of residual plastic deformations (0\%, 0.6\%, 1.8\% and 4.8\%) were applied to the specimens with a tensile material test machine. After that, different cycles of fatigue damage (0, 100, 500, 1000, 2000, 5000, 10000 cycles) with a loading aptitude of 500 MPa were applied to each sample respectively and NDE experiments using an integrated MBN, MIP and MFL measurement system developed by authors [3] were taken during each loading gap.

The examples of the experimental results are as shown in Fig.1. The Root Mean Square (RMS) which shows an intensity of MBN signals, the imaginary peak value of the MIP butterfly trajectory represents the imaginary part of maximum permeability, and K factor of MFL signals describes the distortion level during magnetization are taken as feature parameter of each NDE method respectively. The feature parameters of these three methods show a downward tendency with the increasing plastic deformation before fatigue damage is induced, which is consistent with previous results [2]. In the case of the sample without any residual plastic deformation, the RMS of MBN method, imaginary peak value of MIP butterfly trajectory and K factor of MFL method drop dramatically at a low cycle number which is 100 times in this work. Then the signals are relatively stable with the increasing loading cyclic numbers. On the other hand, in the case for samples with residual plastic deformation, despite the strain levels are different, features of these NDE signals are limited

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influenced by the fatigue damages. In general, the influence of fatigue damage on NDE signals is far smaller than the influence of residual plastic deformation on NDE signals in samples with residual plastic deformation.

![Figure 1](image)

Figure 1. The relationship between NDE signals and loading cycles of RAFM samples with different levels of residual plastic deformation (a) MBN, (b) MIP, (c) MFL.

As conclusion, the experimental results reveals that fatigue damages have some impact on the specimens free of plastic strains at the very beginning while have limited influence on specimens with relative large residual plastic deformation. Among the three magnetic MDE methods, MFL methods has the best stability and repeatability for evaluation of plastic strains in the RAFM steel.

References

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THREE-DIMENSIONAL SIMULATION OF ELECTROMAGNETIC ACOUSTIC RESONANCE METHOD USING CIVA SOFTWARE

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Abstract
Pipe wall thinning due to corrosion is a significant problem that exists in many industries, such as nuclear power plants and chemical plants. The electromagnetic acoustic resonance (EMAR) method using electromagnetic acoustic transducer (EMAT) has been proposed to perform pipe wall thinning measurements [1]. One of its main advantages, compared with traditional piezoelectric transducer, is that it does not need a coupling medium, therefore it can be used for on-line monitoring in harsh environments like high temperature ones. The purpose of the EMAR method is to improve the low signal-to-noise ratio usually obtained with EMAT probes. Its principle is to successively excite the specimen with continuous harmonic waves in order to determine its resonance frequencies, from which the local thickness can be deduced [2].

Effective numerical analysis can not only explain the experimental phenomena but also provide a help for probe optimization. Because the numerical analysis of EMAT involves the coupling of electromagnetic field and ultrasonic wave, its three-dimensional analysis can become difficult and time-consuming when using classical numerical techniques. In addition, EMAR method needs to compute the long time domain signal of a large number of frequencies, which increases the computational burden even more. In this paper, we take advantage of the fast electromagnetic and ultrasonic semi-analytical models implemented in the CIVA software [3,4] to carry out the simulations. Parameters of the configurations studied are recalled in Figure 1. In this study the non-linear behavior of the SS400 material is not taken into account.

Parameter of EMAT
Magnet: Samarium-cobalt magnet (remanent flux density: 1T)
Wire diameter of coil: 0.12 mm
Transmitter coil: diameter 10 mm (40 turns)
Receiver coil: diameter 20 mm (80 turns)
Electric current: 10 A (peak-to-peak)

Parameter of specimen
Material: SS400 low carbon steel
Relative permeability: 110
Electrical conductivity: 4.032 × 10^6 S/m
Density: 7850 kg/m^3
Young’s modulus: 220 × 10^9 Pa
Poisson’s ratio: 0.33

Figure 1. Geometry and parameters of the simulation.

The EMAR response to a set of sinusoidal bursts (100 µs of continuous excitation followed by a period of 200 µs for reception, see Figure 2) with frequencies ranging from 1 MHz to 1.35 MHz, with a step of 10 kHz, are simulated with CIVA. Then, the extraction of each

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maximal amplitude leads to the construction of the EMAR spectrum illustrated in Figure 3. As on can notice in figures 3 and 4, the resonance effect observed in simulation is quite strong and agrees well with the experimental one. When calculating the ultrasonic wave, in order to simplify the calculation, we use Lorentz force distribution at 1 MHz as Lorentz force distribution at all frequencies from 1 MHz to 1.35 MHz, and only change the frequency of input signal at each frequency. The calculation at each frequency takes about three minutes (Dell Precision 7820 Tower/ Intel® Xeon® Bronze 3104, 1.70 GHz, 6 Cores/ 64 GB).

The frequency difference between the two resonance peaks of Figures 3 (observed at 1.13 MHz and 1.291 MHz, respectively) is about 161 kHz, which leads to an estimated thickness [1] of 10.09 mm, close to the true one of 10 mm. In future works, simulations of thickness estimations obtained when scanning a corroded piece will be used to optimize the probe design and assess its performance.

Figure 2. Input signal of 1 MHz burst signal in time and frequency domain.

Figure 3. EMAR spectrum simulated in the range of [1 1.35] MHz.

Figure 4. Simulated Received signals at 1 MHz and 1.13 MHz (resonance).

References

Acknowledgements
This work was partly supported by the Grant-in-Aid for JSPS Research Fellow Grant Number JP 18J11863. A part of this study is the result of “Piping System, Risk Management based on Wall Thinning Monitoring and Prediction” carried out under the Center of World Intelligence Project for Nuclear S&T and Human Resource Development by the Ministry of Education, Culture, Sports, Science and Technology of Japan, and ANR of France.
Magnetic Barkhausen Noise Mapping System for Laser-quenched Zone in Steel Shaft

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Abstract

During the surface treatment process of steel shafts, changes of both micro structures and residual stress will be introduced to the surface material. Evaluation of the homogeneity in the metallographic structure and the residual stress is of importance for the quality control of the surface treatment. When ferromagnetic materials are subjected to AC magnetic field, the inside magnetic domains exhibit discontinuity in motion (referred as Barkhausen jump) due to the pinning of grain boundaries, precipitates and dislocations, etc. The discontinuous jumps process will induce pulsed magnetic field, which can be detected by inductive coils that are placed near the specimen surface. The output voltage of the inductive coil is named as magnetic Barkhausen noise (MBN) signal. The pinning effect applied to the magnetic domains varies as the changes of both micro structures and residual stress. Numerous studies have reported that the MBN signal is very sensitive to the state of both micro structures and residual stress. Therefore, MBN test is a good option for non-destructive evaluation of the homogeneity in the steel shaft.

In this study, an automatic system for conducting magnetic Barkhausen noise (MBN) scanning to a steel shaft is proposed. Laser quenching technology is employed to induce localized surface-hardened zone in the shaft. MBN mapping to the laser-quenched zone is realized and the mapping results of MBN feature parameters may reflect the profiles of metallographic structure and the residual stress in the scanned zone.

The specimen for MBN test is a cylindrical shaft of 45 steel. The shaft has a diameter of 40 mm and a length of 150 mm. Laser quenching treatment was carried out on the surface of steel shaft to form a narrow laser-quenched band as shown in the inset of Figure 1.

Figure 1. Experimental set-up and the software for MBN mapping of shaft

A self-made sensor was used to perform MBN measurements in the steel shaft surface. The MBN scanning system is constructed based on a four-axis motion platform as shown in Figure 1. Both the step motors of the motion platform and the MBN measurement system are controlled by a NI host which is equipped with motor drive card, signal generation card, data acquisition card. The MBN sensor is fixed on the end of the Z-axis of the motion platform to scan along a cylindrical busbar while the yoke of the MBN sensor keep in contact with the

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shaft surface. The shaft is fixed to the rotating platform and the rotation angle against the sensor is controlled by the motion of rotating axis. Through the combination motion of Z-axis and rotating axis, the MBN mapping to the cylindrical surface is achieved.

Ten-cycle sinusoidal signal is generated by the signal generation card. After being amplified by a BOP bipolar power supply, the sinusoidal current is fed into the magnetizer of the sensor. The measured MBN signals are acquired with a sampling frequency of 1MHz. The operations of the entire MBN scanning system are issued by LabVIEW program.

Figure 2 shows the mapping results of peak amplitude of the MBN envelop. In the scanned region, the surface is divided into three regions by two lines with high amplitude, which represent the transition zone from the base material to the hardened zone. The amplitude of MBN envelop obtained from the laser-hardened zone is relatively lower than that of the base material. This is because laser-quenching process causes the phases in base material change into martensite in the laser-hardened zone. Though the correlations between the MBN mapping results and the profiles of metallographic structure or the residual stress still need be investigated, the results in Figure 2 clearly show that the proposed MBN scanning system is feasible for homogeneity evaluation in laser-quenched steel shaft.

![Figure 2 MBN mapping result of Laser-quenched Zone](image)

**References**


**Acknowledgments**

This study was supported by the National Key R&D Program of China (2018YFF01012300) and National Natural Science Foundation of China (Project Nos. 11527801).
MICROMAGNETIC QUANTITATIVE PREDICTION OF MULTIPLE MECHANICAL PROPERTIES OF DP590 STEEL STRIP

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Abstract

DP590 dual-phase steel strips is widely used in the manufacturing process of automobile structural parts [1, 2]. Evaluation of the mechanical properties (such as hardness, yield strength, tensile strength, elongation, etc.) of the strips are important contents in product quality control. In traditional ways, destructive methods (such tensile and indentation tests, etc) are employed to measure the mechanical properties of the steel strips. To achieve non-destructive ways, micro-magnetic test technology is developed for online evaluation of multiple mechanical properties.

In this study, experimental system for micro-magnetic test was established to conduct simultaneous measurements of tangential magnetic field (TMF) [3] and magnetic Barkhausen noise (MBN) [4, 5] in the tested specimens of DP590 steel. The correlations between multiple magnetic parameters and four target properties (hardness, yield strength, tensile strength, elongation) are characterized based on BP neural network method [6, 7]. The accuracy of the established BP model in predicing the target properties are evaluated.

The detail procedures for micro-magnetic quantitative prediction of mechanical properties are as follows. First, forty dog-bone tensile specimens were prepared for two-stage annealing. Through changing the two-stage annealing temperature, mechanical properties of individual specimen are different from the rest specimens.

Second, experimental set-up employing a dual-functional sensor (see Figure.1) is constructed in laboratory. The sensor is composed of a U-shape Fe-Si yoke, an exciting coil and two sensor elements (inductive coil and Hall element). Both ends of the yoke contact with the tested specimen through a cone with inverted pyramid shape. Thus, the yoke is suitable for curved surfaces. The entire experimental set-up was controlled by LABVIEW program run on NI host. Sinusoidal signal with an amplitude of 1V and a frequency of 200Hz is generated by an arbitrary signal generation card and then fed into a BOP100-4ML bipolar

Figure 1. Experimental set-up

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power amplifier. The amplified sinusoidal current is fed into the excitation coil to provide magnetic field for specimen magnetization. The inductive coil and Hall element respectively measure the MBN and TMF signals, which are collected by a multi-channel data acquisition card.

Third, MBN and TMF measurements are repeated three times for each specimen. Tensile test and micro-hardness test are performed to each specimen to measure the target mechanical properties. Finally, the data of MBN and TMF features and the target mechanical properties are used for BP neural network modelling. The effect of input nodes of BP model on the target properties prediction accuracy is investigated. The prediction results of the target properties with and without data screening are shown in Fig.2a and Fig.2b, respectively.

When all the data are used as input nodes of BP model, the averaged prediction error of surface hardness, yield strength, tensile strength and elongation are 4.13%, 6.07%, 2.63% and 9.48%, respectively. Through proper data screening, the averaged prediction error of the BP model for surface hardness, yield strength, tensile strength and elongation can be reduced to around 3.51%, 3.92%, 2.44% and 3.75% respectively.

![Without data screening](a) Without data screening

![With data screening](b) With data screening

Figure 2. Evaluation of mechanical properties prediction accuracy

References


Acknowledgments
This study was supported by the National Key R&D Program of China (2018YFF01012300) and National Natural Science Foundation of China (Project Nos. 11527801).
Abstract

Recently, many non-destructive testing (NDT) methods have been focused on the angular defect characterization/quantification [1-4]. As a typical branch of active thermography techniques, eddy current pulsed thermography (ECPT) has been also used to localize and characterize rolling contact fatigue cracking (a common angular defect) in rail tracks [5-9]. Apart from easily localizing RCF cracks, the challenges for ECPT to characterize inclined defects are proposing robust features for the propagation length or inclination angle quantification with the tolerance of multi-parameter integrated influences. This work introduces two spatiotemporal features for the inclination angle characterization of artificial angular defects. Specifically, based on the binarized thermal distributions (see Table 1), two slope-related features that present the centroid horizontal moving and the area increasing of the binarized distributions are proposed to build the relations to the inclination angle. Results show that the compared to maximum thermal responses, both slope-related features show overall overall monotonic relations to the inclination angle, as shown in Fig. 1.

Table 1. Raw and binarized thermal distributions around the defect vicinity at the end of the heating pulse resulted from different inclination angles

<table>
<thead>
<tr>
<th>Inclination Angle</th>
<th>Raw Distribution</th>
<th>Binarized and Filled Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40°</td>
<td></td>
<td></td>
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<tr>
<td>35°</td>
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<td>30°</td>
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<td>25°</td>
<td></td>
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<tr>
<td>20°</td>
<td></td>
<td></td>
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<tr>
<td>15°</td>
<td></td>
<td></td>
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<tr>
<td>10°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Figure 1. Three features vs. inclination angle. (a)-(c) Max thermal response, slope of the centroid horizontal moving, and slope of the area increasing vs. inclination angle under the 200 ms heating pulse, respectively.

References

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Development of wireless monitoring system for distributed ultrasonic thickness measurement

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Abstract

Ultrasonic testing method is widely used in many areas, due to the advantages of high precision measurement, low cost and good directivity. It is very important in many situations to apply a multi spot thickness real-time monitoring, such as the corrosion monitoring of steel pipe, thickness testing of waterproof coil, and so on. However, most ultrasonic thickness gauge can only measure single point, and has a monotonous function in data presentation. So, it is unsuitable for complex and online measuring requirements. In this paper, a wireless monitoring system for distributed ultrasonic thickness measurement is presented. The STM32 MCU is used as the main control chip of the system, and it controls several independent ultrasonic working modules respectively for transmitting and receiving ultrasonic wave. The chip of TDC_GP21 is used to measure the flight time of ultrasound, and each data is uploaded to the STM32 MCU to convert into thickness value. The MCU and the upper computer software is communicated through wireless network.

System principle

The diagram of the system is shown in Figure 1. The number of the ultrasonic testing modules can be chosen by users according to the actual requirements. Each ultrasonic probe is equipped with a transmitting circuit (T.C.) and a receiving circuit (R.C.). The single chip computer chooses one of the probes and controls the transmitting circuit to send pulse excitation. The received echo signal is processed by limiter circuit, amplifying circuit, filtering circuit, voltage comparison circuit to get the square wave signal. The time interval of the square wave signal is measured by time measuring chip (TDC_GP21). The single chip transmits the measured data to the upper computer through wireless network. The upper computer further processes the data and calculates the measured data. The thickness value of the point is displayed in real time on the software interface. The microcontroller scans all the ultrasonic probes circularly, so as to realize the multi-point measurement.

Figure 1. Diagram of the wireless distributed ultrasonic thickness monitoring system

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The upper computer software of system was designed, which can realize high-speed data transmission, overcome the inconvenience caused by communication cables in the field detection, and improve the stability of the system. According to the need of actual measurement, users can monitor the condition of the measured parts through the upper computer by setting measurement parameters such as material sound speed, measurement period, measurement times, and so on. The data can be plotted and saved by the upper computer, so that the observation of data can be more intuitive.

**Experiment validation**

The experimental system was built for the above designed distributed wireless ultrasonic thickness gauge, the obtained ultrasonic echo signal was processed by the receiving circuit and converted into a square wave signal with steep edges, as shown in Figure 2. The time interval of square wave pulse is measured by the time measuring circuit, then the thickness of the measured point is calculated, and the feasibility of the system is verified.

![Figure 2. Pulse signal of echo signal processed by receiving circuit](image)

**Conclusion**

The distributed wireless ultrasonic thickness measurement system designed in this paper realizes multi-channel cyclic thickness measurement, and overcomes the inconvenience caused by wired detection. The upper computer can display multi-channel measurement data in real time and save data, improve the detection efficiency, and can be applied to various measurement environments. It has broad application prospects.

**References**


**Acknowledgments**

This project is funded by the National Natural Science Foundation of China (Grand No. 51707058, 51807052).
Study on Characteristic of the Common Electromagnetic Acoustic Coils for Thickness Measurement of Steel Plates

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Abstract

Compared with traditional piezoelectric transducer, electromagnetic acoustic transducer has the advantages of non-contact, low requirements on the surface of the workpiece, flexible generation of various waveforms, large detection range and high sensitivity. However, it is largely constricted by some problems, such as the low conversion efficiency and weak echo amplitude. In order to improve the applicability of this method, particularly in the cases of thickness measurement of steel plates, the characteristic of the commonly used RF coils of electromagnetic acoustic transducer are discussed in this paper.

Five different types of two-layer electromagnetic acoustic shear wave coils were selected to test. They were spiral coil, square coil, double rectangular coil, butterfly coil and track coil. We used Ritec RPR-4000 to generate and receive the ultrasonic wave for these coils. The performance of these coils was analyzed by amplitude and signal-to-noise ratio of first echo signal, and voltage variation shown in the instrument. Through these comparative experiments, the variation of the transducing efficiency with the excitation frequency, the number of turns, the coil area, the range of action, and the amplitude-frequency characteristic curve are given, and the optimal operating frequency of each transverse wave coil were obtained, as shown in Fig. 1.

Figure 1. Amplitude-frequency characteristic curves for different coils

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Conclusion
1. From the chart above, the conclusion indicates that the relationship between the frequency and the amplitude of the four coils is roughly ranked as: square coil > spiral coil > double rectangular coil > butterfly coil, and the amplitude decreases with the increase of frequency overall, but there are some fluctuations in the low frequency part.
2. If the outer diameter of spiral coil is constant, while the inner diameter becomes larger, the area and turns also become smaller, then the amplitude of the echoes decreased gradually. If the inner diameter of spiral coil is constant, while the outer diameter becomes bigger, the corresponding circle area and turns are bigger, then the amplitude also increases. According to the slope of the curve, the variation of the inner diameter per unit length has greater influence on the amplitude.
3. For the comparison result of the action range of the butterfly coil, it shows that the middle parallel parts are more important in generating ultrasonic wave than the arc parts.
4. While the vertical parts of the double rectangular coil are isolated, the echo signal disappears, and when the horizontal parts are isolated, the amplitude decreases by about 30 mV. It can be considered that the effective action area of the square butterfly coil is the vertical parts.

References

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Numerical investigation the faults diagnosis for AC induction machine by magnetic flux distribution

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Abstract

Induction machines play an essential role in industrial drives and wind power generation. They are found in use in motor drive systems from few watts to several megawatts [1]. To ensure the reliable operation and long lifetime of these machines, condition monitoring technologies have been developed to detect the occurred faults and predict impending failures.

Induction machines generally operate at harsh environment which leads to approximately 6\% failure rate each year [2]. The faulty induction machines may cause whole drive systems to shut down and even catastrophic damage. Among these failure machines, several surveys have investigated and illustrated the detailed failure types and rates [3]. The common failures of induction machines include stator winding faults, bearing faults, rotor bar/ring faults and shaft failures [4].

To investigate the influence of the rotor speed, rotor eccentricity, rotor bar failure and shaft failure on the magnetic flux density distribution, the FE model based on COMSOL is set up, and the relationship of the faults and the magnetic flux density are studied in detail.

The structures of the AC squirrel-cage asynchronous induction machine studied in this paper is shown in Fig.1. In FE modelling, the electrical parameters and geometric parameters of the machine are listed in Table 1. The material and the material parameters of the stator, rotor, shaft, stator wingding and rotor wingding are listed in Table 2. According to the parameters in Table 1 and Table 2, we can calculate the revolving speed of the magnetic field is 1500 r/min. Because the speed of rotor is smaller than the magnetic field, the speed of the rotor is set as 1485 r/min in simulation.

![Fig.1 the structure of the AC induction machine](image)

Table 1 the electrical parameters and geometric parameters of the machine

<table>
<thead>
<tr>
<th>Rated power (kW)</th>
<th>Armature slot number</th>
<th>Height of air gap (mm)</th>
<th>Pole number</th>
<th>Inter Diameter of stator (mm)</th>
<th>Outer Diameter of stator (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage(V)</td>
<td>3</td>
<td>24</td>
<td>32</td>
<td>6</td>
<td>130</td>
</tr>
<tr>
<td>Rated current(A)</td>
<td>6.8</td>
<td>4</td>
<td>6</td>
<td>120</td>
<td>96</td>
</tr>
<tr>
<td>Height of core (mm)</td>
<td>120</td>
<td>24</td>
<td>24</td>
<td>8</td>
<td>88</td>
</tr>
<tr>
<td>Shaft diameter (mm)</td>
<td>24</td>
<td>50</td>
<td>50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Table 2 The material and material parameters of the key components in machine

<table>
<thead>
<tr>
<th>Components</th>
<th>Core</th>
<th>Stator winding</th>
<th>Rotor winding</th>
<th>Air gap</th>
<th>Shaft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
<td>material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soft steel</td>
<td>Copper</td>
<td>Copper</td>
<td>Air</td>
<td>Steel</td>
</tr>
<tr>
<td>Relative magnetic permeability</td>
<td>H-B curve</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Relative Permittivity</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Electrical conductivity [MS/m]</td>
<td>11.2</td>
<td>59.98</td>
<td>59.98</td>
<td>0</td>
<td>4.032</td>
</tr>
<tr>
<td>Area of cross section(mm²)</td>
<td>/</td>
<td>12.566</td>
<td>21.363</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Turns number</td>
<td>/</td>
<td>30</td>
<td>1</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

To simulate the relative motion of the stator and rotor, the independent coordinate method is considered. In simulation, two coordinate system are set. One is the stator coordinate system which is fixed on stator, the other is the rotor coordinate system which is fixed on rotor. In simulation, the former is static and latter is moving. Fig.2 (a) is the CAD model of machine and Fig.2(b) is the mesh model of machine. The sharing boundary of machine is shown in Fig.2 (c).

Fig.2 FE model of the AC squirrel-cage asynchronous induction machine

Fig.3 is the magnetic flux density distribution of the machine. From Fig.3, we can see the most of the magnetic flux form the closed electromagnetic loop by stator core-air gap - rotor core. A few magnetic flux is leakage magnetic flux because they are surround in the vicinity of the stator core.

Based on the FEM model of the AC squirrel-cage asynchronous induction machine, the influence of the speed of rotor, the rotor eccentricity, the rotor bar/ring faults and shaft failures on the magnetic flux density are investigated. Based on the analysis, the faults diagnosis for AC induction machine by magnetic flux distribution is proposed.
References


IMPROVED DESIGN OF A SIDE-INCIDENT MICROWAVE PROBE FOR NON-DESTRUCTIVE INSPECTION OF METALLIC PIPES

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Abstract

Metallic pipes are massively utilized in various industrial facilities. In an attempt to assure the safe operation of the piping systems, a non-destructive testing (NDT) method using microwaves has been developed to perform the rapid and long-range inspection of pipes [1]. The scheme of this method is to emit microwaves of certain mode(s) into a metallic pipe, while the flaws on the inner surface of the pipe can be detected as well as located by measuring the reflection signals and evaluating the time-of-flight. Some previous studies have verified the applicability of this method to the detections of pipe wall thinning [2] and cracks [3].

In the former studies, circular TM01 mode microwaves were mostly emitted from the pipe end, whereas the pipe end may not be open for microwave probe insertion in some practical conditions. A side-incident microwave probe was designed to emit microwaves from the pipe wall [4]. Moreover, the propagations directions of different microwave modes can be changed by manipulating the sweeping frequency range, which implements the inspections of different directions. Nevertheless, the generated microwaves for detection contain some unwanted spurious modes, which may lead to the dispersed reflection signals and low signal-to-noise ratio.

In this study, an improved design of the previous side-incident microwave probe was proposed to optimize the frequency-domain characteristics of emitted microwaves and suppress the spurious modes. Two types of structures were designed for generating TM01 and TM02 mode microwaves, respectively, using numerical simulation.

Three-dimensional finite element simulations were conducted in the frequency domain. A commercial software COMSOL Multiphysics (v5.2a) and an add-on RF module were adopted for modelling and computation. The governing equation is given as below:

\[
\nabla \times \mu_0^{-1} (\nabla \times \mathbf{E}) - k_0^2 \varepsilon_0 \left[ \varepsilon_r - j \sigma / (\omega \varepsilon_0) \right] \mathbf{E} = 0 , \quad (1)
\]

where \( k_0 = \omega \sqrt{\varepsilon_0 \mu_0} \) is the wavenumber in a vacuum, \( \varepsilon_0 \) and \( \mu_0 \) are permittivity and permeability in a vacuum, \( \omega \) is the angular frequency, and \( j \) is the imaginary unit. Vector \( \mathbf{E} \) denotes the electric field, and \( \sigma \) is the electrical conductivity. Symbols \( \varepsilon_r \) and \( \mu_r \) are relative permittivity and relative permeability. In this computation, these values are: \( \mu_r = 1 \), \( \varepsilon_r = 1.000 \) and \( \sigma = 0 \), for the media air. The physic specifications of the semi-rigid cable which was used to propagate TEM mode microwaves were also given in study [4].

Figure 1 illustrates the geometric model of the numeric simulation. A pair of bent semi-rigid cables were inserted vis-a-vis or reversely into the pipe (inner diameter 19 mm) to convert TEM mode microwaves into TM01 mode (‘LJ’ type) or TM02 mode (‘JL’ type), as displayed in Fig. 1(a) and Fig. 1(b). The generated microwaves can be transmitted to the left or right side of the pipe by emitting TEM mode microwaves at different ports (L or R), while the transmission characteristics were evaluated at the surfaces of the both ends of the pipe (marked with color). Perfectly matched layers (PML) were attached to the pipe ends in order to eliminate the reflections and to simulate the infinite domain. Second-order tetrahedral and triangular elements were used for discretization. The boundary condition was defined as the perfect

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electric conductor. The dimensional parameters $r_c$, $l_p$ and $l_S$ in the figure were altered from 3 to 8 mm in order to maximize the conversion efficiency. The sweeping frequency span for two types of microwave probes are 18–27 GHz and 28–40 GHz, respectively.

Figure 1. Geometric models of the microwave probes in the numerical simulation (unit: mm, not to scale), (a) ‘LJ’ type for generating TM$_{01}$ mode, (b) ‘JL’ type for generating TM$_{02}$ mode.

Figure 2 exhibits two sets of simulation results. Here, only the results obtained using port R were given because those obtained using port L are identical. As shown in Fig.2 (a), the energy ratio of TM$_{01}$ mode microwaves transmitted to the right end of the pipe maintains above 0.5 over the frequency range of 20.5–25.5 GHz, while other those of spurious modes as well as TM$_{01}$ mode transmitted to the left side are basically smaller than 0.1. In Fig.2 (b), when the frequency ranges from 29 to 36 GHz, the energy ratio of TM$_{02}$ mode microwaves transmitted to the right end of the pipe exceeds 0.5, while those of the spurious modes are below 0.05. Note that although the TM$_{02}$ mode in Fig.2 (b) possesses a wider operational frequency span and a better characteristic of single mode propagation, it also decays faster than TM$_{01}$ mode, which indicates that it is more suitable for the short-range inspection but with a higher precision.

Figure 2. Fractional energy of two types of microwave probes, (a) ‘LJ’ type ($r_c$=7, $l_p$=3 and $l_S$=8), (b) ‘JL’ type ($r_c$=5, $l_p$=5 and $l_S$=1).

This study proposed an improved design of the side-incident microwave probe for pipe inspection. More details and the experimental verification will be presented at the conference.

References
 STUDY OF CLOSED CRACK DETECTION BY VIBRO-ACOUSTIC MODULATION UNDER ELECTROMAGNETIC LOADING

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Abstract

In service period, metal structures are often subject to the combined action of surroundings, temperature and cyclic load, and are prone to generate closed crack. The accumulation of closed crack takes up most of the time during the service of the structure, so the detection and evaluation of early fatigue damage is of great importance \cite{1}. In recent years, nonlinear ultrasonic methods have been widely used to detect closed cracks, of which the sensitivity to closed cracks is higher \cite{2-3}. The main problem of closed cracks detection by nonlinear ultrasound is weak response signal.

In the mid-1990s, Russian scholars first proposed the vibro-acoustic modulation (VAM) technique to detect closed crack \cite{4}. The technique is to mechanically load the specimens at low frequency with the vibration exciter to make the specimen into dynamic fluctuation state, therefore the high frequency ultrasonic wave propagating in the specimen will be modulated, which could help to enhance the nonlinearity effect of closed crack. Mechanical loading does have a good effect on improving the nonlinear response of ultrasound. However, the mechanical loading equipment is relatively bulky and prone to cause additional damage to the equipment under test. A new VAM technique for closed crack detection based on electromagnetic loading is proposed in this paper. The principle is to load the closed crack into opening and closing state through coil and magnet rather than mechanical equipment, which could concentrate the loading energy around the closed crack instead of the whole tested specimen.

Figure 1. Schematic diagram of electromagnetic loading (Left). Eddy current concentration and the Lorentz force direction around the crack (Right).

Fig. 1 is a schematic diagram of VAM technique based on electromagnetic loading. The electromagnetic loading device is placed above the closed crack. As shown in Fig. 1, the permanent magnet generates a vertical downward magnetic field in the aluminum plate. By conducting a sinusoidal excitation current into the loading coil, eddy current will be induced in the crack region. Due to the discontinuity of the medium in the crack region, the induced eddy current will concentrate around the crack interfaces.

In the positive half-cycle of the excitation current, the direction of the eddy current is anticlockwise, it can be obtained from the Left-Hand Rule that the Lorentz force of inward compression direction will be generated in both interfaces of the crack. Similarly, in the negative half cycle of the excitation current, the direction of the eddy current is anticlockwise and the Lorentz force of stretching outwards direction will be generated in both interfaces of the crack. Therefore, when a sinusoidal current of a certain frequency is applied into the loading coil, the closed crack will open and close microscopically at the same frequency.

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Figure 2. The tested specimens (Left). Schematic diagram of the experimental set-up (Right).

The tested specimens include an intact aluminum plate and an aluminum plate with a closed crack. The dimension of both specimens is 300 mm×60 mm×1 mm, as is shown in Fig. 2. The defective specimen includes two kinds of defects, namely notched crack ① and closed crack ②. The connection of the experimental equipment is also shown in Fig. 2.

![Figure 2: Specimen and Schematic Diagram](image)

Figure 3. Spectrum of intact aluminum plate (Left) and defective one (Right).

As can be seen from Fig. 3, there are only 1 MHz and 200 kHz fundamental frequency components in the spectrum of the signal collected from the intact aluminum plate. The spectrum of the signal collected from the defective aluminum plate includes not only the fundamental frequency components of 200 kHz and 1 MHz but also the second harmonics of 400 kHz and 2 MHz and the modulation components of 800 kHz and 1.2 MHz. This verifies the feasibility the VAM technique based on electromagnetic loading. Experimental results indicate that this technique shows well detection performance and has bright prospects as a substitution of traditional VAM technique.

In this paper, the vibro-acoustic modulation based on electromagnetic loading is proposed and experimentally studied. Experimental results show that this technique has bright prospect in closed crack detection. The limitation of VAM based on electromagnetic loading is that the location of closed crack should be given first. Future work should focus on the integrating of the transmitter probe, the receiver probe and the electromagnetic loading device. This allows us to scan the whole specimen to determine where the closed crack exists.

References

Acknowledgments
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A0120 Smart Coating based on Frequency Selective Surface for Position Insensitive Crack Monitoring

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Abstract
Passive wireless antenna sensors are receiving increasing attention in monitoring the health of online-service infrastructure. Because of the sinusoidal current distribution when the antenna resonates, the uncertainty in the crack position with respect to the antenna sensor will cause a variation in the sensing sensitivity, resulting in vagueness for crack characterization. This paper proposes a cross type frequency selective surface (FSS) to advance the nondestructive evaluation (NDE) technique for structural health monitoring (SHM). By inserting additional interleaved cells, the dependence of sensitivity with position variation can be suppressed. Due to the absence of electronic device, the proposed smart coating can be used in extreme conditions, e.g., high-temperature environment.

Keywords: crack monitoring, cross resonator, frequency selective surface, smart coating.

Introduction
Passive wireless sensors enabled by radio frequency identification (RFID) tag antenna have been developed for ubiquitous structural health monitoring (SHM) [1]. Multiplexing or tag array can be designed to monitor the crack growth [2]. The results show that the crack parameters affect the resonant frequencies in a way that can be represented by the crack’s cutting effect on the sensor’s current flow [3]. This effect leads to a variation of sensing sensitivity with respect to crack position and antenna mode. At the same time, metamaterials are composed of periodic subwavelength metal/dielectric structures that resonantly couple to the electric and/or magnetic components of the incident electromagnetic fields, exhibiting properties that are not found in nature [4]. This technology can be expected to increase the sensitivity in crack monitoring.

Design and Results
This paper presents a cross type frequency selective surface (FSS) for position insensitive crack monitoring. The cross type FSS has been used to monitor the strain and its induced crack on the resonator itself [5, 6]. Similarly, a cross type resonator is used as a cell. However, we are aiming to suppress the position induced sensitivity variation caused by the sinusoidal current distribution when the resonator resonates. The structure of the proposed smart coating is shown in Fig. 1(a). The polarization of the incident wave is selected to force the surface current flow being cut by the crack. That is to say, the incident wave is y-polarized if the crack is x-directed. The simulation result of the radar cross section (RCS) without the interleaved cells is displayed in Fig. 1(b) for reference. We can find that the sensitivity is maximized at the center of the cross type resonator, where the current reaches its maximum value. The sensitivity will decrease when the crack moves away from the center. With the

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interleaved cells in the cross type FSS, the dependence of sensitivity with position variation is significantly reduced, which can be found in Fig. 1(c).

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![Diagram](image)

Figure 1. (a) Structure and simulation results of radar cross section (b) without the interleaved cells (in the dashed box) and (c) with the interleaved cells, where crack width (w) is fixed at 1 mm.

References
EFFECT OF ELECTRIC ANISOTROPY ON SKIN DEPTH OF INDUCED EM FIELDS IN CFRP DUE TO EDDY CURRENT SENSORS

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Background
Skin depth is a very important parameter in eddy current testing (ECT)[1]. As being heterogeneous, carbon fibre reinforced plastic (CFRP) composite shows a strong anisotropy, and the skin effect in CFRP is quite different from isotropic conductors. Thus, in this paper, the effect of electric anisotropy on skin depth is investigated by means of simulation analysis.

Formulation of skin depth
The standard skin depth \( \delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \) defines the depth where the magnitude of magnetic or electric field decreases down to 1/e of the surface value[1], which can only be applied in certain situation. Actually, the true skin depth not only depends on the frequency, but also depends on the coil dimensions, electrical conductivity and thickness of the test-piece [2].

The 3D FEM software COMSOL 5.0 is employed to calculate the true skin depth. The simulation model is composed of an air-cored coil above a 2mm 16-layer CFRP plate. Each layer can be regarded as a continuous anisotropic sheet, the conductivity tensor with respect to the principal axes is represented as \((\sigma_L, \sigma_T, \sigma_{cp}) \). From Fig.1(b), the air-cored coil mainly generate perpendicular magnetic field and circular eddy current in CFRP plate.

Results and Discussion
Through the calculation, the true decay curves of magnetic field strength \( H_z \) and current density \( J_x \) are depicted in Fig.2, where the outer and inner diameters of excitation coil are 1.2mm and 3.2mm, respectively. In Fig.2(a), the amplitude of \( H_z \) and \( J_x \) decay faster with frequency increasing, and the decay law is the same. However, in the case of unidirectional CFRP, the decay curves appear great discrepancy in Fig.2(b), which is attributed to the resistive loss in anisotropic composite.

By changing the anisotropy ratio, the skin depths of current density under different conductivity tensors at 2MHz are obtained in Fig. 3. It can be seen that the resistive loss is greater in the composite with high anisotropy, so the speed of current decay is accelerated. In order to reduce this effect, composite sample can be prepared by multi-directional lamination, as shown in Fig.4.

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In order to verify the arguments, an absolute type probe is used to detect the 0.5mm deep delaminations in unidirectional and angle-ply plates, respectively. It is obvious that the detection accuracy of unidirectional plate is very low due to the fast decaying eddy current. In comparison, the detection accuracy of angle-ply plate is much better.

References

Acknowledgments
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A0122

3D Defect Quantification Based on Chirp Excitation and High-resolution EC-TMR Sensor

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Introduction
Eddy current testing (ECT) is one of the most widely used nondestructive evaluation techniques, which makes use of electromagnetic induction to detect and characterize surface and subsurface flaws in conductive materials. The penetration depth of ECT is inversely proportional to the square root of the excitation frequency. Therefore, to detect deep defect with ECT, lower frequency should be applied. However, the signal to noise ratio is low with low operating frequency if using conventional coil to measure the ECT signal. This shortcoming can somehow be overcome by replacing the pickup coils with high sensitivity magnetic sensors. B. Rostami et al. presented Super-conduct Quantum Interference Device (SQUID) for deep embedded defect inspection [1]. SQUID has extremely high sensitivity; but it is expensive and has a great limitation in actual operation. Recently, we presented an eddy current probe with large-scale high-sensitivity tunnel magnetoresistance (TMR) array sensors for deep embedded defect inspection [2]. Experiment results demonstrated that this EC-TMR probe can generate high-resolution magnetic field image, which is very sensitive to the presence of a defect. However, how to reconstruct a 3D defect from the magnetic field image is still a reverse problem to be explored.

In this work, we propose using the EC-TMR probe and chirp excitation to quantitatively detect deep embedded defect. Chirp-modulated excitation has rich frequency components in the selected frequency band. The frequency band is chosen accordingly that the penetration depth of the eddy current in this frequency band cover the depth of the sample under test. Therefore, defect embedded in any depth can be detected efficiently. Furthermore, the information of the defect in the depth direction can be obtained by analyzing the frequency characteristics of the magnetic field image resulting in 3D reconstruction of the defect.

1. Theory
Chirp-modulated excitation signal is written as equation (1), where $\alpha(t)$ is the amplitude function and $\Phi(t)$ is the phase function. In practical applications, $\alpha(t)$ and $\Phi(t)$ should be optimized according to the specified problem. Here taking linear chirp modulation with rectangular window as an example to show the operating principle, $\alpha(t)$ is a rectangular windows in [0, T], where T is the period of the excitation signal. $\Phi(t)$ is written as equation (2), where $[f_1, f_2]$ is the frequency band. Assuming $T=0.0109$ s, $f_1 = 50$ Hz and $f_2 = 1 \text{ kHz}$, the waveform of the modulated excitation signal and its corresponding frequency spectrum are as shown in figure 1.

$$s(t) = \alpha(t)\sin(\Phi(t))$$
$$\Phi(t) = 2\pi[f_1 t + (f_2 - f_1) t^2 / 2T]$$

Figure 1. (a) Waveform of rectangular window linear chirp signal and (b) its frequency spectrum

In the EC-TMR probe, the magnetic field associated with the eddy current is measured by an array of TMR sensors. It is worth noting that the response of a chirp modulated excitation is
also a modulated signal. Assume the time domain signal is \( s(t) \). Then the frequency domain signal \( S(\omega) \) is derived by Fourier transfer of \( s(t) \). \( S(\omega) \) has rich frequency components in the selected frequency band \([f_1, f_2]\), with which defect embedded in any depth can be detected. Furthermore, the information of the defect in the depth direction is obtained by analyzing the frequency characteristics of the magnetic field image resulting in 3D reconstruction of the defect. It is derived that the signal of a defect is maximum at a certain frequency \( f_m \). The defect size can be estimated from the 2D magnetic field image at the frequency \( f_m \). Then with this estimation as initial guess, the 3D defect is quantified using conjugate gradient method from the frequency domain images.

2. Simulation Result and analysis

An aluminum sample with rectangular notches mimicking defects was modeled using commercial simulation software comsol Multiphysics. The excitation current was set to be \( J = \hat{y} J_0 s(t) \), here \( \hat{y} \) is the unit vector along the y-axis direction, \( J_0 \) is the current density 1000A/m² and \( s(t) \) is chirp modulated signal as equation (1) shown. The electrical conductivity and relative permeability of the sample were set to be \( 2.3 \times 10^7 \) S and 1 respectively. The sample has 3 layers. The depth of each layer depth is 8 mm.

Firstly, defect located in different layers were studied. The sizes of the defect were set to be length \times width \times depth = 8 mm \times 2 mm \times 8 mm. Figure 2(a) shows the amplitude of the signal verse frequency for defect located in the 1st, 2nd and 3rd layer respectively. It is seen that the frequency spectrum of the signal depends on the embedded depth of the defect. The frequency spectrum of the 1st layer defect is widely distributed in high frequency range. For defect in the 2nd layer, the peak amplitude appears at frequency around 100 Hz. For defect in the 3rd layer, the frequency range of the signal is even lower than the 2nd layer defect.

Secondly, defect located in the 2nd layer but with different depth were simulated. The depth of the defect varies from 2 mm to 8 mm with step size 2 mm. The results are shown in figure 2(b). It is seen that peak frequency for these defects are similar; but the amplitude and width of the spectrum reveal the defect depth.

![Figure 2. a) Amplitude of the signal verse frequency for defect located in the 1st, 2nd and 3rd layer and b) frequency spectrum of defect in the 2nd layer with different depths](image)

**Conclusion**

Magnetic field imaging (MFI) is widely used in non-destructive evaluation of defect in multilayered structure. This paper presents a study of defect detection and quantification using chirp excitation and high resolution MFI obtained with EC-TMR probe. The feasibility of the proposed approach will be studied numerically and validated experimentally. More detailed results will be presented in future submission.

**References**


A mixed strategy for efficient acousto-electric tomography based on complete electrode model

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Abstract. In acousto-electric tomography (AET), the electrical conductivity distribution in a domain of interest (DOI) is constructed from power density data measured under the disturbance of focused ultrasonic wave. However, the power density cannot be measured directly. One needs to reconstruct it from the potential on the full boundary of DOI, which is not practical to measure. A new reconstruction strategy is proposed herein. The boundary potential is firstly reconstructed with electrical impedance tomography algorithm based on a complete electrode model (CEM). The power density is then reconstructed from the boundary potential for reconstructing the power density with an iterative algorithm based on continuum model.

Keywords. Acousto-Electric Tomography, Electrical Impedance Tomography, Singular Value Decomposition

EIT is well-known as the technique for determining the internal conductivity of some physical body from boundary measurements of currents or voltages [1]. It is also known as an ill-posed problem because the boundary measurements are not very sensitive to the local changes of conductivity distribution [2]. Intensive research exists on this topic [3], and many methods have been developed on this ill-posedness and to improve the imaging quality [4,5]. Hybrid imaging methods are also developed for this purpose, where the information from multiple physical modalities is utilized [6]. These methods have been theoretically or numerically substantiated to have the potential to dramatically increase the contrast, resolution, and stability of the reconstruction [7]. AET is one of the hybrid imaging methods [2]. A physical domain imaged by AET is modeled as a domain \( \Omega \subset \mathbb{R}^n \) for \( n \geq 2 \). The changes caused by the acoustic wave can be recorded with EIT measurements on boundary \( \partial \Omega \). The power density in \( \Omega \) is defined as \( \delta(\sigma) = \sigma |\nabla u(\sigma)|^2 \), \( \Omega \subset \mathbb{R}^n \). Here, \( \sigma \) is the conductivity map in domain \( \Omega \), \( u(\sigma) \) is the electrical potential produced by applying either voltage or electric current on \( \partial \Omega \). Given noisy measurements \( \delta(\sigma) \) of the true power density \( \delta(\sigma) \), the problem is to reconstruct \( \sigma \) via solving the minimization problem \( \min_{\sigma} \|\delta(\sigma) - \delta(\sigma)\|_{L^2(\Omega)} \).

The complete electrode model is the most practical model for measuring the boundary potentials on the electrodes with a current pattern as input. The governing equation

\[ \frac{1}{2} \nabla \cdot (\sigma \nabla \phi) + \sigma \phi = 0 \]

where \( \sigma \) is the conductivity, \( \phi \) is the potential, and \( \nabla \cdot \) is the divergence. This model is widely used in electrical impedance tomography (EIT) and its variants [8]. The complete electrode model (CEM) provides a rigorous framework for the electrical measurements and allows for a precise formulation of the boundary conditions [9].

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is $\nabla \cdot \sigma \nabla u = 0$ in $\Omega$. On the electrodes $e_l$, $l = 1, 2, \ldots, L$, currents $I_l$ are applied, and the voltages $U_l$ on the electrodes are measured. \[8\]

To reconstruct the power density, one needs the potential $u$ on $\partial \Omega$, but it is not practical to measure it directly. In the present investigation, one first reconstructs $u$ and $\sigma$ in $\Omega$ from EIT measurements $U_l$. The obtained $u$ and $\sigma$ are used as the boundary condition and initial guess of the conductivity distribution for an iterative reconstruction algorithm for AET.

A singular value decomposition based reconstruction method is applied here to demonstrate the idea. In EIT, the mapping from the input currents $I_l$ to the voltages $U_l$ on electrodes $e_l$ is denoted as $M_\sigma$, which can be represented in a matrix form $M_\sigma$. When a small perturbation $h$ on $\sigma$ is introduced, the map is also changed to $M_{\sigma+h}$, and the difference $M_{\sigma+h} - M_\sigma$ can be approximated with a map $M'_\sigma$ which is the matrix form of the Fréchet derivative of $M_\sigma$. The conductivity reconstruction is simplified to a linear problem of solving $M'_\sigma h = M_{\sigma+h} - M_\sigma$ with a singular value decomposition method. In Fig. 1, the distribution $h$ is reconstructed with 195 singular values, and a relative error $\|\sigma_{\text{recon}} - \sigma - h\|/\|\sigma_{\text{recon}}\| < 0.45$ is achieved. The boundary potential can be computed from $\sigma_{\text{recon}}$ with high accuracy since $U_l$ are not sensitive to the interior changes of $\sigma$ in EIT. $E^\delta(\sigma)$ can be reconstructed from the computed $u$ on $\partial \Omega$ to reconstruct $\sigma$ in DOI.

![Figure 1](image-url)

**Figure 1.** A circular domain with radius $r_0 = 1.0$ and $\sigma = 1.0$ is considered with a small perturbation $h = 0.3$ in a small domain with $r_1 = 0.3$. The singular value decomposition based method is used. 195 singular values are used for the reconstructions with a relative error smaller than 0.45 being achieved.

**References**


Comparison of Neural Network and System Invariant Analysis Technology Applied to Eddy Current Testing
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Abstract
In the broad field of nondestructive testing (NDT), eddy current testing (ECT) technique based on electromagnetic principle are widely used for defect detection and sizing in power industries, machinery, aircraft, etc. to evaluate and to characterize the structural health of conductive materials in order to grant their regular use after testing. With the development of industry and the importance of safety issues, the requirements for accuracy and efficiency of ECT detection are also increasing. During the inspection process, the influence of noises such as probe tilting and lift-off inevitably occurs. Therefore, the trained and experienced person is needed to analyze the ECT raw signals and to distinguish signals and noise to reliable output results. However, the impact of various factors such as extended operating hours and low efficiency make ECT unable to meet the rapidly growing demands for detection. To solve the problems, two methods have been proposed which are based on artificial intelligence technology and a big data analysis. The former is to use established and trained artificial neural networks (ANN) to classify the ECT different defects signals [1]. The other is a big data analysis method using System Invariant Analysis Technology (SIAT) [2].

The artificial intelligence and the big data analysis are used to solve complex problems in other fields such as image identification and weather forecast. To better improve the ECT, it is important to understand the respective advantages of these two methods in the field of NDT. This study describe a comparative study of two methods in ECT experiments to distinguish the defect signals in ECT signals using ANN and SIAT.

The specimen (AISI 316) with three different depth slits and an ECT probe shown in Fig.1 are used to collect data. The electrical resistivity of specimen is 1.39×10⁶ S/m, and the width of slits is 0.3 mm which are fabricated by electrical discharge machining. The experiment is implemented under the frequencies of 10~100 kHz by manual scanning and ECT system which is shown in Fig.2 and consists of eddy current instrument, data acquisition instrument, Labview-based software, and a two-dimensional scanning mechanism. During the scanning process, the probe is scanned perpendicularly to the three depth slits length directions and passes through

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the center of the slit. And as mentioned above, the artificial noise is added in random position during the scanning condition shown in Fig 3. Also, the probe is used to scan on the same specimen without any defects under normal and noise conditions to collect reference data.

Figure 2. Schematic image of ECT setup

Figure 3. Schematic diagram of noise

Then, the collected raw data is processed through setting the maximum amplitude of the Lissajous waveform of 1 mm slit to 1 V and the phase to 90° in each frequency to get apparent features. And the processed data is analyzed by the ANN and the SIAT, respectively. The processed data consist of four kinds of data sets which are, (1) no slits signals without noise, (2) no slits signals with noise, (3) slits signals without noise, and (4) slits signals with noise. For ANN, all the data collected by ECT system are regarded as the training dataset, and the corresponding targets are 1 and 0. If the signals contain the slits signals, it is set to be 1. The training process is to establish a mathematical relationship between training data and corresponding targets. Through an established relationship, ANN can discern whether there are slits signals in ECT signals. For the SIAT, it is an analysis method that determines the abnormal state based on the normal state. In other words, the lift-off and tilting noise can be regarded as the normal states during the manual scanning process, and the defect signals can be considered as unusual states. Therefore, the data collected through scanning on the specimen without slits become learning data, and the SIAT can classify the slits signals according to the learning data.

The accuracy of these two methods is verified using different data. The results are shown in Fig 4. From the results, it is evident that trained ANN (Fig.3 left) can accurately classify the slit signals, and can discern the size of slits. The SIAT can eliminate the noise and can show the location of the slit by showing the large anomaly score (Fig.3 right). The horizontal axis corresponds the location through the scanning time. The functions of ANN depend on training process set and the quantity of training data. SIAT can classify the unusual signals and show slit location, but cannot achieve other functions for example output sizes of slits. The detailed comparison will be presented at the ENDE workshop.

<table>
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<td>2 mm</td>
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<tr>
<th>Signals</th>
<th>No slit with noise</th>
<th>No slit without noise</th>
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<tr>
<td>Output</td>
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<td>0 mm</td>
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<tr>
<th>Anomaly score</th>
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<td>Time(s)</td>
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Figure 3. Verification results of neural network (left) and SIAT (right)

References


NUMERICAL SIMULATION ON STRESS MEASUREMENT WITH EDDY CURRENT THERMOGRAPHY

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Abstract

Stress in components will lead to the change of material properties and even failure. Therefore, the assessment of the stress state of components is an important role of testing industry. As a non-contact and regional nondestructive testing method, eddy current thermography (ECT) could be applied to detect non-homogeneous electromagnetic characteristics parameter distribution in conductive materials. Internal stress and its distribution in a material will affect the value of its electromagnetic characteristic parameters. If an induction current applied on conductive material, Joule’s heat will generate in the sample which will lead to the temperature rise on the surface of the specimen after the induction heating process. The temperature distribution on the specimen surface can be recorded by infra camera and stored as IR images or video. The feature of the temperature distribution and its variation could be used to express the stress state in the specimen. In [1], researchers obtained linear coupling relationship between stress and thermal conductivity by applying uniaxial tensile load on conductive material with eddy current thermography. In [2], tensile stress on the surface of specimen was preliminarily quantified by using eddy current thermography as well.

In this paper, a finite element model (FEM) for stress measurement with ECT is established on the COMSOL Multiphysics platform. The stress of the specimen is loaded with reference to the three-point bending experimental method. During the loading process, compressive stress and tensile stress are respectively generated on the positive and negative surface of the specimen. The load is set as a variable, and the law of the surface temperature changing with the load during the induction heating period is investigated. Accordingly, the relationship between the stress of the specimen and the surface temperature during the induction heating process could be derived.

The mesh and parameter setting are shown in Figure 1. The load F gradually increases from 0 to 4000N (the load of reference specimen is 0N), and the direction of exciting coil is placed in parallel to the stress. The surface temperature of both sides of the three point bending specimens (the longitudinal displacement is negligible) are obtained by induction heating.

![Figure 1. Geometry and parameters of the simulation model](image)

The surface plots of stress and surface temperature distribution on the specimens' surface after the three point bending experiment are shown in Figure 2 and Figure 3. It can be found that the specimen surface temperature of the compressive stress area is lower but that of the tensile stress area is higher than the same area of reference specimen. The larger the load is, the greater the temperature difference on the tensile stress side as well as on the compressive stress.

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side is. Figure 4 shows the relationship between temperature difference and load both on the central lines of the tensile stress side and compressive stress side along with X-axis. Lines in Figure 4 indicate that the surface temperature appreciation of the tensile stress side and compressive stress side has a positive and negative linear correlation with the load value respectively.

Figure 2. Influence of load on temperature distribution of compressive stress side, (a) surface plots of stress and temperature distribution; (b) temperature distribution changes with load

Figure 3. Influence of load value on temperature distribution of tensile stress side, (a) surface plots of stress and temperature distribution; (b) temperature distribution changes with load

Figure 4. Effect of load value on temperature rise at different positions on specimen

References


Acknowledgments

The authors would like to thank China National Science Foundation for financial support for this study under grant NSFC 51275325.
A0129  Evaluation of detectability of differential type probe with directional eddy current for detection of fiber misalignment in CFRP

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Abstract

Carbon fiber reinforced plastic (CFRP) has been increasingly adopted for structural materials in the fields of aerospace and automobile industries. Therefore, the establishment of nondestructive testing (NDT) technique for CFRP products is urgently needed. Eddy current testing (ECT) is the method which is employed as much as ultrasonic testing (UT) for inspection for CFRP because of its ability that can inspect fiber orientation [1].

Fiber waviness is the local misalignment defect that should be inspected since it affects the strength of composite product. For instance, in the case of unidirectional laminate, a waviness with angle of 2º reduces the mechanical strength by about 40% [2]. Therefore, it is needed to detect and evaluate the fiber waviness at an earlier manufacturing stage with suited NDT technique. Mizukami et al. [3] tried to estimate the waviness angle and amplitude with ECT by using a pair of one rectangular driving coil and one circular pickup coil. They macroscopically validated the method by comparing with the values obtained by X-ray CT image. However, the quantitative evaluation of the accuracy of the method and the detection for lower waviness angle less than 6.9º has been not carried out. This evaluation is essential to provide more precise information of waviness to users. To quantitatively evaluate the detection accuracy and to detect the waviness with lower angle, ECT C-scan image with higher resolution is necessary.

To obtain a higher resolution in detectable waviness contour with ECT, it could be effective to load wide-range directed magnetic field to CFRP. Furthermore, Urayama et al. [4] and Kosukegawa et al. [5] indicate that eddy current differential probe with two pickup coils can obtain relatively higher spatial resolution. To generate a wide-range directed magnetic field, we propose two types of differential probes: symmetrical driving (SymD) type and uniform driving (UniD) type. The objective of this study is to quantitatively evaluate the detectability of differential type probes with directional eddy current for detection of waviness contour with lower misalignment angle by comparing with the image obtained by X-ray CT.

Fiber waviness was introduced to the first layer in unidirectional 6 laminates CFRP by pulling the laminates in the lateral direction during compression at 130ºC, 0.5 MPa. The prepreg used was P3252S-25 (Toray Industries, Inc.). The range where fiber waviness occurs is about 20 mm width around the central region of the laminates. The waviness with various misalignment angles occurred in this region. The CFRP specimen was processed into dimensions of 150 × 150 × 1.44 (mm³).

The waviness in CFRP was scanned by X-ray CT and measured by ECT in the same region (50 × 50 mm²). X-ray CT image was obtained by using a microfocus X-ray CT system (inspeXio SMX-225CT FPD HR, SHIMADZU Co.). The tube voltage was 100 kV, and the current was 200 μA. The voxel size was 34 μm.

For ECT, three differential type probes shown in Fig. 1 were used in this study. A CirD is the probe using a circular driving coil that was used in ref [5]. The two pickup coils were arranged such that the axis connecting the centers of the coils was in the direction

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perpendicular to the fiber direction. Exciting current was generated by function synthesizer at 2 MHz and 0.5 V_{pp}, and the real part and imaginary part of complex differential pickup signal of the two pickup coils was obtained through lock-in amplifier. The complex of signal was processed with phase conversion such that the imaginary part has more fiber information. The ECT signal was filtered with band-pass filtering in the range from 50 to 500 m\(^{-1}\) by spatial FFT in the horizontal and vertical directions.

To evaluate the detectability of the three probes, the misalignment angle of line segments in both the images of X-ray CT and ECT C-scan were compared by the following method. First, 20 line segments whose direction deviates from the correct fiber orientation over 2º were extracted from ECT C-scan image by the Hough transform. Then, the tangential lines in X-ray CT image that have the same center coordinates with the above 20 line segments, and the difference of the misalignment angle between these lines was evaluated. The misalignment angle of tangential lines in X-ray CT image was defined as “actual misalignment angle”.

Figure 2 shows the relationship between the estimated misalignment angle of line segments obtained from ECT C-scan image and the actual ones obtained from X-ray CT image. SymD and UniD exhibit lower deviation compared with CirD whose magnetic field is isotropic. Root mean square errors (RMSEs) of SymD and UniD are 2.3º and 1.3º respectively, whereas that of CirD is 4.5º. This result indicates that it is possible to quantitatively evaluate fiber waviness contour from C-scan image of ECT by applying Hough transform. Additionally, magnetic field-directed eddy current differential type probe, in particular, uniform driving type differential type probe is the most effective to detect fiber waviness.

![Figure 1. Differential type probes: (a) circular driving (CirD) type, (b) symmetrical driving (SymD) type and (c) uniform driving (UniD) type. Unit: mm.](image)

![Figure 2. Correlation between the actual (X-ray CT) and estimated misalignment angle (ECT).](image)

**References**

Abstract

In this paper we use tunnel magnetoresistance sensors to inspect an aluminum plate, under eddy current method [1] with sinusoidal excitation at 5 kHz. For the purpose of this work we considered a thin plate with 1 mm of thickness that was inspected using a planar probe with two tunnel magneto-resistive (TMR) sensors. The aluminum plate contained a machined linear through defect with a length \( L = 10 \text{ mm} \) and width \( W = 0.5 \text{ mm} \). The planar probe generates a uniform magnetic field inside a surface with area approximately equal to \( 4 \times 4 \text{ cm}^2 \). The probe generates a uniform eddy current at the aluminum surface that is directed across the linear effect. From now on we shall consider the defect oriented along the x-direction, and the applied excitation field is also oriented on the x-direction. The eddy currents are launched across the defect on the y-direction. Thus, the material surface is oriented parallel to the xy-plane. Two single-axis TMR sensors were used to measure the magnetic field along the y-direction, perpendicular to the defect and along the z-direction perpendicular to the xy-plane.

The general idea of the experimental side of this work was described in the last paragraph. In the next section we shall present and explain the two data field maps obtained directly from the experiments. In section 3 we preview the configuration of the current density on the material surface. The maps were inverted, by considering suitable transformation kernels.

Fig. 1a represents the amplitude of the field measured along the y-direction. Note that the excitation field is mainly directed along Ox, but a small part of the excitation also exists along Oy, and must be removed using adequate signal processing. Note that the real direction of the field \( B_y \) is positive on the first and third quadrants and negative on the second and fourth quadrants. Fig. 1b represents the field measured on the direction perpendicular to the plate surface. Two amplitude picks appear close to the defect tips, due to the higher current density. The eddy currents were launched in the positive Oy direction. In the presence of the defect the eddy currents curl anticlockwise around the right tip and clockwise around the left tip.

![Figure 1. Maps of the measured fields: (a) By and (b) Bz:](image)

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The current density on the material surface is considered as the superposition of small square loops of current. Each square loop has dimensions exactly equal to the scan step.

![Kernel By / μT](image1)
![Kernel Bz / μT](image2)

Figure 2. Maps of the computed field kernels: (a) by and (b) bz.

Fig. 2 represents the magnetic field components $h_y$ and $h_z$ produced, in the $y$-direction and on the $z$-direction, by one loop of current. These are the directions of measurement of the TMS sensors. The field that was effectively measured by the sensors may be arranged as a summation of the elemental fields of the small current dipoles.

$$H_y(i,j) = \sum h_y(i-k, j-l)I_d(k, l)$$

In (1) $I_d$ represents the current in the dipoles. From one single field map it is possible to invert the current map, using discrete Fourier transforms and a regularization method, such as the Tikhonov method.

![Current density from By / A/m](image3)
![Current density from Bz / A/m](image4)

Figure 3. Maps of the reconstructed current density: (a) from $B_y$ and (b) from $B_z$.

We used an image fusion algorithm using discrete Fourier transforms [2]. This method benefits from the fact that we already computed those transforms in the inversion process. Then we also used mutual information concepts [3] to obtain the reduction of uncertainty of each one of the current density maps obtained separately.

References

Acknowledgments
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QUANTITATIVE ASSESSMENT OF STRESS CORROSION CRACKS USING DISTRIBUTION OF MAGNETIC FLUX DENSITY BASED ON EDDY CURRENT TESTING

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Abstract
This paper aims to enhance the assessment of stress corrosion cracks (SCC) by using an eddy current testing (ECT). Components of the magnetic flux density perturbed by the SCC are the main features for the SCC characterization and evaluation by approaching an advanced multimedia element method (MME) based on FEM-BEM computation. Through the forward and inversion strategies, the measured magnetic flux densities obtained from the ECT experiments are used to verify the numerical results and reconstruct the significant SCC parameters. As Consequences, the equivalent conductivity in the SCC region is characterized. The SCC profiles including length and depth are reconstructed as well.

Introduction
Stress corrosion crack (SCC) is one of the major targets for in-service inspection of key structural components in nuclear power plants. Although the eddy current testing (ECT) technique is generally utilized for crack detection, it is still challenging to evaluate SCC due to its complex geometrical configuration. Especially, the local conductivity in the SCC region affects to the ECT signals significantly [1]. Recently, accuracy improvement of the ECT forward and inversion strategies has been intensively studied for SCC evaluation [2, 3]. Furthermore, the numerical studies about the influence of the local conductivity in SCC region on the characteristic of magnetic flux distribution have also been conducted by authors [4]. To enhance the ECT for SCC assessment, this study proposes a strategy for the local conductivity estimation and quantitative crack shape reconstruction from the measured magnetic flux density signals. The advanced multi-media element (MME) method is approached at first to improve the simulation model of an actual SCC. Finally, the feature parameters of the magnetic flux distribution are adopted to quantitatively determine the equivalent conductivity and the shape parameters of the SCC regions.

Forward and Inversion Strategies for Quantitative SCC Assessment
The strategy for SCC assessment using distribution of magnetic flux density induced by eddy currents is shown in Fig. 1(a).

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Owing to narrow shape and complex geometry of the SCC, an advanced MME method is developed by moving node coordinates of the crack edges, and modified the shape function for calculating coefficient matrices of the MME related to SCC region [5]. The MME scheme for treating the SCC region is shown in Fig. 1(b). This approach enables the high efficient calculation of element matrices of the MME for a regular mesh. From the solution of formulae, the change of magnetic flux density created by the eddy current perturbation due to SCC can be easily obtained.

In the inversion procedure, the objective function defined by the mean-square residual of the measured and simulated magnetic field signals are adopted to calculate both the crack conductivity and the crack shape through an iteration procedure. The iteration process is conducted based on the optimization method. In practice, the conductivity and the crack shape parameters are updated recursively. In this way, the SCC can be reconstructed properly even for a conductive crack.

Results and Discussions

For example of a SCC specimen denoted as TP9, numerical results of the equivalent conductivity in the SCC region as shown in Fig. 2 reveals that the profile of the magnetic flux density can give information of the distributed conductivity for a given properly crack sizes. The magnetic field profiles of higher conductivities locate around the edge of SCC, while those of the lower conductivity gradually decrease to the center of the SCC region. Further results of the conductivity and shape reconstructions including the sliced specimen of a natural SCC will be presented in the full paper.

Fig 2. (a) Profile of B above SCC region and its distributed conductivity, (b) Pattern of B along the SCC length at x=0

References


Acknowledgments

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SENSITIVITY ANALYSIS FOR THE INVERSE PROBLEMS OF ELECTROMAGNETIC NONDESTRUCTIVE EVALUATION

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Abstract

The inverse problem of electromagnetic nondestructive evaluation in a general context is dealt with in this work. Model-based inversion consists in reconstructing material defect parameters based on the measured electromagnetic field. This problem is usually traced back to an optimization problem for which various efficient global optimization algorithms have been applied for decades. However, beyond the mere reconstruction of defect parameters, an important feature is the uncertainty of the parameter values obtained by the inversion algorithm. This uncertainty is inevitably present because the measured data are always corrupted by noise and the setup parameters are never precisely known.

Let the vector-vector function \( y = f(x|w) \) be the relationship between

- the observable signal \( y \) (e.g., impedance variation in eddy-current nondestructive testing),
- the ensemble of the defect parameters \( x \) (e.g., crack dimensions) and
- the setup parameters \( w \) (e.g., host material conductivity, probe lift-off, etc.).

The forward operator \( f \) is realized by electromagnetic simulation.

In recent works, the application of global sensitivity analysis of the forward operator \( f \) is presented [1]. Such studies can lead to valuable knowledge on (i) how each setup parameter \( w_i \) contributes to the output uncertainty and (ii) whether the setup uncertainty hinders the reconstruction of small variations of the defect parameters.

In the present contribution, a framework is proposed for the global sensitivity analysis of the whole inverse problem solution as sketched in Fig. 1. For certain values of the measured data \( \tilde{y} \) the optimization-based inversion “inv” is performed to obtain the reconstructed defect parameters \( \hat{x} \) which obviously depend on the uncertain setup parameters \( w \). The quantitative characterization of the uncertainty of \( \hat{x} \) is given by the Sobol’ indices [2], which quantify not only the contribution of each setup parameter \( w_i \) but also of their combinations. The benefit from this global sensitivity analysis is that one gains proper knowledge on how the uncertain setup parameters influence the reconstruction capability of an inversion procedure. This may promote the optimal design of nondestructive testing arrangements with respect to robustness. Furthermore, it can screen the most important sources of uncertainty, which have to be taken into account in another inversion routines, e.g., the model-free approach in [3]. Finally, the proposed method provides a deeper insight into the importance of different physical phenomena behind the nondestructive evaluation method.

Figure 1. Scheme of the sensitivity analysis of the inverse problem
The framework of sensitivity analysis of inverse problems is computationally intensive due to several reasons:

• The optimization-based inversion per se usually involves many evaluations of the forward operator, i.e., the electromagnetic simulation (e.g., method of moments or finite element method).
• The calculation of Sobol’ indices is known to be demanding because a large number of samples (one sample equals to one run of the whole inversion algorithm) are needed when traditional statistical tools are used.

To overcome the computational burden originating from these two reasons, surrogate models are introduced at multiple levels: at the level of the forward model, and of the whole inversion procedure as well.

On the one part, the forward model \( f \) is approximated by a surrogate model based on sparse grid interpolation [3]. This has been proven to be efficient especially when the number of defect parameters is relatively high. Once \( f \) is replaced by its appropriate surrogate model, even sampling-intensive optimization methods (e.g., genetic algorithms) are affordable to perform the inversion.

On the other part, when calculating the Sobol’ indices of the reconstructed parameters \( \hat{x} \) with respect to the setup parameters \( w \), a polynomial chaos expansion (PCE) is applied for the relationship \( \hat{x} = \hat{x}(w) \). In so doing, the Sobol’ indices can be expressed from the PCE coefficients, and much less samples are needed compared to traditional Monte Carlo estimation.

In the extended version of this work, a collection of representative examples from eddy-current and magnetic flux leakage nondestructive evaluation will be presented. Each element of the proposed framework will be explained in detail, and the numerical performance of algorithms will be thoroughly analyzed.

References


Acknowledgments

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Abstract

Piping system is a common structure applied in various industries, which mainly consists of carbon steel pipes due to their low cost and high ductility. Nevertheless, carbon steel pipe is also vulnerable to corrosion and erosion, leading to wall thinning that underlies pipe rupture[1]. Conventional ultrasonic testing is the commonest method applied to measure the thickness of pipe wall. Despite its high accuracy, preparation and manual scanning are rather time consuming and render this method inefficient[2]. Previous studies in our laboratory have proposed a non-contact monitoring method using low frequency electromagnetic fields and magnetic sensors permanently installed outside to detect wall thinning on the inner surface of pipe wall. And an inverse algorithm to estimate the depth of wall thinning has been developed on the basis of this method[3,4]. It adopts the signal features identified from single frequency signals as input variables where the maximum amplitude detected from each defect plays an important role. However, as a monitoring method, the sensor cannot always be situated over the location where the defect signals reach the maximum, which would bring about large error in the results of inverse analysis.

This study aims at sizing the local wall thinning in carbon steel pipes through recognizing a more robust signal feature from the multi-frequency signals obtained by low frequency electromagnetic monitoring method. The signal was analyzed in terms of 3D finite element simulation on COMSOL Multiphysics 5.2 with its AC/DC module. Figure 1 illustrates the geometry used in the simulations where local wall thinning, with different residual thickness \((t_r=1-5 \text{ mm}, \text{ step}=0.5 \text{ mm})\), a longitudinal length of 50 mm and a circumferential angle of nearly 180\(^\circ\), are situated at the middle of the pipe. A coil with a square cross section of 10 mm \(\times\) 10 mm was employed to excite the electromagnetic fields. The excitation current flowing inside coil was defined with a current density of \(2.94 \times 10^5 \text{ A/m}^2\) and five different frequencies, 1, 5, 10, 15, 20 Hz. The magnetic permeability and electric conductivity of the pipe are assumed to be 160 and \(5.2 \times 10^6 \text{ S/m}\), respectively. The axial component of magnetic flux density, \(B_z\), was output along the measurement line (red dotted line) and the signals are normalized by those obtained when no defect presents.

The perturbation in the normalized signals induced by the defects can be observed as indicated in Figure 2 which shows the obtained signals when \(t_r=2 \text{ mm}\). Obviously, the

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maximum values appear at a specific location so that such feature is unlikely to be always detected in fact. Figure 3 shows the change of the amplitude at the location of 0 mm with frequency for each residual thickness. The linear regression was implemented using least square method and the negligible root mean square error proclaims that the amplitude of normalized $B_z$ is linearly correlated with the frequency. Meanwhile, the change becomes larger as the residual thickness decreases, therefore, the slope of fitted line can be mapped to the defect depth. The slopes of the multi-frequency signals at 10 randomly selected locations were calculated and shown in Figure 4. When the residual thickness is greater than 2 mm, the difference between the slopes corresponding to different locations is small.

![Figure 2. Sample signals when $t_r=2$ mm](image)

![Figure 3. Signals at the location of 0 mm when $t_r=1-5$ mm](image)

![Figure 4. Slope of multi-frequency signals at different locations when $t_r=1-5$ mm](image)

The above results and discussion confirmed that the slope is correlated with the residual thickness of pipe wall and slightly affected by the sensor’s location, therefore, it can be used as an input to size the local wall thinning more robustly.

References


Time delay and interface roughness estimation of pavements using modified MUSIC: experimental results

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Abstract

In civil engineering, Ground penetrating radar allows rapid data collection for surveys and can be applied on several media such as rocks, soil, ice, pavement, etc. The centimeter-scale wavelengths are often used for the specific application of pavement survey and more specifically for measuring the thickness of different layers. In this paper, like in \([1,2]\), we consider a pavement which is composed of homogeneous layers separated by rough interfaces. Therefore, the influence of interface roughness is taken into account in the signal model. The interface roughness can be characterized by the frequency behavior of the backscattered echoes, which decreases with the frequency. Like in \([1]\), the modified MUSIC algorithm is proposed for the time delay estimation. In \([1]\), modified MUSIC is used only to estimate the time delay and the maximum likelihood method is applied for the interface roughness estimation. In this paper, we make full use of the mathematical formalism of MUSIC to estimate the two parameters (time delays and interface roughness) with only one method.

In this paper, the focus is on the first two or three layers of the roadway, which are low-loss media \([3]\). From the work in \([4]\), for low-loss media, the dispersivity of the media can be neglected. According to \([1]\), the signal model which takes the interface roughness into account can be written as

\[ r(f_i) = \sum_{k=1}^{K} e(f_i) s_k w_k(f_i) \exp(-j2\pi f_i t_k) + n(f_i) \]  

where \(K\) is the number of interfaces, \(e(f_i)\) is the radar pulse, \(s_k\) represents the reflection coefficient of the \(k\)th backscattered echo with flat interfaces; \(n(f_i)\) is an additive white Gaussian noise with zero mean and variance \(\sigma^2\). \(w_k(f_i)\) represents the frequency behavior of the \(k\)th backscattered echo the frequency \(f_i = f_1 + (i-1)\Delta f\) coming from the interface roughness and \(i=1,2...N\), \(N\) is the number of used frequencies.

In this paper, the interpolated spatial smoothing (ISS) technique \([5]\) is applied to decorrelate the correlation between echoes. Thus, \(N\) frequencies and \(M\) overlapping subbands with length \(L\) are considered. Thus, the modified MUSIC presented in \([1]\) allows to estimate the time delay by the following equation:

\[ P(t) = \left\{ \min_k \frac{k^H \tilde{A}(t) U_L U_L^H \tilde{A}(t) k}{k^H \tilde{A}(t) \tilde{A}(t) k} \right\}^{-1} \]  

with \(\tilde{A}(t) = \text{diag}\{\exp(-j2\pi f_1 t), \cdots, \exp(-j2\pi f_L t)\}\) and \(k = [\bar{w}(f_1) \cdots \bar{w}(f_L)]^T\cdot U_L\) is the \(L \times (L-K)\) noise matrix whose columns are the \(L-K\) noise eigenvectors of the data.

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covariance matrix [1], \( \tilde{w}(f_i) \) is the frequency behaviour after interpolation. \( P(t) \) is equal to the minimum generalized eigenvalue \( \lambda_{\text{min}} \) of \( \tilde{A}^H(t)U_kU_k^H\tilde{A}(t) \) and \( \tilde{A}^H(t)\tilde{A}(t) \), (with \( k_{\text{min}} \) the corresponding generalized eigenvector).

In this paper, we propose to use the formalism of MUSIC to estimate the interface roughness. Indeed, the frequency behavior of the backscattered echoes can be calculated from the estimated time delay \( \hat{t} \) as follows:

\[
P = \left\{ \min_k \frac{k^H\tilde{A}^H(t)U_kU_k^H\tilde{A}(t)k}{k^H\tilde{A}^H(t)\tilde{A}(t)k} \right\}^{-1},
\]

where \( k_{\text{min}} \) is the corresponding generalized eigenvector of the estimated time delay whose elements contain the information of the frequency behavior after interpolation. By calculating \( k_{\text{min}} \), the estimated frequency behavior of the backscattered echoes can be expressed as \( B^{-1}k_{\text{min}} \) with \( B \) being the transformation matrix of interpolation (the details of \( B \) can be found in [1]).

In the followings, the proposed modified MUSIC is tested on experimental data. We study a pavement made of three rough interfaces separating media. The first and the third layers are asphalt layers. The second layer is a sand layer with a thickness about 1 cm and a relative permittivity about 5. In far field, a step frequency GPR is applied, with studied frequency band \( f \in [0.8, 10.8] \) GHz (401 samples), with \( L=200 \). We focus on the second layer, therefore, the time delays and frequency behaviors of the second and third echo should be estimated. In the time delay estimation, the time delays are 4.017 ns and 4.143 ns, respectively; thus, the estimated thickness of the second layer is about 8.5 mm. Fig. 1 shows the frequency behavior of backscattered echoes (representing the roughness). From this experiment, we can conclude that the proposed algorithm is able to estimate the time delays and interface roughness.

References

DETECTION OF IMPACT DAMAGES ON CFRP USING EDDY CURRENT PULSED THERMOGRAPHY

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Abstract

Carbon Fiber Reinforced Polymer (CFRP) materials are widely used in aerospace due to their low weight and high strength. With the increase in the use of composite materials, the Non-Destructive testing of these materials finds an important place in the quality control services. Induction Thermography is a new NDT technique that can be exploited as a promising technique for fast and global maintenance of aerospace structure. However, the detection of typical flaws in carbon composites such as delamination, fibers rupture and impact damages need to be further investigated in order to optimize the technique. Optimization can be done in the test configuration level and by the use an appropriate image processing technique for impact sample. In this paper Eddy Current Pulse Compression Thermography (ECPuCT) is used to detect impact damages on CFRP materials. The Principal Component Analysis (PCA) based image processing technique is used to detect and visualize impact damage area from transient thermal images. Flaw detection results using experimental measures are evaluated and discussed.

I. Introduction

In aerospace industries, CFRP materials are widely used due to high strength to weight ratio compared to other conventional materials. Eddy Current Pulsed Thermography (ECPT) and Eddy Current Pulse-Compression Thermography (ECPuCT)[1] can be applied for the non-destructive testing of various kind of conductor work piece such as Carbon Fiber Reinforced Polymers (CFRP). Induction Thermography system combines two techniques: Eddy Current and Thermography. In Induction Thermography, the heat isn’t limited to the sample surface, it can reach a certain depth according to the penetration depth of the electromagnetic wave into a conductive material. Induction Thermography focuses the heat on the defect area due to Eddy Current distorsion. This phenomenon increases the thermal contrast between the defective region and defect-free areas.

In this paper, experimental induction thermography testing will be carried out. The Principal Component Analysis is applied for ECPuCT thermal responses for quantitative analysis of a composite plate with impact damages of 9 J, 15 J, 16 J, 16.55 J, 18 J and 21 J. The defects are evaluated by analyzing the heat distribution and patterns in thermal images. This paper will investigate whether impact damages can be detected using ECPuCT and Principal Component Analysis (PCA).

II. Application on composite plate

Experimental ECPuCT system in figure 2 is used to investigate impact damage in a CFRP sample. The sample is a 37 plies composite plate with six impact damage defects. The composite plate has dimensions of $300\text{mm} \times 300\text{mm} \times 37h_{\text{ply}}$ where $h_{\text{ply}}$ is the thickness of a ply which is equal to 140\text{mum}. The defects are numbered from A1 to A6 as shown in the fig. 1.

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The table 1 gives the dimensions of the composite plate.

<table>
<thead>
<tr>
<th>Number of ply</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lay-up sequence</td>
<td>X/0/Xs</td>
</tr>
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</table>

X = [0°/0°/135°/0°/45°/0°/45°/90°/0°/135°/0°/135°/90°/45°/0°/45°/0°/45°/0°/135°/0°]

Xs denotes the symmetric lay-up sequence of X with respect to 0° ply

Table 1: Characteristics of the composites plate

![Figure 1. Composite plate with impact damages](image)

The fig. 2 shows the schematic diagram of the used Eddy Current Pulsed Thermography.

![Figure 2. ECPT schematic diagram [1]](image)

The figure 3 shows the results after the implementation of the PCA on the thermal data obtained through the inspection of the composite sample near the defective region A3.

![Figure 3. Results of the implementation of the signal processing technique](image)

In the full paper, more details about the signal processing technique will be given.

References


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EVALUATION OF EDDY CURRENT RESPONSE DUE TO THE APPLIED STRESS ON A STEEL PLATE USING PHASE DIAGRAM

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Abstract

Structural health monitoring has become an integral part in the inspection, monitoring, and repair or renewal of infrastructures, particularly those approaching the end of their design life, in order to maintain their safety and serviceability requirements. As a result, various non-destructive testing methods have been extensively used for the structural health monitoring of infrastructures such as bridges. Eddy current testing is one of the popular non-destructive testing methods used for detection of crack due to fatigue [1], determination of reduced thickness due to corrosion [2], etc. in steel constructions, and measurement of tension force in PT tendons and pre-stressed cables used in reinforced structure constructions [3, 4]. It can be deduced that not only in case of the tension force measurements in circular steel members such as PT tendons and cables, the stress state of a steel plate member changes due to the presence or formation of cracks and reduction in the thickness. Hence, in the present study, a new application of eddy current testing in the determination of stress state in steel plate members is proposed, as an important parameter in the structural health monitoring, to evaluate their condition and identify potential failure conditions.

In order to characterize the response of eddy current to the change in stress, three-dimensional numerical simulations are carried out in the AC/DC module of the general purpose FE software, COMSOL Multiphysics 5.2a for a steel plate subjected to uniaxial tensile stress. A reflection probe comprising of an outer exciting coil and an inner detecting coil has been used to characterize the eddy current response with respect to the change in relative permeability of the steel plate, which is highly dependent on the applied stress in a direction. Figure 1 shows that change in relative permeability along a direction, say X-direction, affects the shape of eddy current; it becomes more elliptical as the relative permeability increases along that direction. Hence, eddy current response can be used to characterize the effect of change in relative permeability of a steel plate due to the applied stress. Therefore, the eddy current indicators – real and imaginary voltages and phase are further used to investigate the changes due to the influential eddy current parameters such as lift-offs and excitation frequencies, in addition to relative permeability.

Moreover, a new, concise method of presenting the simultaneous effects of relative permeability, lift-off on the eddy current indicators for a particular excitation frequency in a single graph, hereby termed as Phase diagram, is devised. The real and imaginary voltages detected by the reflection probe are plotted along the X- and Y-axes, respectively to construct the phase diagram, whereby the change due to relative permeability and lift-offs on the eddy current can be easily differentiated from their distinct phases as shown in Figure 2. It is found that at lower excitation frequency, the change of trend of relative permeability and lift-off is consistent compared to the higher excitation frequency. In view of the calibration requirements for determining the stress value based on the selected eddy current indicator, it is concluded that lower excitation frequency is preferable for the measurement of stress by using eddy current.

Hence, phase diagram provides a convenient way to evaluate the effect of various influential eddy current parameters such as relative permeability, lift-off, and excitation

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frequency, on the eddy current indicators. Furthermore, it provides a criteria for the selection of suitable excitation frequency for stress measurement using eddy current.

![Figure 1](image1.png)

**Figure 1.** Change in the shape of eddy current as the relative permeability increases in X-direction.

![Figure 2](image2.png)

**Figure 2.** Phase diagram at (a) lower excitation frequency and (b) higher excitation frequency.

**References**


STUDY ON EFFECT OF ELECTROMAGNETIC CHARACTERISTICS OF DEFORMED 304 STAINLESS STEEL ON EDDY CURRENT TESTING

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Abstract

In this paper, the induced ferrite and other high magnetic microstructures content changes[1] are studied when 304 austenitic stainless steel stripe samples are tested under different tensile deformation, namely its deformation less than 50%. Furtherly, the correlation is measured between the resulting magnetic permeability or coercivity caused by these microstructures and deformation. Meanwhile, surface-breaking notch defects, width and depth 0.2×1 mm, were processed on different deformation specimens. Based on phase difference and amplitude of defect signal, the optimal eddy current excitation frequency of defects detection under different deformation was obtained, which was basically consistent with the theoretical analysis [2]. In addition, other various factors affecting the quality of eddy current testing(ECT)[3], such as temperature and conductivity, are also considered comprehensively during tensile test. These factors are used to Ansys finite element simulation by modifying the empirical strain-permeability relationship formula as the basic material parameters, which are converted equivalently to the material 3-D permeability distribution, of which the effects finally can be analyzed by finite element calculation on ECT signals. The results of experiment and simulation calculation show that when the deformation are within 50% that necking deformation has occurred, the magnetic permeability of samples increases with deformation growing, and gradually begin to have the magnetic properties of weak ferromagnetic materials, resulting in the reduction of the skin depth of ECT, which also changes the optimal excitation frequency that changes 60kHz and 110kHz. The electromagnetic response noise will be increasing, and the impedance plane diagrams of defects are simultaneously distorted because of it. This is mainly because the high magnetic microstructures have a dominant effect on impedance inductance part and the impedance of a certain size defect increase, which leads to the quantitative evaluation error of defects.

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Acknowledgments

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A0143 Study on Detection of Subsurface and Far-surface Defects Based on PMFL

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Abstract. Because of its unique advantages, pulsed magnetic flux leakage (PMFL) has been widely used in the detection of track. In this paper, based on the simulation results of PMFL detection model, two new methods of estimating defect locations are proposed. Finally, the feasibility of above methods is verified by experiments.

Keywords. PMFL, finite element analysis, defect location, defect detection

1. Introduction

Rail transport is closely linked with our daily life, and people have put forward high requirements on the railway safety [1-3]. Here we use PMFL detection technology to detect rail defects. Compared with the traditional magnetic flux leakage (MFL) detection technology, PMFL detection can obtain abundant defect information and has been widely studied in recent years [4-5].

In this paper, we use PMFL testing technology to detect subsurface and far-surface defects. ANSYS Maxwell software is used to establish and simulate the finite element model. Based on the simulation results, we propose two methods of estimating defect locations. Finally, experiments are conducted to verify the feasibility of above methods.

2. Principles and Modeling

The PMFL detection probe is mainly composed of core, coil and Hall sensor [6]. When a square pulse is applied to the excitation coil, an induced magnetic field is generated in the steel plate and a part of the magnetic field leaks from the defect. We use Hall sensor to detect the change of the magnetic field and convert it into a voltage signal. In this paper, we classify the defects into four categories: the external defects on the upper surface are considered as surface defects, and those on the lower surface are considered as back-surface defects; the internal defects within 4 mm of burial depth are considered as subsurface defects, and those above 4 mm are considered as far-surface defects.

We use ANSYS Maxwell software for finite element modeling and simulation. The model is shown in Figure 1. Square wave excitation is applied to the coil at time

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zero, while the excitation frequency is 1Hz and the duty cycle is 50%. We measure the vertical MFL induction intensity to avoid the influence of background magnetic field.

3. Defect Location Estimation by MFL Signal Characteristics

There are two typical MFL signals for surface and subsurface defects, as shown in Figure 2. The defect depth is 6 mm, the excitation voltage is 10 V. Figure 2(a) is MFL signals of surface defects. The relative permeability of core is 100 and 400 respectively. Figure 2(b) is MFL signals of subsurface defects, the buried depth is 2 mm. The relative permeability of core is 100 and 300 respectively. When the excitation voltage and the relative permeability are small, as shown in blue curves, the MFL signals rise rapidly in the initial stage, then gradually fall back after reaching the peak, and finally reach the steady state. We call it the overshoot phenomenon. When the excitation and relative permeability are larger, as shown in red curves, the MFL signals rise rapidly in the initial stage, then decrease slightly or the rising rate slows down, then the rising rate rises again, and finally tends to be stable. We call the change of rising rate as the fluctuation phenomenon in the rising stage.

The typical MFL signals of far-surface and back-surface defects are shown in Figure 3. The excitation voltage is 20V, the relative permeability of core is 300 and the defect depth is 6mm. The blue curve is a far-surface defect 1 mm from the bottom of the defect to the back-surface of the steel plate, and the red curve is a back-surface defect. As can be seen from the figure, both of them increase gradually from zero to steady value with S-shaped curves, and there will be no overshoot or fluctuation in the rising stage.
We suspect the reasons for these two phenomena. When the pulse voltage rises from zero, the eddy effect will hinder the change of the magnetic field. Therefore, in the steel plate, the direction of the magnetic field caused by eddy current effect is opposite to that caused by voltage rise. However, above the steel plate, the magnetic field caused by the eddy current is in the same direction as the leakage magnetic field, which leads to overshoots and fluctuations. When the excitation reaches a steady value, the eddy current effect disappears, so the magnetic field eventually tends to be stable.

When the excitation voltage and relative permeability are both small, the original leakage magnetic field is small, so the effect of eddy current is obvious and leads to overshoot. When the excitation voltage and relative permeability increase, the effect of eddy current decreases, so overshoots gradually become fluctuations and finally tend to be not obvious. Since eddy current has skin effect, far-surface and back-surface defects have no overshoot and fluctuation phenomena regardless of the excitation value.

We obtain the voltage-permeability boundary of overshoot phenomenon by fitting the simulated scatter points, as shown in Figure 4. The curve is an inverse proportional function and divides the figure into two areas. In area I, the MFL signals of surface defects will overshoot, while in area II, there will be no overshoot phenomena.

Therefore, when the excitation and relative permeability is small, we can estimate defect locations according to the MFL signal characteristics. When the signal appears overshoot or fluctuation in the rising stage, it is a surface or subsurface defect. Otherwise, it is a far-surface or back-surface defect. This method is simple and convenient, but the excitation voltage and relative permeability cannot to be too large.

**Figure 3.** MFL signals of far-surface and back-surface defects.

**Figure 4.** The voltage-permeability boundary of overshoot phenomenon.

### 4. Defect Location Estimation by Differential Signal Characteristics

When the excitation is large, the phenomena of overshoot and fluctuation are less obvious and it is difficult to estimate the defect location. Therefore, we amplify the signal characteristics by differentiation. Taking the curve in Chapter 3 as an example, the differential of Figure 2 are shown in Figure 5 and both of the curves has a minimum point. This is because the overshoot and fluctuation phenomena can be thought of the slowdown of the rising rate in a certain stage, which reflect in the differential as a minimum point. Figure 6 is the MFL signal and its differential of defects with burial depth of 2mm and defect depth of 6mm. When the excitation and relative permeability are large, the fluctuation phenomenon becomes not obvious, but we can clearly see that its differential has a minimum point. The differential of Figure 3 is shown in Figure 7,
which is always positive. This curve increases first and then decreases to zero, with a maximum point and no minimum points.

Differentiation further amplifies the MFL signal characteristics of a defect. If there is a minimum point in differential, we can estimate it as a surface or subsurface defect; if there is a maximum point and no minimum points, it is a far-surface or back-surface defect. Using this method to estimate the defect locations has no limitations of excitation value, and it is more accurate and effective.

![Figure 5: Differential of MFL signals for surface and subsurface defects.](image)

![Figure 6: The MFL signal and its differential of subsurface defect under large excitation.](image)

![Figure 7: Differential of MFL signals for far-surface and back-surface defects.](image)
These two methods mentioned above have their own advantages, and we can choose the appropriate method according to the actual situation. As shown in Figure 8, when the MFL signal has obvious phenomenon of overshoot and fluctuation, we can directly estimate it a surface or subsurface defect. Otherwise, we can estimate the defect location by differentiation.

![Diagram of defect estimation methods]

**Figure 8.** Methods of estimating defect locations.

### 5. Experimental Results

Experiments are conducted to verify the simulation results. A test platform of PMFL is set up, as shown in Figure 9. A surface defect with a width of 1 mm and a depth of 7 mm and a back-surface defect with a width of 1 mm and a depth of 10 mm are tested respectively. The results are shown in Figure 10 and Figure 11. The signal of the surface defect overshoots, while that of back-surface defect quickly rises to the steady state without overshoot. The above detection results are differentiated separately. The differential of surface defect has a minimum point, while that of the back-surface defect only has a maximum point. J.W.Wilson's research also shows similar results. The experimental results validate the simulation, and further confirm that the defect location can be estimated by PMFL signal.

![Test platform diagram]

**Figure 9.** Test platform of PMFL testing.

![Detection results and differential]

(a) detection result  (b) differential of detection result

**Figure 10.** Detection result and its differential of surface defect.
6. Conclusion

In this paper, Maxwell software is used to build and simulate the PMFL detection model considering eddy current effect. Subsequently, two MFL signal characteristics are proposed to estimate the defect locations: the overshoot and fluctuation phenomena and the extreme points of signal differential. Finally, an experimental platform for PMFL detection is built, and the simulation results are verified by experiments, which proves the feasibility of above methods.

Acknowledgment

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Abstract:
The thickness of the steel plate can be measured by the electromagnetic acoustic transducer (EMAT), but the accuracy is greatly affected by lifting and limited in practical applications. In this paper, a frequency analysis method is presented to measure the thickness of steel plate and reduce the dependence of the signal amplitude and signal to noise ratio (SNR). The echo signal can be assumed to only related to the frequency of generated wave and the plate thickness. According to the assumption, the echo signals have been processed in the time domain, then the processed signals were used to Fourier analysis. The thickness of the steel plate can be obtained by the peak frequency of specific spectrum.

1. Introduction
Typically, the thickness of steel plate can be obtained by measuring the transit time between two consecutive echoes in an ultrasonic waveform. Measurement of the peak to peak time to try to obtain the acoustic wave transit time is a typical method [1]. But the amplitude of echo signal is affected by lifting, there is paint or coating on the surface of steel plate in practical applications, which leads to low SNR and low measurement accuracy. To obtain higher accuracy, Fourier analysis method was proposed to gauge the thickness of aluminum sheet in 2001 [2]. Because the relationship between reflection and excitation frequency is not superposition. When Fourier analysis is applied to steel plate measurement directly, the peak frequency of amplitude spectrum is not the ultrasonic reflection frequency. To obtain the reflection wave frequency, a signal processing method was proposed in this paper, and higher plate thickness measurement accuracy was obtained.

2. Signal processing method
The echo signal is assumed to be a combination of the vibration caused by the excitation wave and the signal generated by the reflection between the surfaces of steel plate. The relationship of the two factors in the time domain is considered to be multiplied, the echo signal can be expressed as

\[ S(t) = A_0 e^{-\tau t} \sin(\omega_0 t) \sin(\omega_1 t / 2 + \varphi) + S_{\text{noise}} \]  

(1)

Where \( A_0 \) is the amplitude of the signal, \( \tau \) is the attenuation rate, \( \omega_0 \) is the frequency of excitation wave, \( \omega_1 \) is the reflection frequency and \( \varphi \) is the phase difference between the two factors.

According to the Eq. (1), it performs frequency shift of excitation frequency in the frequency spectrum. Measuring the frequency shift of the excitation frequency to measure the thickness is not accurate because the influence of circuit structure and noise. In order to get the reflection frequency which is representing the steel plate thickness, the following process was proposed to process the received signal and obtain the characteristic frequency. The echo signal can be extracted from the received signal which is tested by the EMATs system. For higher frequency resolution, period of echo signals should be extended. Using nonlinear transform to separate the reflection and excitation wave in the frequency domain, the negative values of the signal processed above were set to zero and then Fourier analysis was used to this signal. Select a specific frequency band according to the actual situation, and the frequency point corresponding to the peak of amplitude spectrum in the frequency band can...
be regarded as the reflection frequency. Furthermore, the thickness of steel plate is calculated according to the wave velocity and the reflection frequency.

3. Experimental verification

To verify the method, two steel plate specimens with a thickness of 8mm and 5.35mm made of 16-MnR were used for the experiment, the experiment diagram is shown in the Fig.1. The typical echo signal of steel plate thickness measurement using EMATs in this experiment. The thickness of the plate is 8mm, the signal was averaged 128 times and the paralysis time of the EMATs systems is approximately 20µs. In order to intercept the echo wave and reduce the impact of noise, the 70µs to 100 µs signal after excitation ultrasonic is extracted as echo signal for analysis, the echo signal is shown in Fig.2.

![Figure 1. experiment diagram](image1)

![Figure 2. typical echo signal of steel plate thickness](image2)

Using the signal processing method described above, the frequency band is selected as 0.1MHz~0.35MHz. The frequency corresponding to the peak point of 8mm standard specimen is 199815Hz, according to $V=2D*f_0$ ($V$ is the propagation velocity of ultrasonic wave in the specimen, $D$ is the thickness of the steel plate), $V=3197.04$m/s. The frequency corresponding to the peak point of 5.35mm specimen is 299691Hz, according to the above wave velocity, the calculated thickness is 5.3338mm, contrast with the actual thickness, the error is approximately 0.3%.

4. Conclusion

Higher accuracy can be obtained by using this signal processing method contrast with the traditional method and don’t need to change the original circuit. It is also helpful to increase the using lift-off of the transducer, which has important influence on the applicability of the transducer.

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References

EXPERIMENTAL RESEARCH ON PARALLEL WIRE CABLE TENSION TESTING BASED ON THE PERMANENT MAGNETIZER

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Abstract

The parallel wire cable is widely used as a key component in cable-stayed bridge, suspension bridge and other architecture structures. Obtaining the cable tension accurately is of great significance to the structural safety. Based on the principle of testing stress under the excitation of constant magnetic field, a parallel wire cable tension testing instrument is developed in this paper. The instrument mainly consists of permanent magnet magnetizer which produces a spatially-varying magnetic field along the axial of the cable and array hall elements to measure the outside magnetic flux density distribution. The result of the experiment shows that the developed instrument can realize the measurement of the parallel wire cable tension, and is not affected by boundary conditions of the cable.

1. Introduction

The parallel wire cable is a commonly used component on bridges, dome structures and so on. Measuring the cable tension is of great significance. Presently, there are three often-used cable tension testing method: the lift-off method, the pressure sensor method and the vibration method. The lift-off method is hard to use and has poor efficiency. The pressure sensor method allows testers to obtain the tension information directly, while it requires to pre-install pressure sensors in the cable which raises the cost. The vibration method uses the natural frequency to test the tension, which requires a precise theoretical model. The electromagnetic method has its unique advantages such as low cost, no pollution and most significantly, free from the influence of the boundary conditions. The instrument developed in this article is mainly composed by the permanent magnetizer which produces a spatially-varying magnetic field along the longitudinal direction of the cable and the array hall elements which test the magnetic induction intensity, and the best characteristic parameter can be obtained among them. Experiment shows that the relative error is less than 8%.

2. The Principle

To obtain appropriate magnetic characteristic parameter, the cable needs to be magnetized. The instrument uses permanent magnets to induce an axial-varying magnetic field on the cable. The magnetic flux density is time-independent and is related to the axial position L.

According to the J-A-M model which considers the influence of stress on the magnetizing curve, we have

\[ B_{fer} = F(H, \sigma) \]  (1)

which shows that the magnetic flux density inside the ferromagnetic steel wire \( B_{fer} \) is the function of magnetic field intensity \( H \) and stress \( \sigma \). Under the excitation of the permanent magnetizer, \( H \) is only the function of the axial position \( L \). So, we have

\[ B_{fer} = G(L, \sigma) \]  (2)

Furthermore, we can derive that

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\[
\frac{\partial B_{fer}}{\partial L} = K(L, \sigma)
\]

From Equation (3) we can see that when \( L \) is determined, \( \frac{\partial B_{fer}}{\partial L} \) is only relative to \( \sigma \) which means it can characterize \( \sigma \). If we use the Gauss theorem to establish the relationship between \( \frac{\partial B_{fer}}{\partial L} \) and the radial magnetic flux density outside the steel wire \( B_{rout} \), we can use \( B_{rout} \) to characterize \( \sigma \).

Based on the principle above, a parallel wire cable tension testing instrument is designed, and experiment is carried out.

3. Experiment Results and Discussions

A parallel wire cable tension testing experiment is carried out to verify the above principle. According to the principle, we use permanent magnets to magnetize the parallel wire cable and array hall element to measure \( B_{rout} \). The whole instrument installed on the tensioning parallel wire cable is as shown in Figure 1.

Experimental result is shown in Figure 2. The result shows that the relative error of this character is less than 8%.

4. Conclusion

The relationship between the stress and magnetic character is derived according to the J-A-M model and the Gauss theorem, and it shows that under the permanent magnetizing, the radial magnet flux density outside the cable is relative to the stress. According to the principle, the testing instrument was developed. Experiment shows that the instrument can realize the characterization of the cable tension and the relative error is less than 8%.

References


Acknowledgments

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A0153 NONDESTRUCTIVE EVALUATON OF TROPOSPHERE LOWER LAYERS PROPERTIES BY MONITORING OF ELECTROMAGNETIC ENERGY SOURCES

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Abstract
The paper shows new using of highfrequency electromagnetic field signal using in investigation of properties of low layers atmosphere. We introduce new methods, which can be used not only for dielectric properties of materials investigation, but also in the field of meteorology. In the paper we show the results for tracking the changes of dielectric properties of low atmosphere layers. An integral part of our environment is in addition to the surface of the earth, the adjacent part of the atmosphere, the lower layer of the troposphere. Satellites, radars, and point data collection do not affect the ground-level layers of the atmosphere and do not have sufficient time or spatial resolution in populated areas where the need for detailed information is highest.

Technical means of monitoring the ground layers of the atmosphere
Classical methods include radar measurements, multispectral atmospheric and satellite surface monitoring, ground station networks are not suitable for determining the state of the atmosphere in the ground layer up to the level of 100m, which significantly affects the environment.

UHF emission of electromagnetic energy – sensing the properties of ground layer of atmosphere
Therefore, by using a pragmatic approach, we can ask the question of the potential utilization of this band for the monitoring of the ground layers of the atmosphere, because the amount of radiated energy in this area is high and the density of resources is considerable, especially in areas of interest with higher population concentration. With the monitoring of the transmission of a suitable source, we find that the mean power of the received signal contains a noise component that represents interference phenomena (random reflections from buildings, vegetation, vehicles), and the impact of weather changes can also be traced in this noise component.

1. Stochastic methods
The first method was based on the assumption that the signals at the output of two antennas receiving a signal from a common source spaced by several wavelengths are not correlated with each other in a non-collision state. Fig. 1 shows the result of the experimental measurement during the cold front transition and the meteorological situation during the measurement. In the upper part of the left figure, Fig. 1 there is a graph of the time course of the non-standard coefficient of mutual correlation, in the lower part there are amplitudes of demodulated received signals of both antennas. On the right, there is a meteorological radar record. During the measurement, the cold front passed in several waves of local storms followed by weaker rainfall.

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2. Phase shift method
Since the determination of absolute environmental parameters by passive tracking of a foreign source of electromagnetic energy in ground conditions is obviously not easy to implement, we have developed a method based on evaluating the relative phase shifts of signals propagating at different speeds across different trajectories within the first Fresnel zone. Fig. 2 shows the data from the cold queue transition, phase shift along with solar radiation sensors, temperature and wind speed data for the same real situation showed in Fig. 1.

The above discussed methods can be used for remote monitoring of phenomena in the troposphere at altitude up to 100m with high time resolution below 1sec, in case of simultaneous monitoring of several sources also for spatial localization of observed phenomena - torrential rains, local storms, fog, turbulence and others. The presented research shows new insight into the possibilities of exploring changes in dielectric electrical properties by the new presented methods and can be used also for other dielectrics with changing dielectric properties. The research shows the new milestone in the testing of lower layers of atmosphere in the view of evaluation of electromagnetic signal propagation through the dielectrics with changed properties.

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Abstract

Wood is an anisotropic dielectric and can be considered as a crystal, with 3 axes of coordinates reported to the wood grain direction [1]. Due to the physical-mechanical properties, which can vary considerably from one species to another, each wood essence has certain areas of use. Recognizing wood species and knowing the characteristics is important for obtaining superior quality products if we look at wood as a natural composite material not only used as a decorative material. The dielectric behavior of wood depends significantly on the fine chemical structure and the macroscopic structure. The dielectric properties are usually determined in resonant circuits [2], electronic bridges [3], transient methods in DC [4], etc. Microwave waveguide sensors measures properties of materials based on microwaves interaction with materials, providing information about dielectric properties of investigated dielectric material, characterized with complex permittivity, providing information about moisture content, density, structure, and even chemical reaction [5]. The real dielectrics are defined by relative permittivity \( \varepsilon_r \) and loss tangent \( \tan \delta \). The response of the dielectric to the electric field also depends on the frequency. For this reason \( \varepsilon_r' = \varepsilon_r - j \varepsilon_r'' \) where \( \varepsilon_r' \) and \( \varepsilon_r'' \) are dielectric constant and measure of how much energy from an external field is stored in the material and accounts for the frequency dependency of the dielectric which contributes to losses.

Microwave sensors provide high speed and noninvasive measurement compared with conventional sensors [6]. The sensitivity of conventional sensors using microwave waveguides can be improved using metamaterials structures (MM). The concept of MM as an artificial composite structure with special electromagnetic properties has been extended in applications such as absorbers, filters, couplings, antennas, etc. [7]. The fundamental elements of MM with dimensions under the wavelength, such as SRR, form small-scale sensors in order to improve the sensitivity of conventional sensors in the microwave-terahertz range [8]. Resonant properties can be tuned by controlling geometric and material parameters, such as the width of the space between traces, width of traces, the thickness of the metal layer, the nature of the substrate. Measurements were carried out on the Vector Network Analyzer VNA MS2028C with connected closed waveguide having metamaterial structure in front of waveguide opening (Figure 1).

\[ \text{Figure 1. Microwave testing experimental set-up} \]
The transmission/reflection method was used for measurement. Nicolson-Ross-Weir (NRW) conversion process [9, 10] was used for relative permittivity calculation. Transmission (T) and reflection (Γ) coefficients are extracted from S-parameters measured by VNA.

The microwave measurement method determine the dielectric properties of wood samples and the results are compared with DMA. The experimental measurements have been carried out using the metamaterial structure in the front of a BJ-100 rectangular waveguide. The MM structure is formed by 5×5 split ring resonators (SRR) having the resonant frequency in the range of the system operating frequency.

Two type of alder samples having dimensions to fit inside the waveguide were studied to determine the resonant frequency peaks displacement due to modification of sample dielectric with frequency. Using the results obtained by DMA, and completing with dielectric characteristics, a complete characterization of alder samples is carried out, promoting them for use in different practical application as sound barrier, acoustic cavities, etc.

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References
Reconstruction of Conductivity Distribution with Acousto-electrical Tomography Based on Neumann Boundary Condition

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Abstract. In this paper, a method for detecting the shape and position of object embedded in a closed-domain filled by conductive materials with the acousto-electrical tomography is presented. Due to the difference of conductivity between the inclusion and the background materials, the continuum model with Neumann boundary condition is applied to obtain the spatial potential distribution in the entire domain. In reality, the potential distribution of the boundary can be measured by adding some electrodes on the boundary. In the forward model of this paper, the Neumann boundary condition is applied to the boundary, which can be used to simulate the results obtained with electrode measurements. Then, with the Levenberg-Marquardt iterative algorithm the distribution of conductivity is reconstructed from power density. A two-dimensional example is used to illustrate feasibility of the model.

Keywords. Acousto-Electrical Tomography, Electrical Impedance Tomography, Neumann boundary condition, Levenberg-Marquardt algorithm

The acousto-electrical tomography is a noninvasive type of medical imaging method. The electrical conductivity, permittivity and impedance of a part of the body can be reconstructed from the surface measurements, which is used to form a tomographic image as discussed in [1]. Generally, the problem of recovering the conductivity by measuring surface current and potential is an ill-posed non-linear inverse problem.

In this paper, we focus on a Calderon problem with the Neumann boundary conditions. In order to measure the potential, the boundary is divided into two types of segments, including the part without electrode indicated as \(\Gamma_0\) and the electrode part indicated as \(\Gamma_1\). The electrode part \(\Gamma_1\) is marked as \(e_l, l = 1, 2, ..., L\). The currents \(I_l\) are applied, and the voltages \(U_l\) on the electrodes are measured[2]. Here, according to Maxwell equations, the forward formula is given as \(\nabla \cdot \sigma \nabla u = F\) where the \(F\) is the term of an excited source in a prescribed function. And the boundary conditions are given as

\[
\frac{\partial u}{\partial n} = g \text{ on } \partial \Omega, \quad \text{where } g = \begin{cases} 
0, & \text{on } \Gamma_0 \\
-5, & \text{on } \Gamma_1
\end{cases}
\]

The equation is solved with its weak form. This is taken as a forward model.

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The domain of forward model defines on $\Omega \subset \mathbb{R}^n$ for $n \geq 2$. Then, the spatial potential distribution in the domain is measured from the forward model. The power density in $\Omega$ is defined as $\mathcal{E}(\sigma) = |\nabla u(\sigma)|^2$, $\Omega \subset \mathbb{R}^n$. Here, the $\sigma$ is the conductivity map in the domain $\Omega$. And the $u(\sigma)$ is the electrical potential produced by applying either voltage or current on the boundary.

The problem is to reconstruct the $\sigma$ from the spatial potential with the Levenberg-Marquardt iterative algorithm. The noisy measurements $\mathcal{E}^\delta(\sigma)$ of the true power density $\mathcal{E}(\sigma)$ is given by adding a noisy function. So the equation $\mathcal{E}(\sigma_k) = \mathcal{E}^\delta(\sigma)$ should to be solved. The $\sigma_k$ is the solution that is approaching to the real distribution of conductivity. This problem is equal to solving the minimization problem $\min_{\sigma} ||\mathcal{E}(\sigma) - \mathcal{E}(\sigma_k)||_{L^2(\Omega)}$. With the Tikhonov regularization, the equation is also given as $\sigma_{k+1} = \sigma_k + (F'(\sigma_k)^+ F'(\sigma_k) + \alpha_k I)^{-1} F'(\sigma_k)^+ (\mathcal{E}(\sigma) - \mathcal{E}(\sigma_k))$. A guess of the conductivity distribution is given as the initial value for the Levenberg-Marquardt iterative algorithm. Then, the $\sigma_k$ can be solved through enough iterations and the distribution of conductivity in the domain can be reconstructed.

References

Research on Eddy Current Array Technique for Defect Detection of Aluminum Tubes

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Abstract
Aiming at the difficult problem of rapid defect detection of aluminum tubes, this paper proposes an eddy current array detection scheme for rapid detection of aluminum tube defects. Firstly, the typical defect model of aluminum tube was established by COMSOL simulation software, and the signals of different defects were simulated and analyzed. According to the signal characteristics of typical defect model of aluminum tube, the eddy current array probe was optimized. Finally, the simulation results are verified by experiments. The experimental results show that the proposed method can detect the hole defects of 0.3mm in diameter and the linear defects of 0.13mm in width on the aluminum tube.

References

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Nondestructive Evaluation of Circumferential Defects in Pipeline by Magnetic Measurement with Tunnel Magneto Resistor Sensor

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Abstract: Conventional eddy current testing (ECT) receiver coils are unable to detect circumferential cracks during pipe testing. To solve this problem, the method of measuring the space magnetic field with the tunnel reluctance sensor is used. This method uses a feed-through coil as the excitation coil, and the tunnel magnetoresistance (TMR) sensor receives the defect signal. By simulating the flux density on the defect sample, the signal characteristics on the surface of the defect sample are obtained. The experimental system was established and the defect detection experiment was carried out. Experimental results show that this method is effective in detecting circumferential defects and can evaluate circumferential defects of pipelines.

1. Introduction

Eddy current testing equipment can be high-speed, automatic non-destructive testing of batch metal pipes. In the traditional method of testing a pipe by eddy current, a pair of traversing coils are used as the exciter and receiver respectively. When detecting axial cracks, the detection coil is sufficient to detect the abnormal eddy current distribution caused by the defect. However, because the eddy current flows along the circumferential direction of the pipe, the traversing detection coil is not sensitive to circumferential defect detection.

Therefore, a detection system that can detect and evaluate circumferential defects of pipelines is needed. Compared with traversing coil, TMR sensor has better local detection performance and can receive spatial magnetic field component information. Based on these advantages of the magnetic sensor, we developed a probe using the TMR sensor array to detect and evaluate the circumferential defects of the piping by analyzing each component of the received spatial magnetic field signal.

2. Finite Element Simulation

The 3D FEM model of the circumferential current field is set up by the COMSOL software, as shown in Fig. 1a. The model consists of excitation coil, piping, and circumferential defect. The excitation coil is coaxial with the piping. The axial crack lies on the outer surface of piping symmetrically. The lift-off of the excitation coil is 2 mm and the lift-off of sensors is 1 mm. The size of the crack is 6 mm in length, 1 mm in width, 3 mm in depth. A sinusoidal excitation signal (frequency 100 kHz, amplitude 2V) is loaded on the excitation coil.

The magnetic flux density z component (Bz) characterizes the circumferential crack, as shown in Fig. 1b. Simulation results show that when the probe is scanned along the pipeline...
axis, Bz will show positive and negative peak signals at the defect.

3. Experiment and Analysis
The system includes excitation coil, TMR sensor and amplification conditioning circuit, oscilloscope and pipeline specimen, as shown in figure 2.

![Diagram of the testing system](image)

Fig.2. The diagram of the testing system

Axial and circumferential defects were detected by probe. It is found that when the probe is scanning the region without cracks on the test block, the peak value of the induced signal on the TMR sensor remains unchanged. When the probe scans the crack region at different depths, the peak value of the induced signal on the TMR sensor changes significantly. When the probe enters the crack region, the peak value of the induced signal reaches the maximum value; when the probe leaves the crack region, the peak value of the induced signal appears the minimum value. Thus, the location of the crack can be determined according to the change of the output peak value of the signal on the TMR sensor. The circumferential defects and axial defects can be distinguished by the visualization image made according to the regional data provided by the array probe. The data collected by the data acquisition card are used to conduct differential, filtering, analysis, processing and other links with MATLAB tool, and then the output peak value and peak time characteristics of the defect are extracted, so as to determine the depth of the defect.

References
Abstract
As the use of the carbon fiber reinforced composite materials (CFRPs) is increasing in the industrial field, much attention is devoted to the defects detection using nondestructive testing (NDT) techniques. Eddy current pulsed thermography (ECPT) is an emerging NDT technique and has been successfully used to detect the surface crack, impact and delamination of CFRPs. However, the fast numerical simulation is difficult to be carried out for ECPT applied to CFRPs, due to the high excitation frequency, short heating stage and high anisotropy of material. The edge element and frequency summation method are applied to the simulation of electromagnetic field for 3-D model in this paper. As for the calculation of temperature field, the energy equivalent principle is employed to accelerate the process of simulation. As a validation of validity and reliability, numerical results are compared to experimental results.

Index Terms—ECPT, CFRP, Frequency summation method, Energy equivalent principle

Introduction
Carbon fiber reinforced composites (CFRPs) have been nowadays successfully employed in many engineering applications, due to better mechanical and chemical characteristics with a lower weight. However, the defects, such as surface crack, impact, and delamination might generate in the process of manufacturing and service. These defects will severely degrade the loadbearing capacity and reduce the reliability of the structure. For the purpose of detecting defects and ensuring structural safety, more and more nondestructive testing (NDT) methods, such as ultrasonic testing, eddy current, acoustic emission, microwave and infrared thermography are studied. Eddy current pulsed thermography (ECPT) is an emerging NDT technique, which combines the advantages of pulsed eddy current and thermal wave testing [1]. The ECPT has successfully employed to detect the surface crack, impact and delamination of CFRPs [2-4]. In modeling and simulation of ECPT on CFRPs, a methodology based on shell elements was used to model the electromagnetic-thermal behavior of multilayered conductive composite materials [5]. A model taking into account the influence of different fiber orientations on electromagnetic parameters was presented [6]. A multiscale approach was then used to calculate the electromagnetic and thermal field distribution [7]. However, the high excitation frequency (typically (50-500) kHz) and short heating stage make the process of simulating ECPT signals (temperature distribution) time-consuming through time iteration strategy. In addition, the high anisotropy of material properties, such as conductivity and thermal conductivity, increases the complexity of numerical simulation and reduce the efficiency of calculation. An efficient simulator is urgently needed for the numerical simulation of ECPT applied to CFRPs. According to the above backgrounds, this paper proposed an efficiency numerical method to calculate ECPT signals of 3-D CFRPs models based on the frequency summation method and energy equivalent principle. In addition, the reduced magnetic vector potential method and edge elements are employed in the proposed numerical method, which can greatly reduce the degrees of freedom of the 3-D numerical models.
I Principle of proposed numerical method

A. Numerical methods for electromagnetic fields based on frequency summation method

The excitation current could be treated as a summation of a series of sinusoidal waves with different harmonic frequencies and corresponding amplitudes according to the Fourier transformation method. The electromagnetic response signal of the ECPT could be acquired through calculating the response signal of sinusoidal excitation current of a single frequency first, then carried out a sum of the response signal of every harmonic frequency. In addition, the reduced magnetic vector potential method (Ar method) is employed to simulate the response signal of single-frequency sinusoidal excitation current using edge elements in this study. It worth noting that the material properties can be considered as not dependent of temperature because the temperature rise within the specimen is very low during the inspection process.

B. Numerical strategy for temperature fields

The thermal source, i.e. the Joule heat generated by eddy current, can be calculated from the results of electromagnetic field. The frequency of thermal source is as two times high as that of the excitation current. In order to accelerate the simulation process of temperature field, the excitation of high frequency in the calculation of the temperature field can be transformed to an equivalent simple form according to the energy equivalent method as shown in Fig. 1. In each time step Δt, the sinusoidal thermal excitation of high frequency is transformed to a linear excitation. The energy of the excitations before and after transformation keeps the same, i.e., the area S1 enclosed by the original thermal excitation curve and the x coordinate axis equals to the area S2 enclosed by the transformed thermal excitation curve and the x coordinate axis. The temperature distribution signals of ECPT can be calculated through the time iteration strategy.

Figure 1 Equivalent principle of the energy equivalent method

References


Acknowledgments

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Design of A Novel Magnetizing Probe for Eddy Current Testing of Small Defects in Ferromagnetic Steel Plates

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Abstract
The early service of ferromagnetic steel plates in China is affected by the long working environment. The surface of the steel plate is rusted and causes defects such as corrosion, cracks and small holes. In order to avoid the substantial damage caused by defects, it is necessary to carry out periodic inspection of ferromagnetic steel plates. Aiming at this problem, this paper designs a rectangular detection probe composed of magnetized permanent magnets based on eddy current testing. In the eddy current testing process, the magnetic permeability of the carbon steel plate is inhibited by the probe magnetization. The misdetection caused by the difference in signal caused by the difference, so that the fine defects and deep defects of the ferromagnetic tube sheet can be detected more accurately. The test of the ferromagnetic steel plate was carried out by experiments, which proved that the method is feasible.

References

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SPARSIFICATION OF BEM MATRICES FOR EDDY CURRENT NONDESTRUCTIVE EVALUATION

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Abstract

Eddy current testing (ECT) is used in a variety of industries. Eddy current simulation can reduce the time cost and make accurate predictions for experiments. Numerous methods can be used for modeling of eddy current non-destructive evaluation (NDE) problems. The most successful ones are the finite element method (FEM) [1] and the boundary element method (BEM) [2]. However, the FEM needs to discretize much bigger solution domain with volume meshes.

The BEM has many advantages for solving eddy current NDE problems over others. One main advantage is that only the surfaces of considered domains need to be discretized and nearly arbitrary shaped configurations can be modeled. However, the BEM leads to a huge memory requirement and computational time when the number of unknowns increases. Many fast algorithms have been proposed to accelerate BEM, the multilevel fast multipole algorithm (MLFMA) [3] is one of the most efficient algorithms while it needs to deal with kernel functions of integral equations which lacks generality. The kernel-independent rank-based methods are more general methods to accelerate solutions of BEM.

In this paper, a BEM based multilevel adaptive cross approximation (MLACA) algorithm [4–5] is proposed to accelerate solving the eddy current non-destructive evaluation problems. The Stratton-Chu formula, which does not have the low frequency breakdown issue, is selected to model the NDE problems. The Rao-Wilton-Glisson (RWG) vector basis functions and the pulse basis functions are used to expand the equivalent electric and magnetic surface currents and the normal component of the magnetic field. The MLACA uses the butterfly algorithm and ACA algorithm to approximate the well-separated blocks in the impedance matrix to make the matrix sparse. Numerical tests are preformed to optimize the sparsification over group sizes, number of levels in MLACA, and tolerance and stopping criteria. Numerical results on impedance changes are compared with the analytical, the semi-analytical predictions [6] and experimental results to show both the efficiency and robustness of the proposed method.

References


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An Improved Multi-Frequency Eddy Current Excitation Method

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Abstract
The traditional multi-frequency eddy current excitation signals generally use the same amplitude, and the frequency component is the sine wave superposition of the fundamental frequency and its harmonic component. However, the traditional method of multiple frequency did not consider the following questions: multifrequency signals in each frequency component for sensitive degree of different defects, lead to signal amplitude of each frequency component is different, this means that for the same defect the stimulating signals of different frequency, needed to get close to the amplitude of each frequency component of the signal amplitude are also different. To solve this problem, this paper proposes a method to determine the amplitude of multi-frequency excitation signal based on the amplitude of each frequency component in the detection signal spectrum. By the amplitude of each frequency component of the detection signal, the amplitude relation of the excitation signal is determined. In the existing literature, multi-frequency eddy current testing for composite materials has proved the feasibility of multi-frequency eddy current technology for defect detection [1]; Multi-frequency eddy current to detect the thickness of the material, the application has proved the feasibility of the technology about material thickness detection [2]. Therefore, a multi-frequency excitation signal with adjustable amplitude of each frequency component is used for defect detection, so as to achieve the optimal amplitude of each frequency component in the detection signal. Finally, a series of simulation experiments were designed to adjust the amplitude of each frequency component in the excitation signal according to the defect of different depths, which proved that this method could optimize the amplitude of each frequency component in the detection signal.

References

Acknowledgments
Theoretical explanation from teachers and classmates
Localization of Multiple Acoustic Emission Sources in Switch Rail Using Near Field Multiple Signal Classification

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Abstract

Fatigue cracks are prone to appear in the tongue rails and the center rails of switch rails during the service of railway. Acoustic emission (AE) detection technology has unique advantages in evaluating the dynamic characteristics of fatigue cracks [1]. This paper applies AE technology to the monitoring of switch rail cracks by a established sensor array. A multi-AE sources locating method based on correlation subspace method (CSM) combined with near-field multiple signal classification (N-MUSIC) algorithm is proposed.

At present, the most widely used AE source locating method is the time difference locating method. Nevertheless, there will be a large positioning error when the estimation of arrival time (AT) of signals and time difference of arrival (TDOA) between sensors is inaccurate or in variable wave velocities situation [2]. The method based on MUSIC can estimate the positions of AE sources, and has the advantages of simple sensor arrangement, reduced channel attenuation, and simultaneous localization of multi-sources [3]. When the AE sources are in the near field condition, the MUSIC method can not only estimate the azimuth angle of the sources, but also estimate the distance between the sources and the reference sensor.

The AE signals received by the sensors are the aliasing of coherent broadband sources. The widely used broadband signal processing technology in the field of array signal processing technology is to decompose a broadband source into a number of narrow frequency subbands. The correlation subspace method (CSM) algorithm can remove the signal correlation and construct a frequency focus matrix \(H(f)\) to map the signal subspace of a frequency point to a reference frequency point, and then the covariance matrix of all frequency components is averaged as follows:

\[
R(f) = \frac{1}{J} \sum_{j=1}^{J} H(f_j)X(f_j)X^H(f_j)H^H(f_j) = A(r, \theta, \theta, f_0)A^H(r, \theta, \theta, f_0) + R_n(f_0), \quad (1)
\]

Where \(R(f)\) is the autocorrelation matrix after focusing, \(f_j \quad (j=1-\text{J})\) means the central frequencies of J narrow frequency subbands, \(f_0\) is the reference frequency and \(A(r, \theta, f_0)\) is the direction matrix determined by the distance \(r\), the azimuth angle \(\theta\), and the \(f_0\). Then the \(R(f)\) is decomposed by eigenvalues and the noise subspace \(U_N\) is constructed. The spatial spectral function \(P(r, \theta)\) is constructed by MUSIC algorithm:

\[
P(r, \theta) = 1/\| A(r, \theta, f_0)U_N \|_F^2, \quad (2)
\]

Where \(|l|_F\) is F norm, \(r\) and \(\theta\) are searched in two dimensions. When \(P(r, \theta)\) reaches peak values, the corresponding \(r\) and \(\theta\)s represent the positions of AE sources.

When a broadband AE signal being analyzed is divided into \(J\)th narrow frequency subbands, the complexity of computation increases with the increase of \(J\), so the first

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step of this paper is to decompose the signal into a relatively narrow frequency band by modal AE theory and wavelet filtering. Then the number of sources is estimated by Akaike information criterion (AIC) to construct $U_N$. CSM combined with N-MUSIC algorithm is used to locate the multi-AE sources in switch rail. Figure 1 shows the flow chart of the proposed method.

![Flow chart of the proposed method for locating AE source in switch rail](image1)

**Figure 1.** Flow chart of the proposed method for locating AE source in switch rail

In the simulation research of this paper, a three-dimensional rail finite element model is established by ABAQUS software as shown in Figure 2, and the multi-crack AE sources are simulated by several force dipole sources, four receiving points are set up at the rail web to simulate the linear uniform sensor array. In the experimental study, the crack AE signals are excited in the switch rail simulated by pencil-lead break (PLB) test and the CSM plus N-MUSIC program is written by matlab.

![Finite element model of rail](image2)

**Figure 2.** Finite element model of rail

The results show that the proposed method can effectively locate two AE sources in three dimensions, but the localization effect of three and more AE sources is not good and needs to be further studied. More details and the experimental verification will be presented at the conference.

**References**


A0173 EVALUATION OF TEMPERING INDUCED CHANGES IN THE MECHANICAL PROPERTIES OF 24CRNIMO STEEL USING MAGNETIC BARKHAUSEN NOISE ANALYSIS

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Abstract
The effect of tempering on the magnetic Barkhausen noise signal was studied in 24CrNiMo steel using a series of parameters for the analysis of the mechanical properties. Due to coarsening of the microstructure, the MBN level increases with tempering gradually. By investigating the interrelation of the MBN signal parameters such as RMS, power spectrum density and the area of signal envelope, the Brinell hardness and tensile strength of steel and the characteristics of microstructure, the result indicates that the area of envelope of MBN signal has the best fitting relation and prediction precision while other parameters has the greater error relatively for the prediction of alloy steel quantitatively.

Keyword: magnetic Barkhausen noise (MBN); mechanical properties; Microstructure; prediction precision
FAST 3D MODEL DEDICATED TO THERMOGRAPHIC INSPECTIONS OF PLANAR COMPOSITE STRUCTURES

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Abstract

Thermographic inspection is a popular nondestructive testing (NDT) technique that provides direct images of temperature distribution over large areas at the surfaces of inspected objects. A major application of this method is the inspection of composite materials during manufacturing or in service, in view of detecting delaminations possibly appearing between the layers of the structure [1]. Simulation of these inspections proves useful to complement experimental studies, evaluate the performance of a given setup in terms of detection and support model-based algorithms aiming at characterizing flaws.

This communication presents a 3D semi-analytical model, jointly developed at CEA LIST and Laboratoire des Signaux et Systèmes to address the special case of planar stratified media [2]. Each layer composing the structure is assumed to be homogeneous and infinite in the transverse directions, but can have anisotropic electrical conductivity and magnetic permeability. Flaws considered are a set of thin horizontal delaminations with arbitrary shape. Hence, the proposed model is well suited to simulate composite inspections by means of active, passive or lock-in thermographic setups, either in transmission or in reflection, as shown in Figure 1.

Figure 1. a) Typical simulated inspection setup in reflection. b) Typical simulated inspection setup in transmission.

The theoretical approach adopted benefits from the assumptions described above to yield a modal description in space of the temperature distribution at the surface of the structure. This approach, called Truncated Region Eigenfunctions expansions (TREE), was first introduced in

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the context of quasi-static electromagnetic problems like simulation of eddy current testing [3].

Using the separation of variables, the heat equation (1) describing the problem is solved in Laplace domain with respect to time, which allows to freely choose the time samples where the solution is computed and thus to save computational time. For each value of the Laplace variable, a linear system of equations is obtained by means of the method of moments after projections of the unknown onto a basis of sine functions along x and y directions, which are the eigenmodes of the Laplacian differential operators. The very sparse linear system thus obtained can then be solved within seconds on a standard laptop PC. In equation (1), one considers a composite made of n layers, the i\textsuperscript{th} one being defined by its diffusivity coefficient \( \alpha_i \), derived from the material thermal conductivity \( \kappa_i \) (W.m\(^{-1}\).K\(^{-1}\)), its heat capacity at constant pressure (J.K.kg\(^{-1}\)) and its density (kg.m\(^{-3}\)).

\[
\left( \nabla^2 - \frac{1}{\alpha_i} \frac{\partial}{\partial t} \right) T^{(i)}(r,t) = 0 , \quad \text{with} \quad \alpha_i = \frac{\kappa_i}{c_p d_i} \tag{1}
\]

The contribution of the flaw is taken into account through local modifications of the boundary conditions at the interfaces separating the layers. Instead of ensuring the continuity of temperature and heat flux, the boundary conditions include, in presence of a thin delamination, an additional term proportional to the thermal resistance \( R \) characterizing the delamination. Simulation results obtained, like the one shown in Figure 2, will be compared to reference data and the performance of the model will be discussed in terms of accuracy and computational speed. A strategy for fast characterization of damages based on this forward model will also be presented.

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**Figure 2.** Simulated temperature distribution observed in transmission for a two-layer metallic plate at an early time sample (0.05s).

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**References**


DEPENDENCE OF CORECIVITY AND MBN SIGNAL ON MARTENSITIC STAINLESS STEEL WITH AND WITHOUT QUENCH

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Abstract
The demands of nondestructive sensing technologies for monitoring degradation and health of infrastructures in power plants strongly advance in recent year. The material characterization or nondestructive testing using magnetic measurement such as hysteresis loop [1, 2] and Barkhausen noise (MBN) [3, 4] has been proposed and it is expected to be a candidate contributes to technologies with rapid diagnosis and low cost. The steel of turbine components used for a thermal power generation plant is typically quenched to enforce its performance. On the other hand, during long term operating plants, the residual stress is formed, which sometimes has potential to lead to a failure of turbine components. Therefore, quantitative assessment of the residual stress is important. At this moment, X-ray diffraction is often used for such request, however, the requirement of pretreatment, time consuming for measurement, and difficulty of in-situ measurement are demerit of the techniques. The magnetic measurement may be expected to be an alternative method of X-ray diffraction. Therefore, in this study, as a first step, we investigated the magnetic properties and microstructures of martensitic stainless steel used as turbine component steel for thermal power generation plants when the material includes both non-quenched and quenched area. Although our final goal is to evaluate residual stress quantitatively using magnetic measurement, the magnetic properties are very sensitive to not only stress but also microstructure changes, thus we need to comprehend basic magnetic characteristics attributed to microstructures changes due to quench not including stress effects.

The martensitic stainless SUS420 steel was used for the experiments. Specimen size is 70 mm × 17 mm × 8 mm. The specimen was quenched over the area from one of edge to 20 mm in length direction (See. Fig. 1). The value of Vickers hardness of quenched area was about 450 -500 and non-quenched area 290. Then hysteresis curves and MBN properties were measured using a magnetic yoke and a pick-up or an air-core coil, respectively. A triangular current \( I \) of 0.1 or 1 Hz with an amplitude of 1A is applied to an excitation coil winding around the yoke for magnetizing a specimen, and an induced voltage at the pick-up coil wounded the yoke leg or the air-core coil located at the surface of the specimen was measured. The output at the pick-up coil is used for calculation of flux density \( B \) and the output at the air-core coil was amplified by 1000 times, filtered (100 – 200 kHz) and then captured by a PC as MBN signal. The moving average value of MBN signal was considered as \( V_{\text{rms}} \) value. The root mean square value of a half cycle of the output at pick-up coil was evaluated as the RMS voltage. The quenched edge is defined \( x = 0 \) and length direction of the specimen is \( x \) - direction. Then the yoke moves along the \( x \) -direction and hysteresis curves and MBN signal were measured.

Figure 2 shows the hysteresis curves depending on position \( x \). The applied field was parallel to the \( x \)-direction. The curves for the quenched area show the

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inclined loops and the large coercive force. The curve gradually rises up and the coercive force decreases with increasing position $x$, and the loops show a similar shape over $x = 25$ mm; these areas are non-quenched area.

Figure 3 shows the MBN profile at each position. In the quenched area, the profile shows small and broad peak, while the sharp and higher peak appears on the profiles at non-quenched area. At the intermediate area, peak height increases and peak position shift to lower field strength gradually when $x$ changes lower to higher, that is, the quenched area to non-quenched area. We observed the microstructures of specimen by EBSD. It was confirmed that grains are subtilized at quenching area. The grain boundaries act as pinning sites for the domain wall motions, thus, the number of pinning sites increases, which is attributed to the increases in coercive force and Vickers hardness of quenching area. On the other hand, as to MBN signal, the length of domain wall movement decreases with increasing pinning site density, consequently, MBN signal decreases at quenching area.

References

Design of Power Grid Intelligent Patrol Operation and Maintenance System Based on Multi-Rotor UAV System

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Abstract: In this paper, the micro multi-rotor UAV system for power grid inspection is taken as the research object, and the micro multi-rotor UAV system suitable for different patrol situations is studied by using intelligent robot technology, mobile interconnection key technology, geographic information technology and so on. The intelligent patrol UAV system of power grid is developed, that is, the intelligent patrol (Esmart), is an automatic intelligent control software system based on iOS mobile operating system, which is deeply customized according to the characteristics of power inspection operation. It has the general functions of KML, Excel file import, flexible flight parameter setting, automatic route planning, one-click take-off and landing, automatic operation, intelligent security inspection, real-time picture transmission and so on. Panoramic acquisition module, fine inspection module, channel / tree barrier inspection module and rapid mapping and other intelligent business operation modes can meet the data acquisition needs of various application scenarios, timely and comprehensive. The high resolution aerial image of the inspection line is obtained efficiently, which improves the operation efficiency and ensures the safety of the operation. The time of the front-end signal acquisition to the terminal decoding and playback is 1.5s. The system supports TDD-LTE, FDD-LTE, WCDMA, CDMA2000 and other network systems. It also support the video input signals with the resolution of standard 576i, HD 720p, HD 1080i and HD 1080p. It can also set up a variety of transmission formats and codes according to the network situation.

Key Words: Multi-Rotor UAV System, Intelligent Patrol Operation, path planing

With the development of UAVs and the wide application of UAVs, the application of UAVs in the field of power grid has been extended from the pre-grid survey and design to the operation and maintenance of the power grid. The application field, the technical means and the related extension have great development. The application of unmanned aerial vehicle (UAVs) in power grid inspection has entered a rapid development stage from the exploration stage. The traditional mode of operation inspection has the following characteristics: (1) the information acquisition mode is traditional and the source is single; (2) the device state perception is still the power failure maintenance and off-line experiment; (3) the data utilization rate of the advanced means such as on-line monitoring, live maintenance, robot and unmanned aerial vehicle is not high. Under this condition, the intelligent transportation inspection concept supported by the "large cloud movement" of modern information technology has come into being. The unmanned aerial vehicle auxiliary power grid inspection is an important part of the three-dimensional inspection system based on the intelligent equipment. Based on the current situation of the application of the unmanned aerial vehicle auxiliary power grid inspection operation and the possible development direction, the research and development system of the project, namely the electric network intelligent inspection unmanned...
aerial vehicle system (Esmart), can push the power grid inspection to more automatic and intelligent, New heights of high efficiency. The power grid intelligent inspection unmanned aerial vehicle system is an important part of the three-dimensional inspection system based on the intelligent equipment, and is an important aspect of the current inspection technology research. The unmanned aerial vehicle auxiliary power grid inspection operation can effectively solve the problems of large workload, low efficiency, high risk, high line patrol cost of the manned helicopter, complex flight approval procedures, limited operation environment and the like. In this paper, the micro multi-rotor UAV system for power grid inspection is taken as the research object, and the micro multi-rotor UAV system suitable for different patrol situations is studied by using intelligent robot technology, mobile interconnection key technology, geographic information technology and so on. The intelligent patrol UAV system of power grid is developed, that is, the intelligent patrol (Esmart), is an automatic intelligent control software system based on iOS mobile operating system, which is deeply customized according to the characteristics of power inspection operation. It has the general functions of KML, Excel file import, flexible flight parameter setting, automatic route planning, one-click take-off and landing, automatic operation, intelligent security inspection, real-time picture transmission and so on. Panoramic acquisition module, fine inspection module, channel / tree barrier inspection module and rapid mapping and other intelligent business operation modes can meet the data acquisition needs of various application scenarios, timely and comprehensive. The high resolution aerial image of the inspection line is obtained efficiently, which improves the operation efficiency and ensures the safety of the operation.

Fig.1 introduction to the function of intelligent patrol UAV system in power grid

Reference:


Acknowledgments
This work in this paper is supported by the Sichuan Province Science and Technology supporting plan (No.2019YFG0129)
Design of synchronous Motor Operation Control platform based on DSP

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Abstract: The platform takes DSP TMS320F28335 as the control core, and uses the CPLD control board designed to improve the frequency converter and the modules including filter module, collection module, conditioning module, and so on. The hardware carrier of simulation and experimental analysis is provided for the control software mentioned above, and a complete real-time simulation platform of PMSM variable frequency speed regulation is established. The correctness and reliability of FOC control are verified by the experiment of PMSM frequency conversion speed regulation on this system.

Key words: permanent magnet synchronous motor; model-based design; field-oriented control; DSP; real-time simulation

Different from the traditional development method of motor control, this system adopts the development mode based on the model design. It builds the control model of the control motor in the upper computer Simulink, and uses the powerful code generation tool to automatically generate the motor, and the control model of the control motor is built in the host computer based on the model design. The C code of DSP can be generated by the control model and downloaded to the DSP controller. The inverter is controlled to generate the variable frequency voltage to drive the permanent magnet synchronous motor (PMSM) frequency conversion start-up.

Because Simulink is a powerful interactive simulation platform, it not only can realize the function of automatic code generation, but also provides the interface to realize real-time simulation. At the same time, we can directly modify the parameters to test the control effect under different control parameters. To this end, we only need to configure the external mode in the Simulink to easily connect the software and hardware together. Timely detection of errors and optimization of the system. The hardware platform of the permanent magnet synchronous motor mainly includes: DSP control circuit, optical fiber transceiver module, frequency converter, filter module, protection device, current and voltage acquisition module, conditioning circuit module, isolation power module, Encoder and permanent magnet synchronous motor. The overall hardware structure of the control system is shown in figure 1.
Fig. 1 overall hardware structure of speed regulating platform

Reference


Acknowledgments

This work in this paper is supported by the National Natural Science fund of China (51677020) and China Southern Power Grid Co., LTD project (No. STKJXM20180060).
Research on the Speed Regulation Strategy of Permanent Magnet Synchronous Motor based on Particle Optimization

Qunying Liu, Bowen Dou, Ruifei He, Zhiqiang Wang, Qing Li, Chuangjia Chen

Abstract: when the PMSM is controlled by PI controller, the parameters of PI controller can only be adjusted artificially for many times to reach the optimal value, and there is no automatic regulation mechanism. For this problem, the particle swarm optimization (PSO) is used to optimize PI controller. Each particle's position represents a set of PI controller parameters, an objective function is set. When the particle's position makes the objective function reach the optimal value, the PI controller's parameters are the optimal value, which can automatically adjust the parameters of the PI controller. However, the PSO has been used to control the speed of PMSM only in offline mode. Because of the change of inertia and disturbance in real dynamic system, only a set of parameters of PI controller can’t meet the needs of the system. Therefore, the parameters of the controller must be fine-tuned in real time to keep the system in a high precision state at any time. Therefore, a PSO algorithm is proposed to optimize the parameters of PI controller for on-line system in real-time for speed regulation of PMSM. The PSO is used to optimize the proportional gain and integral gain of speed PI controller of variable inertia PMSM drive system in real time. Variable evaporation coefficient is introduced to replace the classical evaporation constant. A simulation model is built on the platform of MATLAB/Simulink. The simulation results verify the good control performance of the proposed algorithm.

Key Words: The improved particle swarm optimization algorithm, speed regulation, Permanent Magnet Synchronous Motor

When the permanent magnet synchronous motor (PMSM) is adjusted by PI controller, the parameters controlled by PI can only reach the optimal value by man-made adjustment, and there is no mechanism of automatic adjustment. The particle swarm optimization algorithm is used to optimize the PI control. The position of each particle represents the value of a set of PI controller parameters and sets an objective function. A particle swarm optimization (PSO) algorithm is proposed to optimize the parameters of PI controller in real-time on-line system, which is used for speed regulation of permanent magnet synchronous motor (PMSM). Particle swarm optimization (PSO) algorithm is used to optimize the proportional gain and integral gain of the speed PI controller of the permanent magnet synchronous motor (PMSM) drive system with variable moment of inertia (PMSM) in real time. During the whole process, the group remains active without switching to some off-line mode or rebooting the drive system. The fitness function which affects the direction of travel of the group is selected to rate the particles. Fitness function is shown as equation (1):

\[ J = \left( \sum_{m=1}^{N} w_m^{ref} - w_m(n) \right)^2 + \beta \left( \sum_{m=1}^{N} u^{ref} - u(n-1) \right)^2 + \gamma \left( \sum_{n=1}^{N} \xi(n) \right)^2 \]  \hspace{1cm} (1)
Fig. 1 Speed Control of permanent Magnet synchronous Motor based on Particle Swarm Optimization

Fig. 2 the values of $K_p$ with the iteration changing, $\rho = 0.999$

Fig. 3 the values of $K_i$ with the iteration changing, $\rho = 0.999$

Reference


Acknowledgments
This work in this paper is supported by the National Natural Science fund of China (51677020).
NUMERICAL ANALYSIS AND INTERPRETATION OF EDDY CURRENT MAGNETIC SIGNATURE MICRO-MAGNETIC NONDESTRUCTIVE TESTING & EVALUATION METHOD

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Abstract

Since decades, iron and steel production and exploitation have largely surpassed any other metal ones. In this domain, the demand for nondestructive testing and evaluation (NDT&E) is enormous. Corrosion, cracks and all the so-called “macroscopic defects” are of course targeted, but recent progress in instrumentation and numerical tools open the way to new types of imperfections and/or micro-structural properties such as residual stresses, elastic, plastic deformations and in a general way all the likelihood of failure due to creep or fatigue. One group of NDT&E method is unique to steel: the magnetic methods. These methods are based on the intrinsic ferromagnetic property of iron which is the main component of steel. A local characterization of the magnetic signature can be considered as an indirect way to get information on this micro-structure. Mechanical properties like residual stresses, elastic and plastic deformations have by instance a huge influence on this magnetic signature. Eddy current testing (ECT) has been the first micro-magnetic NDT&E method. Even if ECT is not restricted to ferromagnetic materials but can be applied to all electrical conductive materials, ECT can still be classified as a micro-magnetic technique. To perform ECT, operators just scan a treated area while simultaneously recording the evolution of the sensor coil impedance. In the industrial domain, ECT is extremely popular mainly because of its simple experimental setup. On the other hand, ECT precision and potential is very limited. To improve this, at the end of the 20th century researchers from the Fraunhofer IZFP tried with success to couple a classic ECT experimental setup to a slowly varying high amplitude magnetic excitation [1]. The so-called Magnetic Incremental Permeability (MIP) micro-magnetic NDT&E method was born. MIP can be defined as the material’s magnetic answer under the influence of a small amplitude alternative magnetic excitation superimposed to a high amplitude quasi-static magnetic field. The AC excitation contribution is of very weak amplitude, consequently the reversible magnetization will be mainly solicited (magnetic domain thin wall motions around hooking points from a global demagnetized state up to a saturated one), MIP will stimulates the easy domain wall motions, the ones which require very low energy contribution, the ones which are particularly affected by the mechanical damage (plastic deformation, fatigue damage …). Recently, based on the MIP experimental setup an even more sensitive method has been suggested by Matsumoto and al. [2][3]. This new technique, so-called, Eddy Current Magnetic Signature (EC-MS) consists of plotting the imaginary versus real part of the sensor coil impedance or of the permeability during the magnetization process. The resulting trajectory observed in the impedance plan can be considered as the EC-MS characteristics signature. The shape, the dimension and the orientation of this signature are extremely dependent on the distribution of the residual stress (figure 1).
A mathematical model has been developed for the simulation of the EC-MS trajectory. For multiple reasons, [4][5] (geometrical properties, numerical convergences and simulation times …) we supposed the scanned area as magnetically homogeneous in space. To simulate MIP characteristic butterfly loop, a lump scalar analytical model, where the induction field $B$ and the excitation field $H$ are supposed collinear, is then the best simulation option. For this model, we opted for a modified Jiles-Atherton approach where the accommodation issue (i.e. it takes many cycles for a minor hysteresis loop to stabilize) is resolved by considering the AC field amplitude weakly enough to annihilate hysteresis during the minor loop states. The EC-MS simulation is somewhat a little more complicated, the simulation of the sensor impedance modulus is not enough and the phase variations have to be taken into account as well. In the simulation scheme an additional dynamic contribution (frequency dependent) is necessary [6]. After several tests, the most efficient dynamic contribution for the simulation of EC-MS can be obtained by using the product of a $B$ dependent damping parameter $\rho(B)$ to the time domain derivation of $B$ as an equivalent excitation $H$ in the J-A quasi-static contribution:

$$B_{\text{quasi-static}} \left( H_{\text{surf}} - \rho(B) \frac{dB(t)}{dt} \right)$$ (1)

Optimization code can be run to determine the set of parameters ($\alpha$, $k$, $c$, $a$ the J-A parameters, $\rho(B)$ the dynamic parameters). Fig. 1 shows some first simulation results. Dodd and Deeds analytical method can be used to link the electrical and the magnetic quantities [7].

References
Data Augmentation and Artificial Neural Networks for Eddy Currents Testing

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Keywords. Eddy Currents Testing, Machine Learning, Artificial Neural Networks, Data Augmentation, Principal component analysis

The goal of non-destructive testing (NDT) is to determine the position and size of structural defects, in order to measure the quality and evaluate the safety of materials used in building or transport industry. Most NDT techniques make use of Eddy Current (EC) to test metal materials. An Electromagnetic field is then induced into the material under test. Variations on the generated currents as well as on the coil impedance are eventually monitored to detect and characterize defects. Due to the difficulty to estimate size and depth of defects via inverse algorithms based on physical models, new approaches focused on Artificial Neural Networks (ANN) [1][2][3] and simulated data are nowadays of great interest, i.e. [4][5][6][7]. The main drawbacks of these techniques still reside in the complexity of the numerical models and the large number of simulated data needed to train and test the ANN, leading to a considerable amount of calculation time and resources. To overcome these limitations, this article proposes a new approach based on a data augmentation procedure via Principal Component Analysis (PCA) applied to a simple numerical model.

At first, finite elements simulations have been conducted following the electric potential vector and magnetic scalar potential T-W formulation [8]. The numerical model implemented here is focused on EC propagation through an Aluminium block, with a large variety of circular defects. In detail, 3200 cylindrical flaws have been simulated (radius from 0.1 to 8 mm and with depth from 0.1 to 4 mm) every 0.1 mm along the top surface of the Aluminium block. The simulated EC probe is a 2.25 mm height coil with inner and outer radius of 2.22 and 2.48 mm, powered by a sinusoidal 1 kHz current.

From simulated resistance and reactance, the PCA approach proposed here has the aim to create new variables (Principal Components), concentrating useful information in a small data-set [9]. Hence, a first estimation has been performed using the first two Principal Components, calculated for the entire simulated data-set, as input to an ANN presenting 20 neurons in the hidden layer and two outputs giving the estimated depth and radius of each defect. Additional tests have been conducted eliminating data from
September 2016

**Figure 1.** Estimation made by the ANN on the test samples and radius and depth estimation as a function of the two principal components.

**Figure 2.** Same results obtained decimating and then augmenting the training set.

the training data-set and subsequently replacing them with artificial points calculated by data augmentation algorithms based on 3D interpolations.

Results show that data augmentation allows the use of a reduced simulated training data-set without deteriorating the ANN prediction performances. The final results are depicted in Figures 1 and 2. As future work, the authors count on validating the proposed method with experimental measurements.

**Acknowledgments**
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**References**


OPTIMAL DESIGN OF REMOTE FIELD EDDY CURRENT TESTING USING SHIELDING PLATE AND FERROMAGNETIC RING FOR FERROMAGNETIC PIPERLINE INSPECTION

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Abstract
Remote field eddy current (RFEC) non-destructive testing has its unique advantages in defect detection of metal pipelines, such as being unaffected by skin effect and material properties [1-2], but its probe size is large and the detection signal by the test coil is weak [3-4]. In this paper, a shielding plate is introduced between the excitation coil and the test coil, and a ferromagnetic ring is introduced outside the ferromagnetic pipeline. Simulation have been carried out, the models for theoretical analysis are shown in Fig.1 and Fig.2, respectively. The theoretical analysis of ferromagnetic ring is highlighted.

For ferromagnetic ring, it can be analyzed from the relationship between magnetic resistance $R_m$ and permeability $\mu$, The formula is shown in (1)

$$R_m = \frac{l}{\mu A}$$

(1)

Where, the permeability $\mu$ is inversely proportional to the magnetic resistance $R_m$. The magnetic permeability in air is much smaller than the magnetic permeability of the ferromagnetic ring, so the magnetic field will be collected in the ferromagnetic ring through the pipe, and then passed through the pipeline to reach the test coil.

When the excitation coil is energized, the magnetic field will be generated in the space. If the shielding plate has large conductivity, the eddy current will be induced in the shielding plate. And then, the opposing magnetic field generated by the eddy current in shielding plate will weaken the magnetic field in the near field region and the transition region, and this allows the distribution of the spatial magnetic field to enter the remote field faster. The simulation model and result are shown in Fig.3 and Fig.4, respectively.

Figure 1. The model for ferromagnetic ring
Figure 2. The model for shielding plate

Figure 3. The simulation model with shielding plate and ferromagnetic ring
Figure 4. The simulation result with shielding plate and ferromagnetic ring

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The result of finite element simulation shows that the distance between the excitation coil and the test coil can be shortened after adding the shielding plate, when the thickness of shielding plate is 1mm and the distance to excitation coil is 5mm, particularly, which can shorten the distance between excitation coil and test coil by 2 times, the quantitative indicators of the simulation results of the shielding plate are shown in Tab.1.

A ferromagnetic ring is introduced outside the ferromagnetic tube to strengthen detection signal, and the magnetic flux density of test coil is stronger when the lateral distance between the ferromagnetic ring and the test coil is closer, and the height between the ferromagnetic ring and the pipe is between 10mm and 20mm. the quantitative indicators of the simulation results of the ferromagnetic ring are shown in Tab.2.

Therefore, this study can provide a direction for the structural optimization of the remote field eddy current testing device.

<table>
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<tr>
<th>Table 1. End point of the transition zone under different type</th>
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<td>End point of the transition zone (mm)</td>
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<th>Table 2. Magnetic flux density under different type</th>
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<td>Value</td>
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<td>Magnetic flux density (mT)</td>
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References

Acknowledgments
This study was supported by the National Natural Science Fund of China for International Cooperation and Exchanges (Grant No.61811530331), and China Postdoctoral Science Foundation Funded Project (Grant No. 2017M612549).
Evaluation of local wall thinning of carbon steel pipe based on multi-frequency electromagnetic field

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Abstract: This paper proposes to evaluate the local wall thinning of carbon steel pipe from multi-frequency electromagnetic field. Firstly, the feature signals are determined by correlation analysis of the signals and the wall thinning sizes. Subsequently, the models for estimating the residual wall thickness $r_t$ and wall thinning length $w$ are constructed respectively using Gaussian process regression (GPR) and linear regression. Finally, the applicability of the models to the evaluation of local wall thinning is verified by simulation and experiment.

Keywords: local wall thinning, multi-frequency, correlation, GPR, linear regression

1. Introduction
Carbon steel pipe is widely used in industrial equipment because of their high welding ability and low price, but the wall is thinned due to flow accelerated corrosion and liquid droplet impingement [1]. At present, some non-destructive testing methods have been proposed, such as conventional ultrasonic testing and eddy current testing, but the results are not very satisfactory. One of the simplest methods is to use multi-frequency measurement [2-3].

In this study, the method using multi-frequency electromagnetic field detection was proposed, and the regression models for evaluating local wall thinning are established.

2. Numerical simulation

2.1 Signal Analysis

Figure 1 presents the simulation model. The excitation frequencies are 1, 5, 10, 15 and 20 (Hz). Figure 2 respectively show the amplitude of normalized $B_z$, $\alpha$, the amplitude of normalized $B_r$ and $\beta$ along the measurement line $L_1$, where $\alpha, \beta$ are the phase differences of $B_z$, $B_r$, respectively. The extreme values of the signals are selected as the feature signals. The signals are represented by $B_{z\text{max}}$, $\alpha_{\text{min}}$, $B_{r\text{max}}$, $B_{r\text{min}}$, $\beta_{\text{max}}$, $\beta_{\text{min}}$, respectively, and subscript max, min is the maximum or minimum value at $i$Hz for more concise. Distance between the peaks and valleys of normalized $B_z$ and $\beta$ are defined respectively as $d_1$ and $d_2$.

2.2 Correlation analysis

The correlation coefficients of $B_{z\text{max}}$, $\alpha_{\text{min}}$, $B_{r\text{max}}$, $B_{r\text{min}}$, $\beta_{\text{max}}$, $\beta_{\text{min}}$, and $r_t$ are greater than 0.75, wherein $B_{z\text{max}}$, $\alpha_{\text{min}10}$, $B_{r\text{min}}$ and $\beta_{\text{min}20}$ have the highest correlation with $r_t$ in the respective signals. The correlation coefficients of $d_1$, $d_2$ and $w$ are greater than 0.99, wherein $d_2$ (15 Hz) has the highest correlation with $w$.

2.3 Evaluating local wall thinning

According to correlation analysis, the correlation between $B_{z\text{max}}$, $\alpha_{\text{min}10}$, $B_{r\text{min}}$, $\beta_{\text{min}20}$ and $r_t$ is high. The relationship between them through GPR can be expressed as:

$$y = f(X) + \epsilon$$

Where $y$ is the vector of $r_t$, $X$ is the feature signals matrix, $\epsilon$ is Gaussian noise. Figure 3-a shows the evaluation of the model. The root mean square error (RMSE) is 0.016, indicating that the model can evaluate $r_t$ well.
From the correlation analysis above, it is known that $d_2$ (15 Hz) has the highest correlation with $w$, after linear regression analysis, $d_2$ (15Hz) and $w$ satisfy a linear regression relationship:

$$y = ax + b$$

Where $y$ is $w$, $X$ is $d_2$(15Hz), and $a$, $b$ are regression coefficients. Figure 3-b shows the evaluation effect of the model. The root mean square error (RMSE) is 0.564, indicating that the model can evaluate $w$ well.

Figure 1. Schematic of numerical simulation

Figure 2. The change of signals along $L_1$

Figure 3. Compare the true and estimated of $rt$

Figure 4. Compare the true and estimated of $w$

3. Experimental verification

The experimental verification was carried out. Figure 4-a shows the results of evaluating $rt$, RMSE = 0.497, and Figure 4-b shows the results of evaluating $w$, RMSE = 2.724. The evaluated values of $rt$, $w$ are close to the true values, indicating that the above regression models can well evaluate the local wall thinning.

4. Conclusion

This paper mainly uses multi-frequency electromagnetic fields to evaluate local wall thinning. The models for evaluating $rt$, $w$ are established respectively based on the regression analysis, and the validity of the models is verified by simulation and experiment.

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The authors would like to thank Tohoku University for the JASSO Scholarship and the chance.

References


DEVELOPMENT OF A SIGNAL PROCESSING METHOD FOR METAL PIPE INSPECTION USING MULTI-MODE MICROWAVES

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Abstract

A piping system is one of the most crucial components of the power plants. Although various nondestructive methods have been proposed to maintain their safety, most of conventional methods consume a large amount of time to scan because of the complexity and hugeness of the piping systems. In order to enable the quick inspection, a nondestructive microwave testing method has been proposed[1,2]. The basic principle of this method is to propagate microwaves as a pulse into a pipe and locate flaws by evaluating their time-of-flight (TOF). Generally, generating a sharp pulse in the time domain requires providing a wide bandwidth in the frequency domain. On the other hand, multiple modes can propagate into a circular pipe in the higher frequency region, which makes signals complicated due to their individual dispersibilities. Although a signal processing method has been developed to compensate the dispersion[3], this method is available only for the single-mode propagation. Therefore, the operational frequency ranges of mode converters were limited to the low frequency region[4,5]. To remove this limitation and widen the available frequency bandwidth, this study developed a new procedure to detect the signals from a flaw even though multiple modes propagate.

Figure 1 shows the flow chart of the new procedure. ‘F’ and ‘T’ stand for signals in the frequency domain and the time domain, respectively. This is developed to extract the signal caused by the propagation of each predicted mode. On the assumption that microwaves went as $X_1$ mode (in-bound) and backed as $X_2$ mode (out-bound) with the traveling distance $L$, the signal that corresponds to the assumption $F_3$ is extracted and deducted from the original signal $F_0$. Then the deducted signal $F_0 - F_3$ is defined as $F_0$ anew. This routine is repeated for each predicted $X_1$, $X_2$ and $L$ which are not desirable. Finally, the processed signal is obtained by conducting the step 2 on the assumption that $X_1$ and $X_2$ are the desired modes.

The experiment was conducted to validate the method. The measuring system is set up to propagate microwaves inside brass pipes with the inner diameter of 19 mm from the center of the pipe to the each end, which is the same as an earlier study[5]. The mode converter (probe) was situated at the center of the measuring pipe, which mainly propagates TE-mode microwaves into the pipe two directions. A 5.5-m pipe and a 6.0-m pipe were connected to each end of the converter, respectively. In this paper, the sweeping frequency span is 20-25 GHz (3,201 points). A network analyzer (Agilent Technologies, E8363B) emitted microwaves and measured reflections as scattering parameters in the frequency domain. A slit was machined on the pipe wall at the distance of 2.0 m from the mode converter, which has an axial length of 30 mm and a width of 1.0 mm.

Figures 2 show the comparison of the peak prediction between with and without executing the new procedure for some major microwave modes. The peaks at $L_p = 2.0$ in both Figure 2(a) and (b) are the reflections at the slit. As shown in the figures, the noise was reduced by conducting the procedure. This implies that the signals are detectable even though the multi-mode microwaves exist. Further discussion will be presented at the conference.

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1. Prepare the original signal $F_0$

2. Compensate $F_0$ for the $X_1$-mode and $X_2$-mode propagation with the distance of $L$ → Signal $F_1$

3. Process IFFT to $F_1$ → Signal $T_1$

4. Multiply a window function to $T_1$ that extract the pulse → Signal $T_2$

5. Process FFT to $T_2$ → Signal $F_2$

6. Compensate $F_0$ for the $X_1$-mode and $X_2$-mode propagation with the distance of $-L$ → Signal $F_3$

7. Calculate $F_0-F_3$ → Signal $F_0$ anew

**Figure 1.** Flow chart of the new procedure

(a) Desired mode: TE$_{01}$(round-trip)
(b) Desired mode: TE$_{01}$(in-bound) and TE$_{21}$(out-bound)

**Figure 2.** Comparison of the results with and without the procedure

**References**


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THICKNESS EVALUATION OF COILED TUBING USING PULSED UNIFORM ELECTROMAGNETIC FIELD

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Abstract
As for shale gas exploration in recent years, the dosage of the coiled tubing has increased dramatically[1]. In order to guarantee the safety in the process of using, it is particularly important to evaluate thickness of coiled tubing [2]. In this paper, the measurement of the thickness of the coiled tubing was investigated based on the pulsed uniform electromagnetic field detection technology. Based on the finite element software COMSOL, the coiled tubing thickness measurement model of pulse uniform electromagnetic field was developed. The decay segment of Bx signal is selected as the feature of thickness measurement, and the relationship between feature and thickness is analyzed. According to the detection characteristics of the coiled tubing, measuring probe and system for the thickness evaluation of the coiled tubing is designed and established. And a test experiment is carried out on different thickness of coiled tubing. The test results show that the detecting system can quantitatively evaluate the thickness of the coiled tubing accurately.

A thickness evaluation system of coiled tubing was built is Fig. 1, which includes instrument, axial scan table, probe, coiled tubing and computer. The probe consisted of four detection points, which were evenly arranged in the circumferential direction of the coiled tubing. The excitation source producer an pulsed voltage signal with frequency 10 HZ duty 50 % and voltage=10 V. The turns of coils were 200 total. The voltage signal was applied to the excitation coil through the power amplifier. The detection sensor is TMR, which are high sensitivity and linearity. The signal were amplified and filtered. Then the signal were converted into digital by capture card. And a thickness evaluation software were developed.

Fig 1. The experimental setup

To actually test the detectability of thickness of coiled tubing, the coiled tubing whose thickness vary from 2 mm to 4 mm with a 0.5 mm increment was shown in Fig 2. Coiled tubing was moved by the scanning gantry at 5 mm/s. Using the obtained four sets of thickness signals, the thickness of the coiled tubing was reconstructed by interpolation was shown in Fig. 3.
In this work, a novel thickness measurement method is proposed using pulsed uniform electromagnetic field detection technology. The law between thickness and feature was analysed by simulation. Coiled tubing thickness evaluation system was established. It is concluded that the thickness evaluation of coiled tubing system can realize the detection of coiled tubing thickness by different thicknesses of coiled tubing.

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PROBABILISTIC EVALUATION OF THE DETECTION CAPABILITY OF EDDY CURRENT PROBES AGAINST CORROSION PITS ON INNER SURFACE OF PRESSURE VESSEL

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Abstract
The inner surfaces of large-scale pressure vessels are commonly cladded by austenitic stainless steel in order to protect it from corrosion. However, austenitic stainless steels are susceptible to chloride ions [1]. Once the inner surface faces liquid containing chloride ions, performing non-destructive inspection quickly is necessary to maintain the soundness of pressure vessel. Eddy Current Testing (ECT) is one of the most suitable methods for this purpose because of its high inspection speed and high remote operability. However, the noise due to various factors, such as inhomogeneous property of material and rough surface of weld, leads to the uncertainty of detecting corrosion pits. It is thus reasonable to evaluate the detection capability of ECT against corrosion pits on weld probabilistically.

On the basis of this background, this study compared the detection capability of different types of ECT probes against the corrosion pits on the cladding of austenitic stainless steel with the aid of probability of detection (POD) method[2,3].

This study prepared SM490 plates cladded by US-B309L using strip electrode welding in order to simulate the inner surface of a pressure vessel. The thickness of cladding is approximately 5 mm and the width of each welding bead ranges from 5 to 7 cm. Ferrite contents of sample plates, measured by a ferrite content measurement scope (Ferrite scope FMP30, Fischer Instruments K.K), are from 4 to 8%. Artificial pits to imitate corrosion pits were fabricated by drilling; the ranges of diameters and depth are from 1 to 5 mm and from 1 to 4 mm, respectively.

Inspections to gather signals from pits on weld were conducted using a commercial ECT instrument (aect-2000N, Aswan ECT Co., Ltd). Eddy current probes used in this study are: pluspoint probe, pancake probe and uniform type eddy current probe. The length of pluspoint probe is 5 mm; the outer diameter of pancake probe is 3.2 mm; the length of exciting probe and the outer diameter of detecting coil of uniform type eddy current probe are 10 mm and 6 mm, respectively. Pluspoint and uniform type eddy current probes are put in the direction at angles of 45 degree and 90 degree to the direction of weld pass because of their directional sensitivity. The lift off and exciting frequency are 1 mm and 100 kHz, respectively. The probes were manoeuvred by an X-Y stage (Coms Co., Ltd) and scanned the surface of the plates with a 1 mm pitch.

Figure 1 shows the result of POD method from all signals measured using the pluspoint probe. The POD curve indicates that a50, a90 and a90/95 are 1.76 mm, 3.40 mm, and 3.73 mm, respectively. Figures 2 and 3 show the results of POD evaluation towards defects on the center of beads and those located between beads, respectively. In the case of defects on center of beads, a50, a90 and a90/95 are 1.81 mm, 3.39 mm and 3.84 mm, respectively, and in the case of defects between beads, a50, a90, a90/95 are 2.01 mm, 3.69 mm and 4.54 mm, respectively. The above results proclaim that the detection capability of ECT using the pluspoint probe against defects between beads is lower than against defects on center of beads, which might be attributed to the effect of lift off. The results of other probes will be presented in the conference.
Figure 1. Regression and traditional POD curve against all defects

Figure 2. Regression and traditional POD curve against defects on center of beads

Figure 3. Regression and traditional POD curve against defects between beads

References
EDDY CURRENT TESTING AS AN EVALUATION METHOD OF THE PHASE TRANSITION OF AUSTENITIC STAINLESS STEELS BY HYDROGEN CHARGING

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Abstract

Recently, hydrogen has been focused on as a cleaner energy carrier to conventional fossil fuels. For instance, hydrogen fuel cell vehicles have been rapidly developed during the past decade. However, the spread of hydrogen stations has not progressed yet because of the problem of the hydrogen embrittlement of hydrogen components.

Concerning the hydrogen embrittlement of austenitic stainless steels which widely used as materials for hydrogen components, it has been reported that there is a correlation between their stabilities of austenite phases and susceptibilities to hydrogen embrittlement[1]. Nevertheless, the mechanism of hydrogen embrittlement, especially the effect of strain-induced martensite (α’) on hydrogen embrittlement, has not been clarified in detail yet, and it is one of major issues for the spread of the hydrogen stations. Although a quantitative monitoring of an amount of α’ phase is required to clarify the correlation between the amount of α’ and hydrogen embrittlement, an in-situ measurement method of the amount of α’ has not been established.

Therefore, we focus on a kind of non-destructive evaluation methods, the eddy current testing (ECT) as an in-situ measurement method of the amount of α’ phase. ECT signal is affected by a permeability of material, so a change of an amount of α’ in the austenitic stainless steel could be evaluated by ECT signal. Actually, in the previous study, it was clarified that ECT can quantitatively detect the change of the amount of α’ with increasing a residual strain in the austenitic stainless steel (AISI 304) plate, and the possibility of in-situ measurement of the amount of α’ by ECT was suggested[2].

In this study, in order to examine the possibility of ECT as an in-situ measurement method of the change of the amount of α’ phase in austenitic stainless steels by hydrogen charging, we evaluate the phase transformation of hydrogen-charged austenitic stainless steel. ECT is applied to the specimens with different amounts of plastic strain to evaluate the change of the relative permeability of the specimens.

Figure 1 shows the dimensions of the specimens used in this study. AISI304 plate was processed into a dog-bone-type tensile specimen. Hydrogen was charged into this specimen by using a high pressure hydrogen vessel for 300 hours in hydrogen gas. The temperature and the gas pressure were 270°C and 100 MPa, respectively. Next, slow strain rate tensile tests

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were performed on the specimens at a strain rate of $5.0 \times 10^{-4}$ s$^{-1}$ to investigate the effect of the hydrogen charging on phase transformation. The applied plastic strain $\varepsilon$ was varied to 8, 10, 13, 15, 18, 20, 22%, and eight kinds of specimens were prepared.

Figure 2 show a schematic illustration of an experimental setup of ECT. A transmitter-receiver type probe consists of two identical coils was used. The outer and the inner diameter, the height, and the turns of the coils are 1.77 mm, 0.77 mm, 2.5 mm, and 410, respectively. A distance of the two coils is 2.0 mm. The ECT signal was obtained by placing the probe on the reduced section of the specimen.

To estimate the relative permeability of the specimens with different strains, the electromagnetic field analysis based on a deformed magnetic vector potential method was performed with changing the relative permeability of the material. The results of the analysis and the ECT signals obtained by experiments were compared and the relative permeability of the specimens was calculated by interpolating the analysed results. Figure 3 shows the relative permeability of the specimens as a function of the applied strain. Regardless with or without hydrogen charging, the relative permeability of the specimens increased with increasing the applied plastic strain. It appears that the increase of the relative permeability of the samples was caused by the increase of the amount of $\alpha'$, which is the magnetic phase, by the strain-induced martensitic transformation of the austenite phase by applying the plastic strain. Moreover, an increase of the magnetic phase by only hydrogen charging was suggested because the relative permeability of the hydrogen-charged specimens were larger than these of the uncharged specimens even applied strains were same.

From these results, it was clarified that ECT can evaluate the phase transformation of AISI304 caused by the hydrogen charging and the strain application, and the possibility of ECT as an in-situ measurement method of the amount of $\alpha'$ in austenitic stainless steels was suggested. However, further analysis is needed to measure the amount of $\alpha'$. In the presentation, we will show the results of the analysis for $\alpha'$ phase determination, and will discuss the relation between ECT signal and the amount of $\alpha'$ in more detail.

**References**


**Acknowledgements**

This work was partly supported by JKA and its promotion funds from KEIRIN RACE (No. 158), “Research and development on visualization by electromagnetic sensing of hydrogen embrittlement process of austenitic stainless steel auxiliary project.”
THE AUTOMATIC INSPECTION OF PHOTOVOLTAIC CELL BASED ON CNN AND THE REGISTRATION OF EL AND ET IMAGES

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Abstract: In the production of photovoltaic (PV) wafer, cell and module, the quality control is essential. This paper aims to detect these defects with the pixel-level registration of electroluminescence (EL) and electro-thermography (ET) images. EL is able to detect the abnormal luminescent spot quickly while ET can capture the abnormal hot spot effectively. Then deep convolutional neural network (CNN) is used to classify the registered images in patch level. We have tested a ResNet-based CNN and a VGG-based CNN on the registered images. The results show that applying ResNet-based CNN on registered image can realize accurate and automatic PV inspection.

Keywords: Photovoltaic cell inspection; electroluminescence; electro-thermography; image registration; deep convolutional neural network

In the production and manufacturing process of photovoltaic cells, damage will inevitably occur, and these damages will affect the efficiency and durability of photovoltaic cells. Therefore, it is necessary for the factory inspection of photovoltaic cells. This paper aims to realize accurate and automatic inspection of PV based on CNN and the registration of EL and ET images.

Figure 1 shows thermal images and short-wave infrared images under positive and negative biases collected during the experiment. Applying a certain positive voltage to a photovoltaic cell, the internal PN junction is turned on, the electrons and holes are combined, and the photons are radiated to luminescence (EL), which is called electroluminescence (EL). Applying a negative voltage to a photovoltaic cell, those defects with lower breakdown voltage will breakdown first and the temperature rises sharply, which is called electro-thermography (ET). According to the experimental phenomenon, this paper mainly deals with short-wave infrared imaging under positive bias and thermal imaging under negative bias.

![Figure 1. ET and EL images under positive and negative bias](image)

To achieve the pixel-level registration, we have used hough transform considering the contour of PV cell. For normal hough transform is sensitive to parameters, we combine the sample pyramid and hough transform to overcome this shortcoming. The algorithm is detailed as follows and illustrated in Figure 2.

1. Use gaussian pyramid to down sample and up sample twice to get five images of different sizes.
2. Apply normal hough transform to each image and get the intersection of all hough lines within the image coordination limitation.
3. Find the area and center coordinate of max outline consisted of the intersections.

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4. Use pauta criterion ($3\sigma$) to get rid of outliers and average the others.
5. Use least square method to fit the transform matrix to normalize the image size to $256\times 256$.
6. Warp the image sequence with the transform matrix.

![Figure 2. Registration based on pyramid hough transform](image)

After the registration, principle component analysis (PCA) algorithm is used to compute the sequence, select the second frame of PCA data for deep learning. As shown in figure 3, the images are labeled in patch level of $32\times 32$. The image patches are classified into three classes, non-defects, artificial defects, and internal defects. There are 32 PV cells, each of which is divided into $8\times 8$ patch. Therefore, $2048\times 32\times 32\times 4$ patches are to be learned by the residual network[1] (ReNet). Data augment are to used to make the quantity of each class equal. Train sets and test sets are allocated by 5:1.

![Figure 3. Patch level classification using ResNet](image)

Accuracy is selected as the parameter to evaluate the results. Besides, we have built another VGG[2]-based CNN as comparison shown in figure 4. It shown that the ResNet-based CNN is much better than the VGG-based CNN on accuracy. Combining ResNet and image registration is able to inspect PV accurately and automatically.

![Figure 4. Accuracy of ResNet and VGG](image)

**References**


**Acknowledgments**

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APPLICATION OF ARTIFICIAL NEURAL NETWORKS IN FAULT DETECTION AND DIAGNOSIS: THE CASE OF ARTIFICIAL INTELLIGENCE IN MONITORING MECHANICAL STRUCTURES

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Abstract

The monitoring and diagnosing of mechanical structures to detect faults are important problems for engineers based on the systems and facilities that they build. On a vast scale, these can cause significant uncomfortable in the process and commit unacceptable malfunctions. Meanwhile, detection is very complicated, because these defect sometimes may depend on many factors that may sometimes seem impossible to identify. Since fault must be accurately located and then prevent its causes, this is where an Artificial Intelligence comes into action. In this current research work, we developed an Artificial Neural Network model to predict the malfunction of a liquid ultrasonic flowmeter based on features such as flatness ratio, symmetry, crossflow, speed of sound in each of the eight paths, average speed of sound in all eight paths and gain at both ends of each of the eight paths. The deep neural network was implemented based on three dense layers with two dropout regularization. The model was then evaluated using 10-fold cross validation and the optimal and best model was selected at batch size of 25, 500 epochs and using the Root Mean Square Prop optimizer. The model achieved an accuracy of 95% which to the best of our knowledge deemed fit to detect fault and diagnose a liquid ultrasonic flowmeter. Artificial Intelligence is currently shaping the future of Nondestructive Evaluation, and not having the intention to replace the human force work but rather to assist NDT inspectors and provide better and good performances to mechanical systems.

Introduction

![Diagram](image)

Figure 1. The process of Fault detection [2]. The measurements consist of the expert knowledge generic to the system. The features, decisions and classes are based on machine learning techniques

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Results

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<th>Layer (type)</th>
<th>Output Shape</th>
<th>Param #</th>
</tr>
</thead>
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<tr>
<td>dropout_15 (Dropout)</td>
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<td>0</td>
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<td>dense_29 (Dense)</td>
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<tr>
<td>dropout_16 (Dropout)</td>
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<td>0</td>
</tr>
<tr>
<td>dense_30 (Dense)</td>
<td>(None, 1)</td>
<td>7</td>
</tr>
</tbody>
</table>

Total params: 271
Trainable params: 271
Non-trainable params: 0

Figure 2. The summary of the architecture of the neural network.

Figure 3. The last eight (8) epochs of the model and its error rates

<table>
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<th>f1-score</th>
<th>support</th>
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<td>0.94</td>
<td>0.94</td>
<td>18</td>
</tr>
</tbody>
</table>

Figure 4. The accuracy of the model based on the testing data.

References

A0190 Multilayer CFRP fiber orientation characterization using FEM and eddy current pulse compression thermography

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Abstract: Eddy current stimulated thermography techniques are one of the important NDT techniques for ensuring the integrity and safe operation of aerospace composite components. However, thermography techniques can only inspect surface thermal distribution and reconstruction of layer information at various depths is challenging due to anisotropic thermal diffusion caused by heterogenous structure of CFRP. This paper extracts the layer information by the implementation of carbon fiber orientation segmentation using eddy current pulse compression thermography. The multilayer anisotropic CFRP is firstly modelled by FEM method to obtain the simulated surface thermal distribution and the mapping matrix from time to space. Experiment of benchmark sample with layers of different orientations is conducted by ECPuCT system. The iterative calculation between simulation and experiment is conducted to reconstruct the thermal distribution in time. After that, layer reconstruction is applied by mapping the data in time to data in space. Results indicate the good agreement between FEM modelling with experiment and layer information can be reconstructed by proposed methods.

Keywords: Eddy Current stimulated Thermography, Multiplayer CFRP, FEM modelling, Iterative Calculation

1. Introduction

Eddy current stimulated thermography has been widely used for detection, imaging, and sizing of structural imperfections for CFRP aerospace components. Applications range from diagnosis of delaminations[1], impact damage[2-4], and to material characterization[5, 6]. The distinct advantage of Eddy Current stimulated Thermography (ECPT) over other AT techniques is that in most of the cases the stimulation can be considered volumetric due to the low electrical conductivity of CFRP. Depending on the excitation frequency of the eddy current and the sample thickness, the typical eddy current (EC) skin depths are greater than or comparable to the sample thickness [7]. Despite of the advantages of volumetric heating for layers in composites, the infrared camera can only inspect surface thermal distribution, reconstruction of layer at different depths for providing comprehensive view of the component integrity highly rely on time reversal on transient response (e.g. virtual wave concept [8]). While characterization of transient response is severely influenced by anisotropic thermal diffusion caused by heterogenous structure of CFRP, it is less accurate and computation-expensive to perform time-inverse reconstruction.

To tackle with these challenges, this work used FEM method to simulate multilayer CFRP to obtain the simulated surface thermal distribution and the mapping matrix from time to space. After simulation, the benchmark sample is excited by eddy current pulse compression thermography system which can help increase the image SNR to retrieve the impulse response. The layer information is reconstructed by mapping from time and space based on iterative calculated surface thermal distribution.
Fig 1 System diagram

Fig 2 FEM modelling results : (a) Temperature field (b) Layer response at 1-4 layers.

Acknowledgments

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Reference
A0192 Robot-aided Micromagnetic Testing System for Complex Automobile Body Components

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Abstract

The mechanical properties such as yield strength, elongation, etc., of the automobile body components is directly related with the anti-collision performances of the automobile. Therefore, evaluation of the mechanical properties of the automobile body components is quite important for the quality control in the automobile body component manufacturing. Currently, most of the automobile body components are made from ferromagnetic advanced high-strength steels[1]. Numerous studies[2-6] have been reported that micromagnetic testing methods can be applied for nondestructively evaluate the microstructural changes and the mechanical properties of ferromagnetic materials.

In general, micromagnetic testing methods are performed by measuring the magnetic Barkhausen noise (MBN), incremental permeability, tangential magnetic field, etc., to characterize the target properties, such as microstructures, mechanical properties and residual stress, etc[7]. The traditional micromagnetic testing systems only support point-by-point test. To apply micromagnetic measurements for complex components, robot-aided system is required to achieve surface scan to the components.

In this study, a self-developed micromagnetic testing system is combined with a ABB IRB 1200-5/0.9 robot, which is capable of carrying the sensor to conduct curve scanning to complex automobile body components. The entire system is shown in Fig.1a. The micromagnetic testing system is composed of a multifunction sensor and a signal generation and acquisition board which is constructed by NI series host and cards. The operation of the entire system is commanded by the LabVIEW program. The multifunction sensor is made of a U-shape magnetic yoke, an excitation coil, a MBN receiving coil and a Hall element. A clamp is used to connect the sensor with the beam end of the robot.

![Figure 1. Pictures of a) the entire system and b) automobile door component](image)

1- micromagnetic testing system;2- multifunction micromagnetic sensor;3- robot; 4- automobile door component

The scan path of the sensor along the component surface is pre-derived by using the teaching program mode of the robot. The actual scan path crossing a recessed area in an automobile door is shown in Fig.1b. During the curve scan process, simultaneous measurements of MBN and tangential magnetic field are performed under the magnetization field with a frequency of

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5Hz. MBN butterfly curves are drawn using the measured signals. The values of the features of MBN butterfly curves, Hcm and Mmax, are extracted. The dependency of the values of Hcm and Mmax on the scanned positions are respectively shown in Fig.2a and Fig.2b. The error bar of the data is very short, which represents the robot-aided micromagnetic testing system is stable for measuring the MBN signals from the complex automobile body components.

In future, the relationship between the MBN features and the microstructural changes or the mechanical properties or residual stress will be investigated by careful experiments.

![Figure 2](image-url). The results of the parameters of a) Hcm and b) Mmax measured at different positions

References

Acknowledgments
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MODELING OF THE TRANSDUCTION OF ELECTROMAGNETIC ACOUSTIC TRANSDUCERS OPERATING ON FERROMAGNETIC MATERIALS BASED ON EQUIVALENT SURFACE FORCE

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Abstract
Due to characteristics of non-contact transduction, the inspection using the electromagnetic acoustic transducers (EMAT) can do the ultrasonic test with removing coating of specimen [1]. This advantage makes EMAT suit for the steel structure inspection in the complex environment. There are three mechanisms on the transduction of EMAT on ferromagnetic materials, Lorentz force, magnetic force and magnetostriction. Studies show that Lorentz force is the dominant mechanism when the bias magnetic field is normal to the specimen and the magnetostriction is the dominant mechanism when the bias magnetic field is parallel to the specimen [2]. However, some application of EMAT need to consider these three mechanisms to get precise acoustic field, because the bias magnetic field are not uniform. The finite element model of EMAT include these three mechanisms is complex and the computational efficiency is very low. It is due to that the Lorentz force and magnetic force are body force and magnetostrictive strain in the EMAT finite element model. The method improve the computational efficiency and make the model can be used in a large analysis.

The figure 1 shows the EMAT used in this paper. It consists of a cylinder magnet, two spiral plane coil for generation and detection respectively and are used for preload measurement [3]. This EMAT on the end of a bolt are modeled by a cylindrical coordinate system. The specification of the bolt is M24X150. The equivalent surface force of Lorentz force, magnetic force can be calculated easily by an integral along the direction of depth, which is direction of Z axis. Due to the skin effect of eddy current, the depth of body force is much smaller than the wave length. Therefore, the error produced by the equivalence is small. The magnetostriction can generate four different strains in the specimen. The equivalent surface force of the magnetostriction is the sum of four equivalent surface force. Equation 1 shows the r axis component and z axis component of the equivalent surface force of the magnetostriction.

Figure 1. The structure of EMAT

Figure 2 The geometry of EMAT model

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\[ P_{r}^{MS} = P_{r,1} + P_{r,2} + P_{r,3} + P_{r,4} \]
\[ P_{z}^{MS} = P_{z,1} + P_{z,2} + P_{z,3} + P_{z,4} \]  
(1)

Where subscript 1 stand for strain \( \varepsilon_{rr}^{MS} \), 2 stand for strain \( \varepsilon_{\phi\phi}^{MS} \), 3 stand for strain \( \varepsilon_{zz}^{MS} \), 4 stand for strain \( \varepsilon_{rz}^{MS} \). Analyzing the boundary conditions and constitutive relation, the equivalent surface force of strain \( \varepsilon_{rr}^{MS} \) can be obtained.

\[ P_{z,3} = \frac{\lambda}{2(\lambda + 2\mu)} \rho d_{33} \delta^2 f(r) e^{\frac{\varepsilon_{rr}}{2}} \]  
(2)

Where \( f(r) \) is distribution r component of dynamic field intensity, \( d_{33} \) is a number of magnetostrictive matrix. The other term of equation 1 can be obtained in same way.

The displacements on the end which have the EMAT are shown in the figure 2. The waves are generated by the EMAT and are reflected by another end. The mode conversion is appeared and produces the echo wave on the 80us. The figure 3 is the experimental results of the EMAT on a M24X150 bolt. Due to the thread which is not exist in FEM model, the noise is large. However, several mode conversion waves can be observed in the simulation result and experimental result. It is proved that the method of equivalent force is valid. The method can be used in the analysis of EMAT test with a large specimen.

![Figure 2](image1.jpg)  
**Figure 2.** The r axis (left) and z axis (right) displacement on the end of bolt calculated by FEM model based on equivalent surface force.

![Figure 3](image2.jpg)  
**Figure 3.** The experimental result of the EMAT. The right picture change the amplitude for observing the mode conversion echo.

References


Acknowledgments

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CRACK SHAPE RECONSTRUCTION USING AN ADAPTIVE GENETIC ALGORITHM FROM MULTI-FREQUENCY EDDY CURRENT TESTING SIGNALS

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Abstract

In the regular nondestructive testing for key structural components of nuclear power plants, quantitative evaluation of stress corrosion cracking (SCC) profile is necessary to guarantee both the safety and high efficient operation when SCC occurs. SCC reconstruction often occurs multiple local optimal solutions due to its complicated property and ill-posedness of the inverse problem [1]. In order to improve the accuracy and efficiency of SCC reconstruction, the relation between features of multi-frequency eddy current testing (ECT) signals and SCC parameters was investigated through numerical simulation. Numerical results showed that ECT signals of different excitation frequencies varied differently with the change of crack parameters, especially the change of the crack conductivity distribution. Therefore, in order to fully exploit measured information, multi-frequency ECT signals are used to crack reconstruction, in which it is defined as an optimization problem of mean-squared residual

\[ \text{min } \epsilon(c, \sigma) = \sum_{i} \sum_{j} |Z_{ij}(c, \sigma) - Z_{ij}^{obs}|^2, \tag{1} \]

where \(Z_{ij}(c, \sigma)\) and \(Z_{ij}^{obs}\) respectively are the calculated signals and measured values at the \(i\)th scanning point corresponding to the excitation frequency \(j\), which have been normalized; \(c\) is a vector of the crack shape parameters, and \(\sigma\) is a conductivity distribution vector.

SCC parameters that need to be reconstructed include the crack shape parameters and the conductivity distribution in the depth direction. The crack shape parameters only comprise the crack depth and length; the crack width is fixed to a certain value in this paper [2-4]. This is a multi-variable optimization problem and genetic algorithm (GA) is suitable for solving it. However, as the number of variables increases, the search space increases dramatically and it tends to converge to a local optimal solution.

According to the correlation analysis between features of ECT signals and SCC parameters, although the crack conductivity and depth had similar effect on ECT signals, the influence of crack conductivity on ECT signals could not be effectively replaced by changing the crack depth. Therefore, an adaptive genetic algorithm is proposed for the multi-variable optimization problem by continuously adjusting range of the solution space and discrete precision for each crack conductivity parameter. The basic flows of the proposed strategy are as follows:

Step 1 The possible range of solution for each crack conductivity parameter is divided evenly into 10 values. The length and depth of the crack are uniformly dispersed according to a certain precision within their respective feasible solutions. The conductivity and shape parameters of the crack are coded.

Step 2 \(N\) individuals were randomly selected as the initial population. Using GA to search for the optimal solution of crack parameters. After a certain number of generations, the
optimal fitness value and the corresponding crack parameters are recorded. Go to Step 3.

Step 3 If the terminate condition is satisfied, output the best solution; if not, find the value of each crack conductivity corresponding to the optimal fitness; with the value of each crack conductivity as the center, the possible solution range of each crack conductivity is reduced by half; return to Step 1.

The main implementation procedure of GA for SCC reconstruction are as follows:

1) Coding: Each potential solution to this problem is represented in binary as a string of 0s and 1s, and the value of a string is known as a chromosome. For a two-dimensional rectangular crack model, the crack shape parameters only comprise the crack depth and two crack edges in the crack length direction. For example, if defining the range of the crack length is [-6, 6] and the required accuracy is 0.2 mm, a crack edge in the length direction needs a string of 6 bits. For a string of 6 bits, the parameter of one crack edge \( x \) can be parameterized as a decimal integer

\[
M = \frac{2^6 - 1}{12}(x + 6).
\]  

(2)

Similarly, if defining the range of crack depth is [0, 5] and the required accuracy is 0.1 mm, the depth parameter needs a string of 6 bits; if defining the initial range of a crack relative conductivity is [0, 1] and the required accuracy is 0.1, the crack conductivity parameter needs a string of 4 bits. If 3 conductivity parameters in the crack depth direction are used for SCC reconstruction, the full length of crack parameters coding is 30 binary bits.

2) Fitness function: The objective function can be easily converted into the fitness function by the following

\[
f_i = C_{\text{max}} - \varepsilon_i,
\]  

(3)

where \( f_i \) is the fitness function of the \( i \)th individual, \( \varepsilon_i \) is the mean-squared residual corresponding to the \( i \)th individual, and \( C_{\text{max}} \) is a constant large enough.

3) Genetic operators:

Replication is the basic operation of GA and the excellent individuals reproduce to the next generation of new groups, which embodies the natural selection law of survival of the fittest. To avoid premature convergence, a sequential selection strategy was used in SCC reconstruction. The crossover probability and mutation probability were adjusted in real time according to fitness value in the process of evolution to improve the evolution speed and prevent the population from premature.

By continuously reducing the solution space range for each crack conductivity and improving its discrete accuracy, the reconstruction accuracy and efficiency of crack parameters are expected to be improved by using the adaptive genetic algorithm. Reconstruction results from simulated and measured ECT signals will be implemented to verify effectiveness of the proposed strategy.

References

HYBRID FORMULATION DOMAIN DECOMPOSITION FINITE ELEMENT METHOD FOR SIMULATING EDDY CURRENT TESTING

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Abstract

Simulation of eddy current testing (ECT) with scanning of ferrite-core coil using the conventional finite element method (FEM) requires remeshing as it uses one solution domain to cover all the conducting and magnetic materials, which is cumbersome and results in low computation efficiency. The authors have proposed the unitary-formulation domain decomposition finite element method (UF-DDFEM) that does not require remeshing and thereby greatly improves computation efficiency [1]. In this method, the solution domain is divided into the subdomain of test sample S₁ and the subdomain of ferrite core S₂. The subdomains are discretized separately. Both subdomains employ the \( A_r, V \) formulation where \( A_r \) and \( V \) stand for the magnetic vector potential and the electric scalar potential, respectively. In this paper, the method is improved to further increase computation efficiency. The \( A_r, V \) formulation is still used in \( S_1 \) whereas the \( \phi \) formulation is used in \( S_2 \), the latter allowing less number of unknowns to be solved. The method of employing different formulations in different subdomains is named hybrid-formulation domain decomposition finite element method (HF-DDFEM).

The solutions of the subdomains are coupled, as shown in Fig. 1. The density of the excitation current is denoted as \( J \). The magnetic vector potential (MVP) in \( S_1 \) generated by the excitation current, i.e. \( A_s \) and the magnetic field intensity in \( S_2 \) due to the excitation current, i.e. \( H_{\text{sc}} \) are calculated analytically and used as the inputs of the formulations in \( S_1 \) and \( S_2 \), respectively. \( A_r \) and \( V \) in \( S_1 \) as well as \( \phi \) in \( S_2 \) are obtained after solving the governing equations of the corresponding formulations. Then, the eddy current (EC) density \( J \) in the test sample and the magnetization \( M \) in the ferrite core are calculated. \( J \) and \( M \) are taken as another excitation sources of \( S_2 \) and \( S_1 \), respectively. The magnetic field intensity in \( S_2 \) contributed by the EC, i.e. \( H_{\text{sc}} \) and the MVP in \( S_1 \) contributed by \( M \), i.e. \( A_{\text{AM}} \) are computed analytically. The sum of \( A_s \) and \( A_{\text{AM}} \) in \( S_1 \) and the sum of \( H_{\text{sc}} \) and \( H_{\text{sc}} \) in \( S_2 \) are used as the new inputs of the formulations and \( A_r \) and \( V \) in \( S_1 \) and \( \phi \) in \( S_2 \) are updated. The iterative process stops when the calculated coil voltage converges.

Fig. 2(a) illustrates the ECT of an aluminum plate (Sample A) with fixed ferrite-core coil. The problem is solved by the UF-DDFEM and the HF-DDFEM. The coil voltages due to EC obtained by the two methods are similar. The computation time of the HF-DDFEM is 27.6% less than that of the UF-DDFEM, which proves the advantage of the new method in computing efficiency.

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Fig. 2(b) illustrates the scanning of an aluminum plate with ferrite-core coil. Three samples are tested: Sample A as shown in Fig. 2(a), Sample B as shown in Fig. 2(b) with a surface flaw of 4 mm × 0.5 mm × 2 mm, and Sample C that is identical to Sample B except that the flaw is at the bottom of the plate. The signals predicted by the UF-DDFEM and the HF-DDFEM match well as shown in Fig. 3. The computation time of the UF-DDFEM is 4.35 h and that of the HF-DDFEM is 3.13 h, respectively, indicating that the new method is superior in computation efficiency.

Experiments of the scanning testing problems are performed and the results are also shown in Fig. 3. It is seen that the experimental results are similar to the computed signals. In the magnitude signals, the surface flaw is easy to detect and the subsurface flaw is not discovered. In the phase signals, both the surface flaw and the subsurface flaw are easy to be detected.

References


Acknowledgments

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REMOTE FIELD EDDY CURRENT TESTING OF FIBER FRACTURE IN UNIDIRECTIONAL CFRP

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Abstract
Unidirectional carbon fiber reinforced polymer (CFRP) is widely used in wind turbine blade, architecture, sucker rod for oil field, etc. Fiber fracture is a common type of defect that reduces the tensile strength of CFRP and causes stress concentration. Eddy current testing of unidirectional CFRP is difficult in that the material has very small and anisotropic electrical conduction performance. Making use of the fact that the eddy current (EC) in the unidirectional CFRP varies slowly along the fiber direction [1], this paper applies the remote field eddy current (RFEC) testing technology in detecting fiber fracture. The principle of testing is illustrated in Fig. 1. The reception coil is far from the excitation coil such that the useless signal associated with the direct energy coupling between the two coils is small. Since the EC mainly flows along the fiber direction and changes slowly, the useful signal due to EC takes up a large proportion in the total signal. If there is fiber fracture, the EC will be perturbed and a measurable change in the total signal will be detected.

Figure 1. Principle of RFECT of unidirectional CFRP

A RFEC probe consisting of two pancake coils is designed. A notch of 15 mm × 1 mm × 0.42 mm is made in the unidirectional CFRP sample. The experimental results are shown in Fig. 2. The scanning signals over the notch possess dual-valley characteristic, the distance between the two minima identical to the distance between the coil axes. Another notch of 4 mm × 1 mm × 0.5 mm is made. The locations of the above two notches in the test sample are different. The notch of smaller length is not detected by the pancake-coil RFEC probe. Then the RFECT probe with rectangular coils is designed. The scanning result is shown in Fig. 3. This result implies that rectangular-coil RFEC probe has advantage in detecting short defect.
Figure 2. Experimental results of scanning unidirectional CFRP using the pancake-coil RFEC probe
(a) Testing the intact CFRP sample (b) Testing the defected CFRP sample

Figure 3. Experimental result of scanning unidirectional CFRP using the rectangular-coil RFEC probe

Reference

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Rail Damage Imaging Method with Multi-objective High Resolution Autonomous Focusing Based on Time Reverse Operator Decomposition

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Abstract

Lamb wave is a kind of ultrasonic guided wave propagating in plate structure. It has a long propagation distance, slow attenuation and is sensitive to surface defects. It has been widely used in structural health monitoring. Rail is a long-term in-service engineering structure. Using Lamb wave to monitor rail damage can timely and effectively understand the health status of rail. Rail material is an isotropic homogeneous material, but the long lateral distance and short longitudinal distance of rail waist lead to the strong reflection of lamb wave. The superposition of reflection wave and damage scattering wave will affect the arrival time of damage scattering wave. In view of the structural characteristics of rails, high range resolution can be obtained by compressing the excitation signal, which reduces the interference of the primary reflection wave from the upper and lower interfaces of rails to the scattered wave, and improves the resolution of defect recognition on the other hand. Basically, in order to effectively detect multiple damages in the monitoring area, the transfer matrix and time reversal operator are obtained by excitation and array reception. By eigenvalue decomposition of time reversal operator, the focus of different damages in the monitoring area is obtained, and the autonomous focus of multiple damages is realized.

In this paper, ABAQUS simulation data are used for analysis. Firstly, as shown in Figure 1.1, two defects are set at the rail waist. Five sensing points are set up, one is the excitation point and the other four are the receiving point. When the step signal is excited at point 1, the step response of the system can be received at the receiving point. The transfer function \(H(\omega)\) of the system can be obtained by deriving the step response. The input response of each receiving point can be obtained by convoluting the excitation signal with each transfer function.

![Figure 1.1: Compression of Excitation Signal](image)

The rail waist width is 80mm. According to Huygens-Fresnel principle, the reflection point of sound wave can be regarded as a new sound source. When the excitation point is in the center of the rail waist, besides the excitation point, the primary reflection point of the upper and lower interfaces can also be regarded as a sound source. Then the distance difference from any point in the detection area to the excitation point and the interface reflection point can be approximately half of the rail waist width, which is about 40 mm. In theory, when the
wavelength is less than 40 mm, the acoustic wave of the excitation point can be distinguished from that of the primary reflection point.

In this paper, the excitation signal of three-wave packet sinusoidal modulation signal with center frequency of 80KHz is taken as an example. The excitation signal is further compressed in the spatial domain. As shown in Fig. 1.2 (a), the spatial domain diagram of the excitation signal is uncompressed. As shown in Fig. 1.2 (b), the spatial domain diagram of the excitation signal is obtained when the distance domain width scaling factor $M = 4$.

2 Eigenvalue Decomposition of Time Inverse Operators

For convenience of description, the frequency $\omega$ is omitted in the following analysis. If the input signal is $E$ and the transfer function is $H$, then the received signal $R$ of the receiving array is:

$$R = EH;$$  \hspace{1cm} (1-1)

The received signal is processed by time reversal and then loaded to obtain the output signal of the system as follows:

$$R_t = EH^*H$$  \hspace{1cm} (1-2)

$H^*$ is a time inverse operator in the formula, and eigenvalue decomposition of the time inverse operator is carried out

$$H^*H = U \Lambda U^*$$  \hspace{1cm} (1-3)

$A$ denotes a diagonal matrix. Elements on the diagonal matrix are eigenvalues. In the case of point targets, column vectors of matrix $U$ are eigenvectors. If the target can be well distinguished by the system, the number of principal eigenvalues is equal to the number of targets. Each principal eigenvector has a one-to-one correspondence with the target. The defect of this simulation experiment is set to 5mm*10mm, which is less than half of the wavelength. It can be regarded as a point source. Figure 1.3 (a) is the waveform of eigenvector 1, and Figure 1.3 (b) is the waveform of eigenvector 2.

(a) Waveform of eigenvector 1          (b) Waveform of eigenvector 2

Figure 1.3 Focused waveform of two damages after eigenvector decomposition
References


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Analysis of Magnetic Flux Leakage In-line Inspection Data Based on Multi-sensor Data Fusion Technology

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Abstract: Pipeline inspection is an important measure to discover hidden dangers and ensure safe and reliable operation of oil and gas pipelines. Magnetic flux leakage in-line detection is the main means and trend of pipeline inspection, and inspection data analysis is the premise and guarantee of pipeline inspection results. By analyzing the inspection data, we can get the information on the type, size, shape, position and orientation of the metal loss and the pipe features. In this paper, I make up the multi-sensor composition from the multi-sensor leakage magnetic detector system, and through the distributed multi-sensor data fusion analysis technology, make the data analysis based on the respective characteristics of the signal about the master hall sensor, sub-Hall ID/OD Identification Sensor, axial mileage recording sensor, circumferential point position sensor, and auxiliary sensors such as pressure, temperature and speed of the Magnetic flux leakage in-line pipeline detector, and then perform correlation data analysis use the technology of the RBF neural network fusion, finally I completed the comprehensive analysis of the data. By the Multi-sensor data fusion technology, we can effectively improve the comprehensiveness, quality and accuracy of data analysis of the magnetic flux leakage in-line inspection.

Key words: in-line inspection; magnetic flux leakage; multi-sensor; data fusion; data analysis

1 Introduction

Pipeline inspection is an important measure to discover hidden dangers and ensure safe and reliable operation of oil and gas pipelines. Through in-line inspecting, it can be found that pipe deformation, metal increase, defects and pipe characteristics, etc[1]. At present, the magnetic flux leakage detection technology has become the most widely used and mature in-line inspection technology[2]. Data analysis of magnetic flux leakage in-line detection is the most important part of detection, and it is the premise and guarantee for providing pipeline inspection results.

Currently data analysis rely mainly on the leakage magnetic field of magnetic flux leakage main sensor signal, but defects of different geometries may produce similar magnetic field distributions. Therefore, there is uncertainty in inverting the defect geometry from the magnetic field distribution[3]. The acquisition of magnetic flux leakage detection information depends on the sensor of the detector. Data analysis using single sensor information sources has some limitations and one-sidedness. The magnetic flux leakage in-line inspection detector is a multi-sensor system. Multi-sensor data fusion analysis technology can realize the analysis and judgment of data in all directions and multiple angles. This paper analyzes the data of magnetic flux leakage in-line inspection based on multi-sensor data fusion technology. Through this technology, it can effectively improve the comprehensiveness, quality
and accuracy of data analysis.

2 Structure of multi-sensor data fusion analysis

Because there are many sensors in the Magnetic flux leakage in-line pipeline detector (including main sensor, sub sensor, circumferential clock point, axial mileage, auxiliary sensor, etc.), the classification method is adopted to separately analyze the data collected by each sensor separately. Then carry on the correlation analysis of data fusion, and finally make a comprehensive data analysis judgment.

This paper adopts a distributed data fusion analysis structure, that is, each sensor sends the detected data information to the fusion analysis center, first analyzes the local detection data according to the feature quantity, and then inputs each result from the local data analysis. Convergence analysis center to make comprehensive final decision based on the judgment of each sensor and other relevant information[4]. The distributed fusion analysis structure adopted in this paper is shown in Figure 3.

![Figure 3 Magnetic flux leakage in-line inspection data fusion analysis framework](image)

3. Conclusion

The pipeline magnetic flux leakage in-line inspection detector is a detection device of a multi-sensor integrated system. Each type of sensor has different functions, and the acquisition of pipeline inspection information depends on various types of sensors. Multi-sensor data acquisition can obtain detection information in all directions and has certain complementarity and redundancy. It can better establish the organic connection of each sensor and improve the reliability and real-time performance of the data fusion analysis system.

Multi-sensor data fusion analysis technology can effectively avoid the limitations and one-sidedness of single-sensor data analysis, while multi-sensor data fusion analysis is global and comprehensive. Multi-sensor data fusion analysis can effectively establish the connectivity and globality of each sensor, avoiding the isolation and one-sidedness of single sensor data analysis.

In this paper, distributed multi-sensor fusion analysis technology is adopted to establish the basis of data fusion analysis by the feature quantity of time domain signals of each sensor system, and the RBF neural network method is used to carry out the fusion training and analysis of feature layers. Can effectively improve the comprehensiveness, quality and accuracy of data analysis for magnetic flux leakage detection.
Tensor based Finite element model for the calculation of leakage field in magnetic flux leakage testing

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Abstract

Magnetic flux leakage (MFL) testing is a widely used electromagnetic nondestructive testing (NDT) method, which has the ability to detect both surface and sub-surface defects in conductive materials. One of its best features is its ability to mathematically model field leakage from the defect area in a magnetized material. In this paper, we propose a tensor based finite element model (TFEM), for the calculation of leakage field in MFL. This model using the Einstein’s convention eliminates the bulky nature of traditional FEM based on its matrix algebra formation allowing for easy implementation and fast calculations. The proposed model achieves this by reducing the set of matrix equations into a single equation using suffixes which can then be solved with regular mathematical operations.

Introduction

With magnetic flux leakage (MFL) testing, two basic models are used for the prediction and visualization of magnetic field interaction with defect region. The analytical model, which was the first theoretical model to relate the shape of defects with the magnetic field strength, material permeability and magnetic field leakage[1], has contributed greatly to the understanding of how the MFL technique works. Even though this model greatly simplifies the difficulties associated with MFL analysis, too many assumptions are made, making it challenging for practical applications. More so, results from this model can only explain simple and regular defects[2]. The second basic model which is widely used is the numerical model. This model has shown more advantages as compared to the analytical model for MFL. According to Lord and Hwang [3], who first introduced the finite element method (FEM) to the calculation of the magnetic leakage field, proved, through the study of how different shapes, angles, depth and width influence magnetic field. They then concluded that the only feasible solution for solving complex shape defects problems is through numerical calculation. Since then the finite element method (FEM) has been greatly explored and a lot has been achieved due to its flexibility and robustness. Even with all of its advantages, the finite element method (FEM) has its challenges, some of which include excessive need for computing resources and time depending on the number of elements to be processed, making the process time consuming and computationally expensive [4], [5].
In this paper, we proposed a tensor based finite element model which is based on Einstein’s convention for the calculation of leakage field in magnetic flux leakage (MFL) testing.

The quantitative detection of defect using MFL is a non-linear inverse problem for which the electromagnetic field applied to the material could be time harmonic[6]. The electromagnetic field which is then described using Maxwell’s equation for which a forward problem in the case of time harmonic fields can be solve.

Partial differential equations (PDEs), are a function of continuous variables in time domain. They are solved using conventional techniques taking boundary conditions into consideration. With FEM, a test function is proposed which allows for the calculation of dependent variables without having to solve the PDE. For example $\phi = V_i a^i$ is a simple test function, where $\phi$ is the potential, $V$ is the shape vector, $a$ the row vector and $i=1,2,3,4……..$, which is the Einstein’s summation convention. According to the Einstein’s summation $e_i f^i = e_1 f^1 + e_2 f^2 + e_3 f^3……..$, where $e$ and $f$ are the functions of $i$. $V$ in the test function can further be defined as $V_1 = 1, V_2 = x$ and $V_3 = y$, whiles the values of $a^i$ as $a^1 = a$, $a^2 = b$ and $a^3 = c$ where the values of $a, b$ and $c$ are unknown constants. The equation $\phi = V_i a^i$ requires a system of $i$ equations so as to solve for the unknown constants of $a^i$. For this reason, 3 different potentials representing the linear variation of $\phi = V_i a^i$ is introduced considering a triangular region of 3 nodes in space. The system of equations is then redefined as $\phi_j = G_j a^i$, where $j = 1, 2, 3$ the linear variations of nodal potentials as said earlier and $G_j$ represents the geometrical weighted tensor. The nodal potentials $\phi_j$ are unknown variables, hence the constant $a^i$ may be defined as functions of these potentials, given by $a^i = g^i_j \phi_j$ where $g^i_j = G_j^{-1}$. Combining the potentials $\phi = V_i a^i$ and $\phi_j = G_j a^i$ we obtain a linear variation of the potential with the region specified by $j = 1, 2, 3$ given as $\phi = V_j g^j_l \phi_j$ where $V_j g^j_l$ is a set of linear equations.

Conclusions
This paper presents a tensor based finite element model for the calculation of leakage fields in MFL. This model eliminates the bulky nature of traditional FEM based on matrix formation by reducing the set of matrices into a single Equation without changing the original meaning. With the proposed method, finer meshes can be generated and calculated within a short period of time with minimum computer resources.

References


EDDY CURRENT PULSED THERMOGRAPHY FOR METAL ADDITIVE MANUFACTURED PART DEFECT DETECTION

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Abstract

Additive manufacturing (AM) is a new technique used for direct part production from the data of a 3D model in the aerospace industry. However, AM process-induced defects such as porosities, lack of fusion and cracks are detrimental to a fabricated part in terms of its physical and mechanical properties. Nondestructive evaluation (NDE) is an effective approach for quality examination of the AM part. The electromagnetic properties of powder feedstocks and solid AM metal parts is potential to be used for the evaluation of surface and subsurface discontinuities. Considering complex geometry of the AM part and accessibility of detection, this paper proposes an eddy current pulsed thermography (ECPT) method for metal AM part defect detection. The mechanism of AM defects effect on eddy current and stimulated thermal responses is investigated based on multiphysics simulations. The influence of surface roughness on defect size prediction is discussed for the evaluation of surface breaking cracks. Subsurface porosities and incomplete fusion holes are simulated in order to analyze defect detection capability of the proposed method for micro-defects with difference depth and size. Results demonstrate promising feasibility of the ECPT system combining with 3D scanning measurement of complex shaped AM part for the future quantitative NDE.

1. Introduction

Additive manufacturing (AM) is a new technique rapidly developing used for direct part production and part repair of metal in the aerospace industry. Based on the AM process e.g. powder bed fusion (PBF) or directed energy deposition (DED), a part is fabricated layer by layer from the data of a 3D model. Although the AM process offers a great advantage in manufacturing complex parts, defects are inevitably introduced if any of process parameters are improperly chosen. The AM defects such as porosities, lack of fusion and cracks are detrimental to a fabricated part in terms of its physical and mechanical properties. Nondestructive evaluation (NDE) is an effective approach for quality examination of the AM part. The electromagnetic properties of powder feedstocks and solid AM metal parts is potential to be used for the evaluation of surface and subsurface discontinuities[1-3]. However, traditional NDE methods have many limitations e.g. accessibility of eddy current probe detection for complex AM parts with topology optimization design. To enable the electromagnetic imaging NDE of complex shaped part, this paper proposes an eddy current pulsed thermography (ECPT) [4-5] method for metal AM part defect detection.

2. Methodology and Results

Based on the previous studies of the ECPT [4-5], this paper carry out simulations for a typical titanium-alloy AM part by using COMSOL Multiphysics 4.3b software. A uniform electromagnetic-thermal field excitation configuration is introduced for the complex shaped AM part. Figure 1 shows preliminary simulation results of the ECPT with electromagnetic-thermal field interactions. As shown in Fig. 1(a), the applied alternating magnetic field is

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perpendicular to the induced eddy current based on the proposed uniform excitation. The induction heating field and thermal patterns around defects with different temperature values on the surface of metal AM part are shown in Fig. 1(b). It can be seen that higher temperature is presented around defective area with distinct contrast to defect free region. The defect length and orientations are clearly recognized by using thermal patterns. Based on the Fig. 1(b), there are still several ununiform heat distribution around the edges of metal AM part. Therefore, the influence of edge effect will be discussed in order to optimize the proposed excitation configuration. The surface roughness influence and the multi-physics based thermal patterns response to different subsurface porosities and incomplete fusion holes will be discussed in the full papers.

![Simulation results with electromagnetic-thermal field interactions](image)

Figure 1. Simulation results with electromagnetic-thermal field interactions. (a) Alternating magnetic field and induced eddy current distribution, (b) Induction heating field and thermal patterns around defects exist in additively manufactured metal part.

3. Conclusion and future work

The current result in Fig. 1(b) demonstrate promising feasibility of the ECPT system combining with 3D scanning measurement of complex shaped AM part for the future quantitative NDE. The material anisotropy factors along with growing direction due to layer by layer manufacturing process will be discussed in the future to optimize the ECPT approach for the electromagnetic imaging NDE of the metal AM part.

References

Abstract

Electrical steels are a key material for power apparatus in electric home appliances, industrial machinery and transport equipment. Understanding and control of the corrosion process pertaining to electrical steels’ deterioration and subsequent failure has long being a human quest. Corrosion is the gradual destructive attack of metallic materials by chemical and/or electrochemical reaction with their environment.

The most occurring faults and failures in a power transformer happen in the protection system with a failure priority number (PN) between 22 and 64 [1]. It is well documented that moisture in mineral oil cooled and insulated power transformers has detrimental effects [1][2]. Doubling the moisture content in a transformer could have the effect of halving the life expectancy of the unit, dramatically reducing the expected return on investment. This takes place during direct exposure of the transformer to air humidity at installation and repair or due to water vapour pressure difference between the atmosphere and the transformer gas space or oil. In addition to moisture, acids, bases, salts, oils, and aggressive metal polishes are examples of environments which favour the chemical combination of electrical steel to form more chemically-stable compounds with lower energy levels [3].

Of the most detrimental corrosion failure mechanisms is stress corrosion cracking (SCC). It is the cracking induced from the combined influence of tensile stress and a corrosive environment, in the form of directly applied stresses or residual stresses. Classified as a catastrophic form of corrosion, SCC features have a brittle appearance at macroscopic scales, with fine cracks whose detection can be very difficult and subsequent damage rarely predicted. SCC cracks propagate over a wide range of velocity from about $10^{-3}$ to 10 mm/h, depending upon the combination of alloy and environment involved.

The ascension of magnetic-based non-destructive testing (NDT) techniques as a result of the direct coupling between stress and magnetic field within small magnetic domain structures of ferromagnetic materials has drawn attention to an old Austrian patent of Werner [4] for magnetic characterization [5]-[10]. His invention, known as the needle probe technique, makes it possible to measure the flux density in the area surrounded by two point probes from the potential difference produced by eddy currents generated by ac magnetization [11]-[13].

This paper compares the stress corrosion cracking effects on electrical steel sheets due to surface induced-residual stresses. The test samples are five identical wrought iron strips, four of which subjected to bending stress to create 130°, 150°, 160° and 170° bending angles respectively, and a reference strip at 180°. These samples were investigated for residual stresses using the needle probe technique and then, set in a muggy environment with humidity level varying within 2 percent of 98 percent for one year.

The results show corrosion spots at the vicinity of the residual stress-induced zones on the samples. This localized corrosion gives sites for fatigue initiation which on further exposure to air humidity may lead to greatly enhanced of the fatigue crack and hence, stress corrosion cracking. The needle probe method will be use to study the stress corrosion cracking effects
on the sample electrical steel sheets. A comparative analysis will hence result to determine the rate of deterioration of the sample steel sheets. A magneto-mechanical model is equally envisaged based on the Jiles-Atherton-Sablik (JAS) model [14].

References

Using Eddy Current Testing to Assess Damage on Carbon Fiber Reinforced Polymer

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Abstract

Carbon Fiber Reinforced Plastics (CFRP) composites are becoming more and more important for several applications because of its unique combination of high strength and low weight \cite{1}. However, CFRP have a low resistance to impacts and failures of composite structures, due to low-velocity impacts, raise a maintenance concern. Unlike metals there isn’t yet any efficient and reliable nondestructive method to inspect CFRP. Therefore, the applicability of ECT is being investigated because it is a non-contact and very sensitive nondestructive method used to inspect conductive materials \cite{2-4}. Because CFRP have an inhomogeneous and low conductivity, different and new problems arise to be studied.

The present work compares the use of three different configurations of an eddy current probe to evaluate damages in a CFRP sample. The specimen to be tested is 12 mm thick, with carbon woven-fabric type fiber [90/0] for each layer. The ECT measuring system includes a two axis positioning system to perform the scan, a function generator to drive the probe, and a digital oscilloscope that acquires the voltage at the sensing coils terminals and the current in the excitation coil. Due to the low conductivity of the CFRP and to attain more induced electromotive force (emf) in the material, the ECT probe was excited with higher frequencies voltages that the traditional EC.

The architecture of the eddy current probe used to perform the experimental study is depicted in Fig. 1. It includes one coil with 160 turns in the center and two other coils with 50 turns each, in the boundaries. The three coils are identical with height equal to 4 mm, outer diameter equal to 4.5 mm and a ferrite core with 2 mm diameter.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{Information about the ECT probe and the resulting current distribution ($J_i$) : (a) Schematic representation of the probe; (b) $J_i$ when the two excitation coils are connected in series in opposite direction; (c) $J_i$ when the two excitation coils are connected in series in the same direction; (d) $J_i$ when there is only one excitation coil.}
\end{figure}

The probe was tested with three different excitation/sensing coils configurations. In the first two cases, coil 1 and coil 3 were used as excitation coils and coil 2 as sensing coil. In the first case, the excitation coils were connected in series in opposite direction to produce eddy currents below the sensing coil in a healthy sample, as depicted in Fig. 1(b). In the second case, the two excitation coils were connected in series in the same direction to produce eddy currents around the probe in a healthy sample, as depicted in Fig. 1(c). In the third and fourth cases, coil 2 was used as excitation coil and the other two coils were used as sensing coils. In the third case, the sensing coils were connected in series in opposite direction. In the fourth case, the sensing coils

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were connected in series in the same direction. The eddy current distribution produced by the excitation coil is presented in Fig. 1(d).

Fig. 2 shows the 2D maps of amplitude and phase shift of the voltage at the sensing coils obtained by scanning the ECT probe, along the y axis as depicted in Fig. 1, around a small hole with 2 mm of diameter and 1 mm of depth, with the four different probe configurations.

![2D maps of amplitude and phase shift](image)

Fig. 2 – 2D maps of the amplitude and phase shift obtained by the sensing coil/s for the four different probe configurations: (a) case 1; (b) case 2; (c) case 3; (d) case 4.

One may conclude that the hole was detected in all the cases. A change in the amplitude of the magnetic field is visible in the region of the damage. The use of two excitation/sensing coils connected in series in opposite direction gives a phase change. The higher changes in amplitude and phase were obtained when the two excitation coils were used in opposite direction. The fibers are visible when the two excitation/sensing coils are connected in series in the same direction.

**Acknowledgments**

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**References**

Wireless Power Transfer Based Eddy Current for Characterization of Crack Orientation

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Abstract: Angular cracks cause damage to a larger region in metallic structures. Their quantification, in terms of length and orientation, is advantageous for ensuring the integrity of the structure. Eddy current testing is generally used to quantify such crack. However, it provides a limited number of features for evaluation. It also uses signal amplitude, which is generally susceptible to noise. Therefore, the resonance frequency feature based on wireless power transfer (WPT) approach is proposed in this research to characterize the orientation of the cracks in a metallic sample. A three-layer, square-shaped, PCB coils with two transmitters (Tx1 and Tx2) and receiver (Rx) is designed and fabricated. The Tx1 and Tx2 are the top and bottom layer while Rx is the middle layer. The Tx1 and Tx2 are connected in differential form and serve as the transmitter (Tx). The fabricated PCB coils are configured as a resonance WPT network and excited with a sweeping frequency signal. Its responses from scanning Aluminium sample were measured for different crack orientation and validated with experimental results. The system has the frequency sensitivity to all crack’s orientation with the least sensitivity to crack oriented along the diagonal of the probe.

Keywords: Coil configuration, Eddy current, Metallic crack, Resonance frequency, Wireless power transfer

Introduction

WPT differs from other eddy current testing (ECT) approach because of its multiple resonance points due to Tx-Rx coupling effect, unlike ECT approaches that use amplitudes of non-multiple resonance features [1]. Furthermore, it employs sweep frequency excitation to solve limited penetration depth and feature variation due to inherent defect parameters which is a challenge to single frequency ECT [1]. Similarly, it overcomes the problems of shorter testing time with less power in each frequency component as exhibited by multiple-frequency ECT [1]. In comparison with pulse ECT, WPT response relies on coupling effect while pulse ECT suffers coupling variation due to lift-off. Of recent, an emerging EC testing explored sweep frequency excitation. However, it has a single resonance point and problems with a precise location of the defect. It uses inductive natural resonance which is a single point of a high-frequency range [2].

For crack orientation, an alternating current field measurement probe [3] and rotating eddy current [4] have been proposed but limited to non-ferrous metals with zero detection for crack orientation of 45° to the scan axis. Additionally, improved oscillatory rotating eddy current [5] characterized crack in both ferrous and non-ferrous materials. However, its orthogonal fields were generated by two separate coils and received by another two different coils. Our proposed Tx has two orthogonal radial fields from the same coil with sweeping frequency excitation linking single Rx. The benefit of such field is for maximum detection sensitivity to both axial and longitudinal cracks.

Method and results analysis

An FR4 substrate is used in our PCB coils fabrication. Then, configured using compensating capacitors to resonate at 180 kHz and excited with sweeping frequency from 50 to 300 kHz. An Aluminium block with five cracks each having 3mm width and oriented at 0, 30, 45, 60 and 90 degrees along the scan axis is scanned. The initial result from ANSYS is presented in this paper.

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Fig. 1(a) shows the Frequency response for different crack orientation. It has been observed that the more crack orientation approaches 90 degree the higher the eddy current influence and frequency shift. The sensitivity is almost uniform after 30-degree to less than 45-degree crack orientation. Similarly, Fig. 1(b) shows the splitting frequency nature of the normalized probe response for three different positions. The designed resonance frequency, 180 kHz split into two. It has been shown that the perpendicular crack also has the highest frequency shift because of higher eddy current influence. Fig. 2(a) shows the top layer picture of our designed PCB and (b) is the eddy current distribution for axial and perpendicular crack. It shows that the induced eddy current focuses on the outer surface and distribute unevenly about the coil center due to the inductance and other contributing factors of the sample [6].

This paper presents a novel scanning-based resonance frequency feature for crack orientation characterization. The influence of WPT splitting resonance frequencies studied in [7] has now been investigated on cracks in an Aluminium sample through our designed coils. It has been shown that the eddy current density is higher at the cracks surrounding area. Similarly, the split frequency is sensitive to crack orientation.

![Graph showing frequency deviation from no-crack position vs crack orientation](image1)

![Graph showing induced Rx voltage at crack center](image2)

**Fig. 1** (a) Frequency shift for different crack orientation   (b) Normalised Rx response for 3-position

**Fig. 2** (a) Designed PCB probe   (b) Eddy current distribution around axial and longitudinal cracks

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**References**


A SELF-SENSING WOVEN HYBRID FIBER COMPOSITE WITH CHIPLESS RFID SENSING ENABLED STRUCTURE

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Abstract

Structural health monitoring (SHM) of composites typically employs embedded sensors and materials, which introduce limitations in size, weight, cost, and adaptability to complex structures. In this paper, a self-sensing woven hybrid fiber composite with chipless RFID based sensing enabled structure is presented. The self-sensing capability is emerged due to its special structural design and configuration, which enables chipless RFID sensing. The composite structure comprises a combination of plain weave carbons, aramids, and hybrid fabrics with configured arrangement and orientation. An array of snipped hybrid fabrics is placed on carbon fabrics and aramid fabrics so that it produces multi-resonance microwave reflection at 2 to 6 GHz. The generated multiple resonances shift accordingly when structural changes occur. Hence, structural damages such as delamination in the composite can be detected and characterized through a non-contact chipless RFID reader.

Introduction

Fiber composite materials have been widely used in aerospace, construction, and automotive applications due to their excellent mechanical properties [1]. Since their structure is more complex than other metals counterparts, structural health issue becomes more relevant. Their structural complexity and anisotropy may result in unpredictable and various damages, such as matrix cracking and delamination [2]. This far, many types of sensing techniques, such as piezoelectric, fiber optics, ultrasonic, eddy current, and materials like graphene and carbon nanotubes (CNT), have been applied to evaluate and monitor the structural health of composites [3]. However, these sensors and materials introduce limitations in size, weight, cost, and adaptability to complex structures [4].

Recently, chipless RFID has gained increasing interests for sensing applications because it is passive, wireless, and operated in broadband, which enables multiparameter sensing [5], [6]. In principle, the sensing information is incorporated in resonances, i.e. notches or peaks, in the frequency signature generated by a chipless sensor tag. Whereas, such resonances behavior can also be generated by composites, particularly hybrid composite materials [7], if the structure is designed with certain arrangement and configuration. In this paper, a self-sensing [8] woven hybrid fiber composite sheet design, which can be sensed using chipless RFID principle, is introduced. The design makes the composite becomes a resonant structure and it produces multi-resonance frequency signature over the microwave range of 2 to 6 GHz. The design and effect of delamination to the frequency signature will be evaluated and discussed in this paper.

Design and Results

Design of the self-sensing woven hybrid fiber composite sheet is depicted in Figure 1. It is composed of woven carbon fabrics, aramid fabrics, and hybrid fabrics with determined layer stacking arrangement and orientation molded in the epoxy resin. The fabrics are based on plain weave fiber pattern modeled in CST Microwave Studio. The entire self-sensing composite sheet is simulated with the varied gap between fabric layers to represent...
delamination as shown in Figure 2a. The setup employs a plane wave source and a radar cross section (RCS) probe to pick up the reflection behavior of the composite sheet. The frequency signature of the composite sheet for different gap of delamination is shown in Figure 2b. It is obvious that the self-sensing composite sheet generates multiple resonances within 2 to 6 GHz. The resonances will shift, mostly to higher frequencies, as the gap of delamination increases. The variations due to multiple resonance shifts can be exploited for structural health monitoring of the composite material using a chipless RFID reader.

![Simulation setup and frequency signature of the self-sensing woven hybrid fiber composite at 2 to 6 GHz with the varied delamination](image)

**Figure 1.** Design of the self-sensing woven hybrid fiber composite

**Figure 2.** (a) Simulation setup and (b) frequency signature of the self-sensing woven hybrid fiber composite at 2 to 6 GHz with the varied delamination

### References


A PHASE MEASUREMENT BASED STRUCTURED LIGHT SENSOR FOR THE INSPECTION OF INTERNAL CORROSION OF METAL PIPES

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Abstract
Gas transmission pipelines are predominantly made of steel in the U.S. One of the many historical threats to pipelines integrity is corrosion (both internal and external corrosion). The internal corrosion can be caused by the gas composition (carbon dioxide, hydrogen sulfide, and oxygen), water and microbial influences and can be accelerated by the flow velocity and pressure [1]. In gas pipelines, the internal corrosion results in material loss that may lead to pinhole leakage, cracks, or even rupture of the pipeline [2]. While external corrosion is easy to check visually, the inner corrosion can only be checked during scheduled maintenance. To reduce the downtime during scheduled maintenance, fast and efficient corrosion detection techniques are required. In this paper, we are proposing the use of a new structured light-based scanning endoscopic system to detect and characterize the shape and size of internal corrosion in metal pipes. The system is inserted into the pipe through a main hole and then pushed along the pipe to provide the operator with a high-fidelity 3D map of the internal pipe surface. Structured light 3D profiling is used to provide the sensor with depth sensing capability. With structured light, a predefined pattern is projected on the scanned surface and the shape is reconstructed through monitoring the projected pattern deformations [3]. A new movement-based phase measurement profilometry (MPMP) technique is also proposed in this paper to exploit the movement of the sensor inside the pipe and enhance the final surface reconstruction. Phase measurement profilometry (PMP) is one of the structured light techniques, wherein phase change in the projected sinusoidal fringes is used to reconstruct the 3D shape of the scanned surface. This method produces high density 3D maps with the number of acquired 3D points equals to the number of camera pixels. The method is based on projecting a sequence of N phase-shifted patterns with a phase difference of 𝜃 between two consecutive frames. The intensity of the projected pattern on the scanned object is given by:

\[ I_n = I' + I'' \cos \left( \phi + \frac{2n\pi}{N} \right), \quad n = 0,1,2,...,N-1, \]  (1)

\[ I_n \] is the intensity of the camera pixel for shifted fringe, \( I' \) is the ambient light intensity and \( I'' \) represents the modulation signal intensity. The phase of each imaged point can be calculated by solving a set of N linear equations. With only three shifted patterns and by assuming a constant ambient light, the phase (\( \phi \)) at each image point is given by:

\[ \phi(x, y) = \arctan \left( \frac{l_1-l_3}{l_2-l_1-l_3} \right). \]  (2)

The arctan function produces a wrapped phase that ranges from \(-\pi \) to \(+\pi \). The absolute phase can then be calculated by adding a multiple of \(2\pi \) to the calculated phase in a process called phase unwrapping [4].

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In traditional PMP scanning platforms, the projected pattern is shifted digitally while having a static scanning platform and any movement during the scanning process affects the accuracy of the reconstructed profile. In our proposed platform, the entire scanning system (camera and projector) is moving along the pipe while projecting a static fringe pattern on the inner pipe wall. This movement will cause the projected pattern on the scanned object to be shifted by a distance $dx$ resulting in a phase shift of $\Delta \phi$ in the projected pattern. This phase shift varies according to the height of the scanned object and the speed of the scanning process. The resulted phase shift from the movement is then used to reconstruct the surface in a similar manner to conventional phase shifting based methods. A large-scale experimental setup is shown in Figure 1a, where we have a structured light system scanning an object with surface deformation. During the scanning process, the setup is moved with a constant speed while projecting a static pattern onto the scanned object. The image stream from the camera is then registered to compensate for the effect of the movement. An initial 3D profile of the scanned object is shown in Figure 1b. The results show that the proposed algorithm is able to reconstruct the actual shape of the scanned deformation. The results also show some artifacts that related to the nonlinear relationship between the phase distribution on the scanned surface and distance from camera. The proposed method facilitates the integration of PMP with the moving scanning platforms, which will lead to the generation high density 3D maps of the scanned pipe surfaces. This method also simplifies the design of the structured light system by eliminating the need for the active projection which enables the fabrication of small size endoscopic sensors.

References

THERMOGRAPHY DETECTION FOR HIDDEN SURFACE CRACKS IN METALS UNDER POLYMER COATINGS

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Abstract
In this paper, the non-metallic polymer coatings applied on the surface cracks in metals will be investigated. The major test was implemented by using optical method. The temperature signal of hidden surface cracks with different coating thickness both in frequency and time domain will be displayed. The optical parameters of coatings including reflectivity and absorption was explained and compared with before research.

Introduction
Optical thermography is a powerful technique to detect surface cracks in metals. The electromagnetic excited thermal wave which was firstly generated on the coating-substrate surface. This can be recorded by an infrared camera. In some cases, the covered coating may have a positive effect by increasing surface emissivity and surface homogeneity. However, it delays and damps the thermal pulse or wave on its way to the coating surface. The previous results thinks that surface cracks in turbine blades can be detected under ceramic thermal barrier coatings [1]. Other studies were focused on detection of cracks under corrosion layers on steel [2] or the detection of corrosion under paint layers [3]. Recently, cracks in steel were detected under a glued CFRP layer [4]. Polymer paint coatings on steel with surface cracks protection were less investigated. Some optical properties of coating were less discussed and therefore the experiment and results will be shown in this paper.

Methodology
Similar to consideration like the EM-wave, another thermal wave generation on the air-coating interface could be investigated by implementing pulsed optical excitation. Thermal waves generated at the air-coating surface propagate towards coating-substrate interface where they are partially reflected back towards the surface. All these reflected thermal waves then interfere with the incoming thermal waves from coating surface. The diagram of such heat transfer process can be seen as Figure 1.

Figure 1: Optical thermal generation mode

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Experiment

The optical heating was generated by using double flash lamps symmetrically placed at 20cm from lamp to sample which is coated by paint on the surface with hidden surface cracks, and the Flir SC5200 thermal detector worked with 160Hz frames rate. The distance between sample and infrared camera was set at 30cm which could get enough field of view of the surface. The single pulse length was set as 200ms after 100ms delay and the acquisition time was 2s.

Results and conclusions

Four cross indications of cracks were applied on the raw image of the beginning after optical pulsed excitation and the phase contrast is recorded as Figure 2. All the curves’ peak were cut off due to the detection ability of IR-camera but the pulse broadening at each crack position with different coating thickness could be obviously seen in Figure 3.

The IR reflectivity spectrum of each paint coating layer above the surface crack at different thickness is shown in Figure 4. The higher emissivity of black paint also has higher absorption without influence of transmittance in this case. The most thicker coating (0.15mm) has a little higher reflectivity and may also have lower absorption.

References


COMPARISON AND FUSION OF MULTI-SENSORS EDDY CURRENT IMAGES BY EXPLOITING HERMITE-GAUSSIAN PATTERN ANALYSIS

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\textsuperscript{4}Dept. of Engineering, University of Perugia, Perugia, Italy,
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Abstract

In Eddy Current Testing (ECT) a variety of sensors, excitation strategies and image processing algorithms have been developed during the last decades. Pulsed, multi-frequency, and coded signals have been optimized for different applications and a variety of feature extraction strategies have been developed to perform imaging and increase the inspection capability with respect to standard commercial ECT instruments, which are still nowadays mainly based on single-frequency excitation and Lissajous diagrams analysis.

At the same time, in the perspective of an increasing automation and integration of NDT in IoT environments, the possibility to compare, integrate and fuse the information from various sensors and imaging procedures is highly desirable. Recent strategies based on machine-learning approaches can provide a reliable solution for comparing and fusing different tests’ results [1-2], and inversion procedures can be designed to process multi-sensor data [3]. The goal of the present paper is analyzing another possible strategy that could be useful to compare, integrate and fuse ECT images. This strategy relies on the Hermite-Gauss hypothesis introduced by some of the present authors in [4] and further analyzed in [5]: for a large variety of ECT sensors and features considered, ECT 2D images of small defects in metallic non-ferromagnetic materials can be modeled as the convolution between the true defect geometrical shape and a 2D Hermite-Gauss (HG) mode pattern characteristic of the sensor. HG modes are defined by the following expression where \( A \) is a constant, \( \sigma_x \) and \( \sigma_y \) are the standard deviation of two gaussian functions related to \( x \) and \( y \) axis, \( H_n \) and \( H_m \) are the Hermite polynomials of order \( n \) and \( m \) respectively [6]:

\[
HG_{n,m}(x,y) = A * H_n \left( \frac{\sqrt{2}}{\sigma_x} * x \right) \exp\left( -\frac{x^2}{\sigma_x^2} \right) * H_m \left( \frac{\sqrt{2}}{\sigma_y} * y \right) \exp\left( -\frac{y^2}{\sigma_y^2} \right)
\]

(1)

The pair of \((m,n)\) values determine the mode, i.e. the pattern of zeros and peaks, \( \sigma_x \) and \( \sigma_y \) regulate the size of the pattern, and the \( H_k(u) \) are Hermite polynomials, e.g. \( H_0(u) = 1, H_1(u) = 2u, H_2(u) = 4u^2 - 2, H_3(u) = 8u^3 - 12u \). Any HG mode can be related to another one by multiple derivative and integration operations, all being derived from the HG\(_{0,0}\), which is a Gaussian function: \( \frac{\partial HG_{1,m}}{\partial x} = HG_{l+1,m}, \frac{\partial HG_{l,m}}{\partial y} = HG_{l,m+1} \). In [5], a literature survey of example of HG patterns emerging in ECT imaging was done. For example, the bipolar HG\(_{1,0}/HG_{0,1}\) modes are usually associated to the measure of the magnetic induction \( B_z \) component perpendicular to the sample surface, while the quadrupolar pattern HG\(_{1,1}\) and to the HG\(_{2,0}\) mode are usually associated to the other field components parallel to the surface. To further corroborate the HG hypothesis and develop suitable procedure to fuse information from various ECT images, in this work we collected measurements and extracted images with different sensors on the same Al sample (2mm thick) containing a set of small notches with 3mm length, 0.1mm width and variable depth from the surface. Three sensors and the relative image processing algorithms
developed respectively by Manchester University [7], by Cassino University in collaboration with Perugia and Calabria [5], and by Newcastle University [8] were used. Data were also collected with the commercial instrument NORTEC® 600 from Olympus. All the sensors produced over the defects exhibit typical HG patterns, even if associated to different modes. In the full paper it will be shown how the various images can be reconducted all to the same “primitive” on by proper processing. Moreover, numerical simulations will be realized to tune the image processing algorithm as well as to test the validity of the present approach to more complex 3D defects’ shape and to ferromagnetic samples.

![HG patterns and ECT images](image)

**Figure 1.** (Left) Examples of some HG patterns; (right) expected ECT images obtained for a linear crack depending on the HG pattern associated to the sensor

![ECT images](image)

**Figure 2.** ECT images obtained with the various sensors on the same defect: (a) Manchester – single-frequency-HG$_{2,0}$; (b) Newcastle-PEC-HG$_{0,1}$; (c) Cassino, Chirp - HG$_{1,1}$; (d) NORTEC®-single-freq.-HG$_{0,1}$

**References**


**Acknowledgement** This research work has been partially supported from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 722134 – NDTonAIR.
Numerical Analysis of the Effect of Varying Thickness on Transduction Efficiency of Lamb Waves

Abstract: Electromagnetic acoustic transducers (EMATs) are widely used in the field of plate inspection. However, its transduction efficiency is much lower than PZTs and needs to be improved. Compared with the plates with uniform thickness, the geometrical configuration of tapered plate is more complicated, thus having an influence on the excitation and receiving process of Lamb waves. Therefore, the effect of inclined angle of tapered plate on the transduction efficiency of Lamb waves is discussed in this paper. The 2D FEM model of excitation and reception of Lamb waves based on Lorentz mechanism is established with the help of finite element analysis software. Based on the 2D FEM model, the effect of several factors——the wire size and the lift-off distance of excitation and receiving coil——on the transduction efficiency of EMATs under the condition of various inclined angle of tapered plate is investigated to achieve the optimization design of EMATs.

Key Words: tapered plate; transduction efficiency; optimization design; finite element method

1、Introduction
Kaltenbacher M et al.\(^{[1-3]}\) improved the transduction efficiency of EMATs used to inspect waveguides with uniform thickness by the reasonable optimization design of structure parameters and dimension parameters of EMATs. L. De Marchi et al.\(^{[4-6]}\) conduct a thorough research on the propagation characteristic of guided waves propagating in the tapered waveguide. But the issue on how to improve the transduction efficiency of EMATs used to inspect the tapered waveguide remains to be studied. In addition, compared with the plate with uniform thickness, the geometrical configuration of tapered plate is more complicated, thus having an influence on the excitation and receiving process of Lamb waves. Therefore, the 2D FEM model based on Lorentz mechanism is established to investigate the effect of inclined angle of tapered plate on the transduction efficiency of Lamb waves in this paper, thus achieving the optimization design of EMATs used to inspect tapered plates.

2、Multi-physics coupling equations of EMATs based on Lorentz Mechanism
According to the equivalent magnetic charge approach, the magnetic field is produced by the magnetic charge. The surface magnetic charge density exists in the uniformly magnetized permanent magnet, but the volume magnetic charge density doesn’t. So the magnetic field equation of permanent magnet is calculated as follows:

\[
\mu \nabla^2 \varphi_m = 0 \quad (1)
\]

Where, \(\mu\) is the permeability; \(\varphi_m\) is the magnetic scalar potential.

The free charge doesn’t exist in the system combined by the coil of EMATs and the specimen to be tested. Supposed that the influence of displacement current is ignored, the dynamic magnetic field equation of pulsed eddy current is calculated as follows:

\[
\frac{1}{\mu} \nabla^2 A - \sigma \frac{\partial A}{\partial t} + \frac{1}{S} \int_s \sigma \frac{\partial A}{\partial t} ds = -\frac{i}{S} \quad (2)
\]

Where, \(A\) is the magnetic vector potential; \(\sigma\) is the conductivity; \(S\) is the cross section area of wire; \(i\) is the total current.

The elastic deformation of the specimen to be tested is produced by the Lorentz force \(f_L\). Supposed that the specimen to be tested is isotropic and is governed by the hypothesis of linear elasticity and continuity, the equations of motion of of particle is calculated as follows:

\[
G \nabla^2 u + (G + \kappa) \nabla(\nabla \cdot u) + f_L = \rho \frac{\partial^2 u}{\partial t^2} \quad (3)
\]
Where, $G$ and $\kappa$ is the Lame constant; $\mathbf{u}$ is the displacement matrix for particle; $\mathbf{f}_L$ is the Lorentz force; $\rho$ is the volume mass density.

When the ultrasound wave reaches the receiving coil of EMATs, the dynamic current is produced by the moving charged particle exposed in the external bias magnetic field, thus inducing the dynamic magnetic field inside and around the specimen to be tested. Therefore, the induced electromotive force (i.e., received signal) is generated in the receiving coil exposed in the aforesaid dynamic magnetic field. In principle, the receiving coil is usually in the open-circuit state, so the governing equation of receiving coil is calculated as follows:

$$
-\frac{1}{\mu} \nabla^2 \mathbf{A} + \sigma \frac{\partial \mathbf{A}}{\partial t} = \sigma \frac{\partial}{\partial s} \int_{\mathbf{A}} ds = \mathbf{J}_L \quad (4)
$$

Where, $\mathbf{J}_L$ is the dynamic current density, $\mathbf{J}_L = \sigma \mathbf{v} \times \mathbf{B}_0$, $\mathbf{v}$ is the velocity of charged particle, $\mathbf{B}_0$ is the bias magnetic field intensity. Electromotive force of one point inside the wire which can be calculated by the integral for electric field intensity over the length of wire gives:

$$
V_{pout} = \int -\frac{\partial \mathbf{A}}{\partial t} \cdot d\mathbf{l} \quad (5)
$$

The output voltage of receiving coil can be calculated by averaging electromotive force of one point inside the wire, so the ultrasonic received signal equation is calculated as follows:

$$
V_{out} = \frac{\iint V_{pout} dS}{\iint dS} \quad (6)
$$

3、2D FEM Model of Excitation and Reception of Lamb Waves

As shown in Fig.1, the 2D FEM model is established with the help of finite element analysis software. The size and material constant of the tapered aluminium plate to be tested in simulation is shown in Table 1.

![2D FEM Model of Excitation and Reception of Lamb Waves](image)

Table 1  The Size and Material Constant of the Tapered Aluminium Plate to be Tested in Simulation

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>200mm</td>
<td>Conductivity</td>
<td>3.5E-7S/m</td>
</tr>
<tr>
<td>Width</td>
<td>200mm</td>
<td>Elasticity modulus</td>
<td>70Gpa</td>
</tr>
<tr>
<td>Thickness</td>
<td>3mm</td>
<td>Poisson's ratio</td>
<td>0.33</td>
</tr>
</tbody>
</table>

4、Simulation and Results

4.1、The Effect of Wire Size of the Excitation Coil
Fig.2 The Effect of Wire Size of the Excitation Coil on the Transduction Efficiency of Lamb Waves under the condition of varying inclined angles of the Tapered Aluminium Plate

4.2 The Effect of Wire Size of the Receiving Coil

Fig.3 The Effect of Wire Size of the Receiving Coil on the Transduction Efficiency of Lamb Waves under the condition of varying inclined angles of the Tapered Aluminium Plate

4.3 The Effect of Lift-off Distance of the Excitation and Receiving Coils

Fig.4 The Effect of Lift-off Distance of the Excitation and Receiving Coils on the Transduction Efficiency of Lamb Waves under the condition of varying inclined angles of the Tapered Aluminium Plate

5 Conclusion

(1) Under the condition of the same inclined angle of tapered plate, the transduction efficiency of EMATs is improved with the increase of the width $w_d$ and thickness $h_d$ of the wire of excitation coil and is enhanced with the decrease of the width $w_d$ and thickness $h_d$ of the wire of receiving coil and is remarkably increased with the decrease of the lift-off distance $h_l$.

(2) Under the condition of the same size of the wire and the same lift-off distance of transducers, the transduction efficiency of EMATs is reduced with the increase of the inclined angle of tapered plate at the inclined angle of $3^\circ$ or lower and tends to be enhanced when the inclined angle is from $3^\circ$ to $5^\circ$. 
(3) The sensitivity of transduction efficiency to the variation of the wire size and the lift-off distance of excitation and receiving coil declines gradually with the increase of inclined angle at the inclined angle of 3° or lower and tends to be improved when the inclined angle is from 3° to 5°.

6. Reference
EFFICIENT CALCULATION OF TRANSIENT EDDY CURRENT RESPONSE FROM CYLINDRICAL CONDUCTIVE MEDIA

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Abstract

In transient or pulsed eddy-current testing (PECT), the excitation coil is usually driven by a pulsed current and the eddy current response is sensed by the same coil or another pickup coil or by magnetic field sensors. Among other applications, PECT has been used in monitoring pipe wall thinning since the growing field experience has demonstrated that PECT is effective for that matter [1-2]. An important feature of the signal is its decay behavior which can be used for the quantitative evaluation of pipe wall thinning due to corrosion. The signal from a thinner pipe wall decays faster than that of a thicker one. Hence, there is a need for accurate evaluation of the response signal in the so called "long time domain".

Nevertheless, the theoretical study and analysis of PECT of cylindrical structures such as insulated pipes is insufficient. It is interesting that such studies are usually of numerical nature while analytical and semi-analytical ones limit themselves to the description of simplified configurations. The main simplification assumes a pipe diameter that is significantly larger than that of the excitation coil in order to model the configuration as a planar geometry [2-3]. Moreover, the transient signal is modeled as a summation of harmonic signals owing to the Fourier superposition principle.

In this work, we study cylindrical structures and for the calculation of the transient excitation we focus on Laplace rather than on Fourier transform in order to avoid Gibb's phenomenon and also describe accurately the long time response. The use of Laplace transform requires an efficient method for inverting the frequency domain expressions to time domain. Various methods can be used for the Laplace inversion [4], depending on the characteristics of the expected time domain signal.

![Diagram](image)

**Figure 1.** Inspection of a layered cylindrical system. In the absence of the inner layers the coil is bobbin (ID). In the absence of the outer layers the coil is encircling (OD). In both cases the coil is driven by a pulsed current.

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In this work, only axisymmetric configurations are studied. Excitation has the form of a coil outside a cylindrical bar and a tube and a coil inside a hole in a conductive space and a tube.

The residue theorem is ideal for the so called "long time" calculation since only a few poles need to be found for the accurate description of the transient signal. An important finding is that the poles are all real, leading thus, as expected, to diffusion modes that are decaying. Suitable methods are utilized for bracketing the poles prior to their exact calculation, following in part the method developed in [5]. A similar approach has been adopted also in [6].

Moreover, for the "short time" signal calculation we use a number of special methods such as Stehfest's or Zakian's [4]. All these methods are tested against purely numerical Laplace inversion. Comparison in terms of accuracy and computation time is provided.

References


Acknowledgments
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RESEARCH ON STRESS DETECTION OF DC01 STEEL VIA BARKHAUSEN NOISE

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Abstract
In this paper, the magnetic Barkhausen noise (MBN) method is used to evaluate the stress of DC01 steel. Combined with the magnetic domain theory and magnetization theory, this work analyzed the MBN signal at the microscopic level from the energy point of view. Quantitatively analyze the correspondence between the tensile stress and MBN signal.

Introduction
Ding S et al. [1] used Magnetic Barkhausen noise (MBN) to investigated the Q235 steel specimens under compressive and tensile applied-stress. The stress effect of single domain crystals was analyzed by Baudouin [2] and Ziman J [3]. Based on the examined data of the sample, this work was divided into two categories: the first one was related to the determination of tensile stress, whereas the second one was related to the energy distribution.

Methodology
Applied stress can be expressed as an additional magnetic field $H_\sigma$:

$$H_\sigma = \frac{3b\sigma M}{\mu_0} \tag{1}$$

Where $M$ is the magnetization and $b$ is the second-order magnetostrictive coefficient, $\mu_0$ represent the vacuum permeability, $\sigma$ is the strength of applied stress.

$s(t)$ is the original signal, $s'_1, s'_2, ..., s'_J$ is the $J$th layer decomposition component of the signal, and $E'_1, E'_2, ..., E'_J$ is the energy of the $J$th layer wavelet decomposition amount respectively. Then the energy of each wavelet decomposition can be expressed as:

$$E'_J(t) = \sum_{t=\tau_0}^{t} (s'_J(t))^2 \tag{2}$$

The overall energy of the signal can be expressed as:

$$E_{total}(t) = \sum_{J} E'_J(t) \tag{3}$$

Experimental Procedure
The sample is plate-shaped and the thickness is 1mm. Set the center point as the test position. The applied stress is less than the yield strength, from 0 - 100 MPa. The measurement was made by using a sinusoidal magnetic wave of 1 Hz and the applied field with 12V was acquired. The MBN signal was obtained by a pick-up coil after superimposed 10 times and then amplified by an amplifier with a gain of 20dB.

The sampling frequency is set to 100 kHz, and the signal frequency is divided into eight parts by three-layer wavelet packet decomposition. Through the energy distribution, the energy inside the domain at each stage can be evaluated.

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Results
In the samples of DC01 steel, with different tensile stress values, the Peak value (Figure 1) and the Root Mean Square (RMS) value (Figure 2) of MBN signal are calculated and compared for estimating the effect of domain wall dynamics. The tensile stresses determined by these two MBN signals followed a similar trend. Both Peak and RMS value increases linearly with tensile stress, the RMS has a higher coefficient $r^2 = 0.9542$ compared with the Peak coefficient $r^2 = 0.9127$. To further evaluate the effectiveness of the magnetic techniques in determining tensile stresses, energy distribution with different tensile stress is presented in Figure 3. It was shown that the MBN signal mainly distributes in low frequency region. Moreover, the energy of each wavelet decomposition shows sensitivity to applied tensile stress, especially at the low frequency part. Figure 4. present the distribution of the approximate coercivity and total energy under different tensile stress. Approximate coercivity presents its sensitivity and linearity to tensile stress below 100 MPa and total energy rises with the increase of tensile stress.

![Figure 1. MBN (peak)-Stress diagram](image1)

![Figure 2. MBN (RMS) -Stress diagram](image2)

![Figure 3. Energy Distribution graph](image3)

![Figure 4. Relationship between stress, energy and near coercive field strength](image4)

Conclusion
Energy were used to evaluate the effectiveness of the MBN in determining the tensile stresses. The results indicated that both Peak and RMS value increases linearly with tensile stress and the energy at each frequency band shows sensitivity to tensile stress below 100 MPa.

References


Acknowledgments
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A0220 RESEARCH ON MICROCRACK ALGORITHM BASED ON EDDY CURRENT PULSED THERMOGRAPHY

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Abstract

In this paper, eddy current pulsed thermography (ECPT) is used to detect the microcracks of rail. According to the result of principal component analysis (PCA), tensor CANDECOMP/PARAFAC decomposition (CP), and Tucker decomposition were horizontally compared, the signal-to-noise ratios (SNR) of the three algorithms were obtained in experimental data processing.

Introduction

Zhou Deqiang[1] used PCA to process the spectral amplitudes of different depth defects, Bin Gao[2] developed a physics-based multidimensional spatial transient phase tensor model. Based on completed experiments and algorithms, the article is divided into three parts: Part I, Basic theory of algorithm; Part II, Simulation; Part III, Result.

Methodology

In ECPT system, According to Joule’s law, the thermal power generated by the internal resistance of the material is:

\[ P_w = \frac{1}{\sigma} |J_e|^2 = \frac{1}{\sigma} |\sigma E|^2 \]  

where \( P_w \) is the thermal power, \( J_e \) is the eddy current density, and \( E \) is the electric field strength. Equation (1) determines the resulting temperature field.

Due to blurring of the edge of the thermographic image, algorithms are needed to process data. PCA and Tensor decomposition is selected to spatially process the image. The main tensor algorithms include CP decomposition and Tucker decomposition.

The CP decomposition decomposes the original tensor into a sum of rank-one tensors. The schematic is shown in Figure 1. Tucker decomposes a tensor X into a core tensor multiplied by a matrix along each mode (that is, three factor matrices a, b, c), where U, V, and W are singular value decomposition of 1-mode matrix, 2-mode matrix, 3-mode matrix of tensor X respectively. The schematic is shown in Figure 2.

\[ X = \sum_{i=1}^{k} \alpha_i \mathbf{v}_i \mathbf{w}_i \]

Fig 1. CP decomposition

\[ X = \mathbf{G} \mathbf{U}^A \mathbf{R}^B \mathbf{T}^C \]

Fig 2. Tucker decomposition

The principle of SNR:

\[ \text{SNR} = 20 \log \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} T_{diij}}{\sum_{i=1}^{m} \sum_{j=1}^{n} T_{nij}} \]  

where \( T_{diij} \) refers to the temperature of each pixel point \((i, j)\) in the image of the defect size \( m \times n \), where \( T_{nij} \) refers to the temperature of each pixel point \((i, j)\) in the image of the size \( m \times n \) around the defect. All area of solid lines in the following are crack areas, and the dashed box is the reference area.

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Experimental Procedure

Figure 3. Experimental platform  Figure 4. The first four principal components of PCA

As shown in Fig 3, the heating source is 350 A, the frequency is 256 kHz, and the heating time is 200ms, the recording system has a 200ms delay, and the total recording time is 2s. The above experimental parameters are consistent with the simulation parameters.

Results

Extracted experimental results at 100ms, the data are performed by the tensor algorithm, the results obtained are shown in Figure 5,6, both containing the low rank (background) part and the sparse (defect) part. When set different number of decomposition components, different image results would be obtained.

![Figure 5. Result of CP decomposition](image1)

(a) Low rank  (b) Sparse rank

![Figure 6. Result of Tucker decomposition](image2)

(a) Low rank  (b) Sparse rank

The result of SNR is shown in Table 1. The results show that even if the tensor algorithm reduced overall brightness, but the background part is subtracted, so crack defect is highlighted. Then the SNR is higher than PCA.

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>PCA</th>
<th>CP</th>
<th>Tucker</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>1.083</td>
<td>0.931</td>
<td>1.561</td>
<td>1.952</td>
</tr>
</tbody>
</table>

Table 1. SNR comparison

Conclusion

The microcrack signal is very weak. Due to thermal diffusion, the signal-to-noise ratio will decrease rapidly during the whole detection process. The optimal observation time is in the first 50ms in heating stage. The tensor algorithm can enhance the crack. Signal to noise ratio.

References


Acknowledgments

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Abstract

Graded materials (GMs) are characterized by continuous spatial variations of material properties. In Functional Graded Materials (FGMs), a class of composite materials, this variation is designed for specific functions and applications, and it is achieved by a gradual spatial change of composition and structure. FGM found applications in many areas [1]: from Aerospace, where their function is withstand very high thermal gradients and surface temperatures, to Defense, thanks to their ability to inhibit crack propagation, to Energy, where they provide thermal barrier and a protective coating on turbine blades, etc.

Thus, there is an increasing demand for Nondestructive inspection of graded materials. This work is a contribution in this framework: it is a feasibility study about a potential imaging method suitable for GMs. The theoretical “tool” that we intend to exploit is the Monotonicity Principle (MP) for Eddy Current Testing/Tomography. MP has been successfully applied for crack/corrosion imaging in metallic materials [2]-[8]. In this setting the electrical conductivity assumes values in a discrete set, usually made by two elements only (two-phase problems). For crack/corrosion imaging MP was “customized” to solve the shape identification problem, where only the support of the anomaly is required. However, MP for two-phase materials arises from a more general “version” which is valid for graded materials. The statement of MP for GMs can be also found in [2], [3], [5], [7].

This contribution is focused on the development of an MP based imaging method for eddy current tomography of conductive materials in the presence of graded materials. We assume that the electrical conductivity $\sigma(r)$ is a continuous (or piecewise continuous) function of the space which may assume any value onto an interval $[\sigma_L, \sigma_U]$, being $0 < \sigma_L < \sigma_U < +\infty$.

To date, there are several version of the MP for ECT. In frequency domain we have one for large skin-depth regimes [3], [5], [6] and one for small skin-depth regimes [4]. In time domain (Pulsed ECT) there is a version for time constants [7].

For imaging GMs, we selected the frequency domain approach in the large skin-depth regime. In this case, we have that

$$\sigma_1(r) \leq \sigma_2(r) \quad \text{a.e. in } \Omega \Rightarrow R_{\sigma_1} \leq R_{\sigma_2} \quad (1)$$

where $\Omega \subset \mathbb{R}^3$ is the material domain, $\sigma_1$ and $\sigma_2$ are two possible spatial distribution of the electrical conductivity, $R_{\sigma_1}$ and $R_{\sigma_2}$ are the corresponding resistance matrices, measured when the frequency is low enough so that the skin-depth is larger than the relevant geometrical sizes and $R_{\sigma_1} \leq R_{\sigma_2}$ means that $R_{\sigma_1} - R_{\sigma_2}$ is negative semi-definite. The resistance matrices are measured with reference to a probe made by an array of coils (Figure 1). Specifically, if the array is made by $N$ coils, then $R_{\sigma_1}$ and $R_{\sigma_2}$ are real and symmetric $N \times N$ matrices.

From (1), one can easily derive:

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\( \mathbf{R}_{\sigma_T} \leq \mathbf{R}_{\sigma} \Rightarrow \sigma_T(r) \leq \sigma(r) \text{ a.e. in } \Omega \) \hspace{1cm} (2)
\( \mathbf{R}_{\sigma} \leq \mathbf{R}_{\sigma_T} \Rightarrow \sigma(r) \leq \sigma_T(r) \text{ a.e. in } \Omega \) \hspace{1cm} (3)

where \( \sigma_T(r) \) is a “test” electrical conductivity and \( \sigma(r) \) is the unknown conductivity.

Equations (2) and (3) mean that from external measurements (the resistance matrices) one can understand is an electrical conductivity does not bound the unknown conductivity, in a point-wise manner.

The tomographic method will be based on this simple idea. However, there is a significant gap between the idea and its translation in term of an imaging method. In the full paper we will fill this gap by presenting a new imaging method based on (2) and (3) that, as for two phase materials, will be suitable for real-time operations.

**Figure 1.** A Personal Computer drives an impedance analyzer and a switch matrix to measure the 3×3 matrix of an array made by three coils. A C-scan of the specimen is performed.

**References**

EFFICIENT NUMERICAL MODEL SOLUTION OF ELECTROMAGNETIC SCATTERING PROBLEMS BASED ON THE DIRICHLET-TO-NEUMANN MAP.

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Abstract

Electromagnetic scattering problems arise in a number of low- and high-frequency applications, such as non-destructive testing (NDT), electromagnetic compatibility (EMC), antenna design, material characterization and so on. In this work the focus is on e.m. scattering for NDT applications, from the perspective of an efficient solution of the direct problem.

As it is well known, the electromagnetic scattering from conducting and/or dielectric objects hit by an e.m. wave can be studied using either integral or differential formulations [1]-[2]. Differential formulations are very attractive because they lead to numerical models characterized by sparse matrices, easier to be stored and inverted, if compared to the fully-populated matrices arising from integral formulations. The main drawback for differential formulations is the need of truncating the computational domain by an artificial boundary, which introduces fictitious wave reflections. Classical solutions to this problem are based on the introduction of proper conditions devoted to “kill” these unwanted reflections, usually by means of Absorbing Boundary Conditions (ABC) [3] or of absorbing boundary layers, such as the Perfectly Matching Layers (PML), [4].

An alternative approach, based on the operator (DtN) mapping Dirichlet to Neumann boundary data onto a proper closed surface S enclosing the scatterer, has been proposed in [5]. The main advantage arising from the DtN operator consists in decoupling the scattering problem in the interior of S from the external one. Moreover the DtN map provides an exact boundary conditions on S, regardless its distance from the scatterer, i.e. there is no need to place S in the far-field region, as usually required in classical schemes. Setting the boundary in close proximity of the scatterer, the computational cost can be significantly reduced.

In this work, the DtN approach is used to analyze the (2D) electromagnetic scattering from a penetrable cylinder of cross section Ω, infinitely long in the z-direction, illuminated by a TMz plane wave (see Fig. 1). The surface S is circular so that the DtN operator is known in analytic form [6],[7], as follow:

\[ \Lambda(E^z|S) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} H_n^{(2)}(kR) \int_0^{2\pi} E^z(R,\theta') e^{-in\theta} d\theta'. \]

where \( k \) is the free-space wavenumber, and \( H_n^{(2)} \) is the Hankel function of the second kind.

The case-study here analysed is a penetrable cylinder with \( \varepsilon_r = 4 \) and radius \( a = 10 \) cm, illuminated by a plane-wave propagating along x direction, with frequency \( f = 300 \) MHz. The boundary of the computational domain is in close proximity of the scatterer (\( R = 12 \) cm). The reference solution of this classical scattering problem is from [7] and is shown in Fig. 1. The performances of the DtN solution are compared to that obtained by the PML approach, a

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reference methods for scattering problems. Specifically, the relative 2-norm error versus the number of non-zero (nnz) elements in the stiffness matrix is showed in Fig. 1, which is a measure of the computational cost. It is evident that for a given computational cost, the accuracy gain in using the DtN is about two order of magnitude better. In the final paper, we will discuss: (i) a proper factorization aimed to further reduce the computational cost, also with respect to our recent work [9] and (ii) numerical examples taken from microwave NDT of plastic pipes.

Fig. 1. Left: EM scattering from an infinitely-long conducting cylinder, illuminated by a TMz plane wave. Center: Scattering from a penetrable cylinder. Spatial distribution of the amplitude of the scattered field, normalized to the incident field. Right: relative error as a function of the total number of non-zero elements. DtN vs. PML approaches. The PML solution has been obtained by Comsol Multiphysics® [8].

References

A0223 Multidirectional Alternating Current Potential Drop Technique for Classifying Defects on Inner Surface of Pipeline

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Abstract The objective of this study was to extend the range of the alternating current potential drop technique to identify unknown defects on the inner surface of a metal pipeline. Because the defects of different geometric shapes correspond to different depth formulas, it is crucial to determine whether the defect is a pit or a crack. Compared with previous investigations of this technique, four sets of potential difference measured on the outer surface could be obtained by adding three sets of excitation currents at selected positions, which were available for obtaining more information to confirm the defect type. The validity of this method was confirmed by carrying out evaluation based on the results obtained by finite element analysis and experimental tests.

The alternating current potential drop (ACPD) technique may be applicable for monitoring defects in a plant operation environment. It can achieve high sensitivity and accuracy with a low injected current. However, defects of different geometric shapes correspond to different depth formulas, it is necessary to determine whether the defect is a pit or crack before assessing it.

In this paper, the multidirectional alternating current potential drop technique (MACPD) was used to obtain sufficient information to assess a defect, especially for cracks in different directions that cannot be identified before. Figure 1 shows the probe array of the MACPD technique, which ensures that at least one angle between the crack and a set of exciting electrode wire belongs to 90°±22.5°. Then a defect can be expressed by using eigenvalues, as follows:

\[
\begin{pmatrix}
    u_{1a} & u_{2a} & u_{3a} & u_{4a} \\
    u_{1b} & u_{2b} & u_{3b} & u_{4b}
\end{pmatrix}
\]

Figure 1. Schematic diagram of probe array.

The four eigenvalues can be considered as vectors such that a support vector machine (SVM) classifier can carry out defect classification. The particle swarm optimization--support vector machine (PSO-SVM) classifier model was applied. The radial basis function

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(RBF) was used for the kernel function. The particle swarm optimization (PSO)\textsuperscript{16} was selected to obtain the punish coefficient (c) and gamma (g).

To verify the proposed method, experiments were conducted on four 110 mm × 110 mm × 10 mm plates, as shown in Figure 2. The power amplifier provided a maximum sinusoidal current (I) equal to 2 A with a frequency of 16.8 Hz from the source signal of the SR850 amplifier (Stanford Research Systems, CA, USA); \(U_{10}, U_{20}, U_{30},\) and \(U_{40}\) were measured using SR850 before machining the defects; \(U_{1d}, U_{2d}, U_{3d},\) and \(U_{4d}\) were obtained with the defects. The defect parameters are listed in Table I.

The defects were classified with an accuracy of 100% (12/12). The test results are in good agreement with the finite element analysis results; therefore, the validity of the method proposed to classify the defects on the inner surface lays the foundation for solving the depth of random defects using the MACPD technique.

**Acknowledgments**

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NONDESTRUCTIVE EVALUATION OF SURFACE CORROSION IN WEAKLY MAGNETIC STAINLESS STEEL PLATES USING DISCRIMINATIVE AND GENERATIVE CLASSIFIERS

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Abstract

In this work, standard machine learning techniques such as simple discriminative type classifiers (Logistic Regression) and generative type classifiers (Gaussian Mixture Model) are implemented [1], regarding the segregation of samples based on various stages of corrosion. The performance of the classifiers is evaluated using a histogram of misclassifications. Surface corrosion has a degrading effect on the material and presents itself normally as exfoliation or surface pitting or a combination of both. Corroded materials, e.g., in pipelines and reformer tubes can pose big threats to the environment, if corrective measures are not taken. Thus it is very important and necessary to detect and characterize the corroded regions. In the characterization of different states of corrosion several NDT techniques can be used [2]. In the case of electrically conductive materials such as reformer tubes, where austenitic or weakly magnetic steels are widely used, eddy current testing is the preferred method and it was used to characterize the state of corrosion of stainless steel plates which were divided in two groups: stage 1-when the corrosion is very small and causes no big threat to the structural integrity of the sample and stage 2 – for samples almost degraded with heavy corrosion. The induced eddy currents are perturbed due to the change in electrical conductivity produced by the corroded regions. This in turn affects the electromagnetic coupling of the coil to the sample and thereby affecting the coil impedance. This change in impedance is observed using an impedance analyser for various positions of the coil over the test specimen. Figures 1 (a) and (b) depict the change in the magnitude and angle of the coil’s complex impedance, respectively, for a line scan performed over the test sample.

Fig.1: Complex impedance - (a) magnitude and (b) angle at every position of the coil (c) Peak feature for samples with corrosion stage-1 and stage-2 at 10 kHz.

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The tests were conducted for several frequencies (10 kHz, 20 kHz, 30 kHz, 40 kHz, and 80 kHz). Every tested sample is assigned 4 features, 2 peak features, regarding the peak value of the magnitude and angle of the complex impedance, and another 2 features for the corresponding signal energy obtained as the sum of the squares of the values at every position. The peak feature is shown in Fig.1 (c) at 10 kHz and could be a potential indicator of the depth of the corroded region. On the other hand, the energy feature could be an indicator of the length of the corroded region over which the scan was performed.

Broadly, there are two kinds of classifiers. One of them simply categorizes the data from the observations, which is a discriminative type classifier – Logistic Regression. The other one learns, how the model was generated from a set of observation data, and then tries to classify based on Bayes’ theorem - Gaussian mixture model (GMM). In this work, both the Logistic Regression and GMM were implemented for the peak features and are shown in Fig.2 (a) and (b) when f= 10 kHz. The performance of the classifiers is based on the error outcome in every trial for 5000 trials. Each trial involves (a) randomizing of the data set (b) using the first 70% as training data and the remaining 30% as testing data. The histogram plot for the number of trials versus the number of misclassifications is shown in Fig. 2 (c). These results show that logistic regression performs better than GMM.

Fig.2: (a) Logistic regression analysis; (b) GMM for the peak features, at f=10 kHz; (c) Histogram plot for the trials versus number of misclassifications

References

Acknowledgments
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A0225 SPARSIFICATION OF THE DTN OPERATOR AND ITS APPLICATIONS TO EDDY CURRENT PROBLEMS

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Abstract

Eddy Current Testing (ECT) is a popular nondestructive testing technique, with a broad range of applications. The primary goal of this work is to develop an efficient and accurate numerical model, which would be readily applicable to simulate ECT experiments.

For a large set of cases, ECT could be described by means of a low-frequency limit of Maxwell’s equations. A common way of solving the arising equations numerically is Finite Element Analysis. Specifically, we focus on a differential formulation of the low-frequency limit of Maxwell’s equations, because this gives rise to a sparse linear system of equations, which can be easily stored and solved. To obtain a unique solution, an appropriate boundary condition needs to be set on the boundary of the computational domain. An exact boundary condition could be imposed by means of the operator $\Lambda$ that maps the tangential fields on the boundary to the tangential components of their derivatives: the DtN operator. This strategy has been initially proposed for Helmholtz equation (wave propagation problems) in [1-4] and extended to ECT problems in [10], [11].

The main contribution of this work is in the same line with [10] and [11]. Specifically, we are going to further improve the computational efficiency of the approach.

The FEM model relies on a well-known $A_r$-$V$ formulation [5]. The DtN operator affects the boundary condition introducing a new term $\gamma$ in the numerical model:

$$[ \begin{bmatrix} G + A + j\omega F^{aa} & j\omega F^{av} \\ j\omega F^{va} & j\omega F^{vv} \end{bmatrix} \begin{bmatrix} a \\ v \end{bmatrix} ] = \begin{bmatrix} K^a \\ K^v \end{bmatrix}. \quad (1)$$

In (1) matrices $G$, $F^{aa}$, $F^{av}$, $F^{va}$, $F^{vv}$, $K^a$, $K^v$ are standard FEM matrices (as in [5], [6]), the discrete version of the DtN operator is matrix $\Lambda$ defined as:

$$\Lambda_{kl} = \int_{\Gamma_0} v_0 A_k [(N_i)_t] \times N_k \cdot \hat{n}_0 dS \quad (2)$$

being $\Gamma_0$ the boundary of the computational domain, $\hat{n}_0$ its outward normal, $N_i$’s the edge-element shape functions and $\Lambda$ is the DtN operator ($t$ denotes the tangential component):

$$\Lambda: (A)_t \text{ on } \Gamma_0 \rightarrow (\nabla \times A)_t \text{ on } \Gamma_0 \quad (3)$$

In the stiffness matrix of (1) only $\Lambda$ is a fully-populated submatrix. Moreover, $\Lambda$ involves the unknowns on the boundary. The number of nonzeros of this submatrix could be larger than the number of nonzeros in the rest of the matrix, despite its size are relatively small, which would result in an increased computational cost. This could be mitigated by exploiting a proper factorization of the DtN operator $\Lambda = USU^H$. 

...
Figure 1. Error of DTN and Dirichlet boundary conditions vs analytic solution. Left: Error vs number of multiplications for one matrix-by-vector product. Right: Error vs number of degrees of Freedom (NDOF).

Figure 1 demonstrates the performance of the proposed method on a model problem (which has a closed-form solution): a conducting sphere in a uniform magnetic field. The sphere is made of aluminium ($\sigma=3.774\times10^7$ S/m, $\mu_r=1.0$) and has a radius of 3mm, the source field has a magnitude of 1T, the driving frequency $f$ is 1kHz. The error is in the $L_2$ norm for the induced current density $J$, vs the analytic solution. In the full paper the complete formulation will be presented together with additional model problems from ECT. A comparison with experimental data will be also provided.

References

**Data Fusion of Holistic NDE for Boiler Inspection**

**CHENGDU, CHINA, SEPTEMBER 11-14, 2019**

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**Abstract**

The largest and one of the most critical components of a thermal power plant is the boiler. The functionality of boilers is vital towards the operation of thermal power plants to obtain high temperature steam, which is converted from energy within fuels. Boilers are susceptible towards various causes of damage. Such damage mechanisms include creep, thermo-mechanical fatigue, erosion, cavitation and corrosion-induced cracking. These damages take place inside the boiler’s furnace chamber [1]. If left unchecked, these damages may lead to catastrophic failures, including loss of life or other serious safety issues. Boiler failures also cost hundreds of millions of dollars in equipment repairs, property damage and production losses. Therefore, a rapid, robust and holistic nondestructive evaluation (NDE) framework is necessary to be developed.

Research in NDE technologies has been rapidly evolved over the past years. This is due to their essential role not only in diagnostic maintenance, but is also emphasized in other supplemental roles such as prognostic maintenance, health monitoring, quality assessment, and in manufacturing processes. These technologies have led to reliable evaluation techniques for surface and subsurface defects and anomalies.

To characterize and evaluate regions of interest (ROIs), many NDE methods have been explored and are currently being implemented. Each NDE method used for detection has its own limitations. In our research, however, a comprehensive and holistic multi-model analysis that consists of images based on eddy current (EC), Near-field Microwave (NFM), Capacitive imaging and Ultrasonic Testing (UT) data obtained from test panels are of great interest. EC inspection systems are generally small, portable and inexpensive, and are capable of providing effective metal loss information [2]. UT methods are effective inspection tools for a number of NDE applications and employ high frequency sound waves [3]. NFM methods enjoy several advantages, including capability of imaging sub-wavelength defects. Therefore, a single NDE method may result in a smaller scope of structure analysis, sometimes inadequate to provide sufficient information, thus, the proposed comprehensive and holistic analysis is needed.

Recent studies have demonstrated that data fusion is effective in overcoming limitations of single NDE method by integrating results of several methods, significant increase in reliability is observed. On the other hand, data fusion offers a solid mathematical framework to enhance data quality obtained across either one sensor of multiple channels/frequencies or multiple sensors of completely different physics, in terms of data process perspective. In a mathematical model, the data are represented by \( X^{s,l} \) with \( s \) and \( l \) denoting different types of sensor and channel respectively. In this study, \( X^{s,l} \) is obtained via experimental and simulation measurements of the same inspection area. Inspired by classification notation, we use \( C_1 \) to specify ROI while other regions of structure under test is marked as \( C_2 \). Fusion process in this paper consists of three steps: a single pixel confidence level calculation, connected neighbor confidence level calculation and in the end, a weighed scheme of combining the former two.

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Single pixel confidence level can be obtained by assigning a ROI representative signature $P$ and background covariance matrix $M$. With $(x, y)$ representing pixel location, pixel confidence level of $(x, y)$ is given by $P^T M P$. Higher confidence implies higher probability of $(x, y)$ classified into $C_1$ and vice versa. Complete calculation across all pixels bring us a matrix called $Z_1$. Then, a fuzzy clustering anomaly confidence measure is applied upon connected 8 pixels, the result matrix for entire image is introduced as $Z_2$. In the end, a weighted scheme on $Z_1$ and $Z_2$ is formed to integrating two terms as $w_1Z_1 + w_2Z_2$, with

$$w_1 = \frac{\sigma^2_{Z_1}}{\sigma^2_{Z_1} + \sigma^2_{Z_2}}$$
$$w_2 = \frac{\sigma^2_{Z_2}}{\sigma^2_{Z_1} + \sigma^2_{Z_2}}$$

So that combined term is expressed as $Z = w_1Z_1 + w_2Z_2$, with $Z$ represent final fused image.

In this work, data fusion scheme described above is employed in an effective way for overcoming the limitations of NDE methods. This may include either one sensor of multiple channels, one sensor of multiple frequencies, or of multiple sensing methods of completely different physics in terms of the data process perspective. In this work the data fusion will be applied on scanning results using the mentioned NDE methods. With the help of holistic and comprehensive NDE measurements, data fusion, performance of boiler inspection will be enhanced.

Reference


Acknowledgments

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Flexible tactile sensors based on patterned nanstructures of graphene and 2D materials

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Abstract

Flexible tactile sensors are of significance towards to artificial intelligence interface, robots. By exploiting atomically thick film of graphene and 2D semiconducting material, we develop highly sensitive and conformal pressures sensors for any curved surface using two-dimensional (2D)nanomaterials. And we fabricate flexible electrical-skin devices for wearable health-monitoring devices and autonomous artificial intelligence systems such as robots using the array of functional microstructure (nanopyramid, patterned film etc ) of 2D materials. Furthermore, the self-powered piezotronic sensors made of these newly developed 2D piezoelectric film have been successfully used for real-time health monitoring, proving their suitability for the fabrication of flexible piezotronic devices due to their large piezoelectric responses and excellent mechanical durability.

Figure 1. Within the abstract space you can put figures

References


Acknowledgments

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Model Based Probe Optimization for Pulsed Eddy Current Testing Inspections of Tubes

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Abstract

This communication presents a collaborative study carried out by CEA LIST and EDF, aiming at designing an optimized probe for the inspection of ferromagnetic steel tubes by means of pulsed eddy current testing (PECT) [1,2]. The objective of the optimization process is to maximize the detectability of thickness losses (represented by external grooves) due to corrosion on the tube outer side. The two best probe configurations, selected are illustrated in Figure 1, have been optimized using simulation with respect to coils geometry and relative positions of the elements.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{a) Transmit-receive probe setup b) a double emitting coils setup with magnetic receiver oriented along the radial direction.}
\end{figure}

PECT signatures corresponding to external grooves are simulated using the CIVA simulation platform, developed at CEA LIST [4]. The model used here is a 2D numerical solver based on the Finite Integration Technique (FIT) applied in time domain [3]. It solves the electromagnetic problem twice (in absence and in presence of the groove, successively) using an implicit time stepping scheme and the same discretization, to reduce numerical noise. In order to explore a large range of variation for the many parameters involved, a database of simulation results was first built using this forward solver and, then, used to train a kernel-based regressor. This quite time consuming operation, sometimes called offline phase in the literature, presents many advantages. First, it allows to greatly accelerate the so called online phase, consisting in solving many times the forward problem in view of online diagnostic or fast optimization, for instance. Secondly, as the metamodel obtained can be evaluated very quickly, it becomes easy to carry out sensitivity studies or to test the robustness of the solution by means of uncertainty propagation. Both phases are illustrated in Figure 2.

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Figure 2. Description of both offline and online phases. Left: Generation of a database of simulation results using the CIVA platform and training of the kernel-based regressor. Right: Acceleration of a classical iterative optimization process by replacing the forward solver with the quasi real time kernel-based regressor.

In this application, uncertainties mainly come from the variability of magnetic permeability of inspected tubes, as well as some slight perturbations of their geometry and some possible probe misalignment with respect to the tube axis. An evaluation of the selected probe performance with respect to these parameters will be presented, together with experimental results obtained with the prototype realized in the laboratory, which is illustrated in Figure 3.

Figure 3. Prototype of the PECT probe optimized for the application, made of two emitting coils and one magnetic sensor as receiver.

References

A0229 COMPARISON OF DIFFERENT APPROACHES TO MITIGATE DIFFUSION EFFECTS ON TIME-ANALYSIS OF EDDY CURRENT SIGNALS

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Abstract

The physics of Eddy-Current Testing (ECT) is well described as a diffusive phenomenon accordingly with the magneto-quasistatic limit of Maxwell equations. Specifically, in an homogenous conducting (and possibly magnetic) material, we have the following relations:

\[
\frac{\partial j}{\partial t} = \frac{1}{\mu \sigma} \nabla^2 j, \quad \frac{\partial E}{\partial t} = \frac{1}{\mu \sigma} \nabla^2 E, \quad \frac{\partial B}{\partial t} = \frac{1}{\mu \sigma} \nabla^2 B \tag{1}
\]

where \(\sigma\) and \(\mu\) are the electrical conductivity and the magnetic permeability of the material, respectively and \(j, E, B\) are eddy current density, the electric field and the magnetic flux density, respectively. The term \(\sigma_m = \frac{1}{\mu \sigma}\) is the “Magnetic Diffusivity” and it is related to how fast the electric and magnetic fields can penetrate/diffuse inside the conductive sample [1].

The most relevant consequence of Eq. (1) is that the fields inside a conductive material can be described by evanescent waves, e.g. exhibiting an exponential decay of the fields amplitude within the sample and also a frequency-dependent phase velocity \(v_{Ec}(\omega)\), both being regulated by the skin depth \(\delta(\omega)\). For instance, Eq. (2) shows a plane wave diffusing along the positive z-direction for the eddy current density \(j\):

\[
\delta(\omega) = \sqrt{\frac{2}{\omega \sigma_m}}; \quad v_{Ec}(\omega) = \sqrt{\frac{2 \omega}{\sigma_m}}; \quad j(z, t) = j(0, t)e^{-\frac{z^2}{4 \delta(\omega)^2}}. \tag{2}
\]

Similar to propagating waves in dispersive media, broadband eddy current signals suffer from a broadening of the signal envelope in time. This is especially true with respect to the signals from hidden defects, which is broader as the depth increases. In addition, the frequency-dependent attenuation due to the skin depth, further emphasizes this process. Indeed, shallow defects are better detected by using “higher” frequency components, while deep defects by the “lower” frequency components. Broadband signals are therefore used in pulsed ECT (PEC) to guarantee a high SNR for all possible defects. As a result, the depth resolution and SNR in PEC, and ECT in general, decreases with increasing inspection depth.

To address this issue, [2] proposed the use of the 1-D Q-transform for converting PEC current data to a pseudo-wave, which is the solution of a proper (fictitious) wave equation associated with Eq. (1). Recently, a similar approach, the so-called virtual-wave, have been successfully applied also to thermography NDT, by combining numerical inversion of the Q-transform for thermal waves with the Synthetic Aperture Focusing Technique (SAFT), an imaging procedure widely used in ultrasonic NDT and in RADAR [3]. At the same time, since the seminal work of Lord and co-workers, a time-of-flight (TOF) approach was introduced by means of the Q-Transform [4, 5]. The idea was to apply the Q-Transform to find a feature of the measured signal, which behaves as the “traditional” TOF for a wave
propagation phenomenon, i.e. a feature proportional to distances as in radar and sonar. In this way, it is possible to avoid the inversion of the Q-Transform, a strongly ill-posed problem.

The expression of the Q-transform for 3D ECT problem is:

\[ H(\mathbf{x}, t) = Q\{\hat{H}(\mathbf{x}, q)\}; \quad E(\mathbf{x}, t) = Q\{\frac{\partial \hat{E}(x,g)}{\partial q}\} \]  

(3)

where \( \hat{H} \) and \( \hat{E} \) are the fields in the fictitious wave propagation problem and \( Q \): \( \hat{u}(x, q) \to \int_0^\infty \frac{q}{2\sqrt{\pi t}} e^{-q^2} \hat{u}(x, q) \) is the Q-Transform operator.

The goal of this contribution is to merge these previous results by applying numerical inversion of the 3D Q-transform applied to PEC signals collected on an Al sample containing small notches at various depths. In addition, the Warped Frequency Transform (WFT) will be used as alternative strategy with respect Q-transform to compensate the dispersion associated to the frequency-dependent phase velocity and the results of the two approaches on the benchmark sample will be compared. WFT was introduced in [6] to compensate dispersion in Ultrasonic Guided Waves. WFT rescales the frequency axis by adopting a proper warping function \( w(\omega) \). Given a signal \( s(t) \) whose Fourier transform \( \mathcal{F}\{s(t)\} = S(\omega) \), the continuous warping operator \( W \) is defined as:

\[ \mathcal{F}\{W\{s(t)\}\} = \sqrt{w(\omega)}S(\omega(\omega)) \]  

(4)

where \( w(\omega) \) is the first-order derivative of \( w(\omega) \). By applying the warped inverse transform, a signal \( s_w(t) \) is obtained in which the phase shift accumulated by the different frequency components due to dispersion is compensated. \( w(\omega) \) is derived from the group velocity \( v_G(\omega) \).

In the case of ECT, evanescent waves do not transport energy, so in theory group velocity cannot be defined. However, from Eq. (2) we can derive \( v_G(\omega) \) as:

\[ v_G(\omega) = \frac{\dot{w}(k)}{\omega} = \frac{4k}{\alpha_m} = \frac{\beta_0}{\alpha_m} = 2v_E(\omega) \]  

(5)

In the full paper, the applicability and the effect of Q- and WFT- transforms will be evaluated on experimental data and the benefits in term of depth resolution and SNR will be evaluated by comparison with standard signal processing applied to PEC data.

References


Acknowledgments

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Parameter Optimization Design of Eddy Current Sensor Based on Finite Element Analysis

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Abstract: The eddy current sensor is a key component of the eddy current testing (ECT) system that directly affects defect inspection. In this study, the detection performance of sensor was analyzed by ANSYS simulation and experimental verification. For further research, the influence of cylindrical coil sensor and rectangular coil sensor on the detection sensitivity of the groove defect in the placement mode and scanning direction were analyzed. The results show that the cylindrical coil sensor got similar results when using two scanning methods.

Keywords: Eddy current testing, Cylindrical coil, Rectangular coil, Parameter optimization, ANSYS simulation

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1. Introduction

Eddy current testing (ECT) is a non-destructive testing method based on the principle of electromagnetic induction [1,2]. At the beginning of the 20th century, ECT has begun to be applied to detect defects. The ECT system excites the alternating current from the signal generator to the detecting coil (sensor), and the detecting coil generates an alternating magnetic field to excite an eddy current in the workpiece which be measured. As the core component of the ECT system, the eddy current sensor was expected to obtain a large linear range and high sensitivity in actual detection. The sensitivity and linear range of the eddy current sensor are mainly affected by the magnetic field distribution of the coil [3-5], and the shape, structure parameters and placement of the coil have a great influence on the magnetic field distribution [6-10].

In this paper, two types of sensor models were established. The sensitivity of the sensor in different scanning direction was explored to optimize the coil structure parameters [11,12]. The simulation results were compared and verified with experimental results. The influence of sensor were studied for the placement and scanning direction, which provided a basis for further designing and optimizing the eddy current sensor to improve the detection.

2. Parameter optimization and simulation

2.1 Performance analysis of rectangular coil

In actual industrial testing, the defect information is often poorly clear before the detection. Besides the sensor structure parameters, the placement mode of sensor and the scanning direction also have an effect on the defect
detection. According to the outer diameter, inner diameter and number of turns of the sensor, several cylindrical sensors with different parameters are designed. The structural parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Number</th>
<th>Outer diameter /mm</th>
<th>Inner diameter /mm</th>
<th>Turns/N</th>
<th>Wire diameter /mm</th>
<th>Placement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>3</td>
<td>400</td>
<td>0.05</td>
<td>Vertical + Horizontal</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>3</td>
<td>600</td>
<td>0.05</td>
<td>Vertical + Horizontal</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>3</td>
<td>1000</td>
<td>0.08</td>
<td>Vertical</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>3</td>
<td>600</td>
<td>0.08</td>
<td>Vertical</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>3</td>
<td>800</td>
<td>0.07</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

Consider the placement of the cylindrical sensor coil, the vertical placement of the defect detection effect is significantly better than the horizontal placement as shown in Figure 1.

Fig.1 The impedance of cylindrical coils in different placement modes

Fig.2 is the impedance of the cylindrical sensor 1 to 5 vertically placed and scanned in different directions for the groove type defect detection. It can be seen from the figure that whether the horizontal scanning defect or the vertical scanning defect reaches the maximum value at the defect center position.

2.2 Performance analysis of rectangular coil

Based on Theodoros study, this paper further studies the placement mode and defect scanning direction of the rectangular sensor, and compares the detection effect of the groove type defect when the rectangular sensor placement method is different. Table 2 is the rectangular sensor coil parameter table.

Table 2 Rectangular sensor coil parameter table
<table>
<thead>
<tr>
<th>Number</th>
<th>Outer diameter /mm</th>
<th>Inner diameter /mm</th>
<th>Turns/N</th>
<th>Wire diameter /mm</th>
<th>Placement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>9</td>
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<td>10</td>
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<td>Vertical + Horizontal</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>9</td>
<td>800</td>
<td>0.08</td>
<td>Vertical + Horizontal</td>
</tr>
</tbody>
</table>

As can be seen from the figure 3, the rectangular sensor is different from the cylindrical sensor, the vertical placement and the horizontal placement have their own advantages.

![Graphs showing impedance of rectangular coils in different scanning directions](image)

(a) horizontal scanning defect  
(b) vertical scanning defect

Fig.3. The impedance of rectangular coils in different scanning directions

The No. 3 sensor and No. 1 sensor of rectangular coils get better results, summarized the results of impedance of the two scanning directions, as shown in Figure 4.

![Graphs showing impedance of rectangular coils in scanning defects](image)

(a) No.1 rectangular sensor  
(b) No.3 rectangular sensor

Fig.4. The impedance of rectangular coils in scanning defects

3. Conclusion

Cylindrical sensor is sensitive to its placement. The detection effect of vertical placement is obviously better than horizontal placement, which is mainly related to the focus position of the cylindrical sensor. After the cylindrical sensor is placed vertically, its horizontal scanning and vertical scanning have similar effects on groove type defect detection, and the vertical scanning mode is slightly better than horizontal scanning.

The rectangular sensor differs from the cylindrical sensor in the influence of the placement mode and the scanning direction on the detection effect. It can be found that the rectangular sensor in vertical placement has better effect on horizontal scanning detection, and the horizontal placement is more suitable for vertical scanning.
References


MATERIAL TOUGHNESS CRITICAL VALUE DETERMINATION FOR THE PIPELINE SUBMITTED UNDER MEDIUM PRESSURE

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Abstract

This paper describes a method for determination of the R-curves strength of materials and results of the steel NIOVAL 47 testing in three different states: A - normalized state, B - old state (10% cold deformed and heated 30 minutes at +250°C) and C - deformed state (10% cold deformed).

Testing has shown that a mechanical properties, and also a fracture mechanics properties of NIOVAL47 material are significantly different in the deformed state (C) or old state (B) from the normalized state (A), which corresponds the manufacturers specification during the pipeline construction. So in the further analysis proper results of the old and deformed state have to be considered, in order to get an objective image of the construction integrity.

Construction represents the pipeline Ø2500x32 mm which operates submitted under internal pressure of 52 bars in HP Perucica, Montenegro. Pipeline has been in the exploitation process for more than 50 years. Material used for the construction of the pipeline is NIOVAL47, manufacturer SIJ – Slovenian Steel Group (ex Zeljzezara Jesenice, Slovenia).

For a determination of the material fracture toughness critical value (in form of $K_I$, $J$-integral, or critical crack opening - $CTOD$) mechanical tensile properties of the steel NIOVAL47 has to be defined, and experiment has to be conducted in accordance with standard ASTM 1820-05.

Experimental determination of the fracture toughness was carried out at compact "CT" test tubes in accordance with ASTM 1820-05. Before fracture toughness testing test tubes fatigue was done (ASTM 1820-05), in order to achieve crack in micro structural level with the smallest possible plastic zone. Fatigue was carried out at servo-hydraulic materials testing machine INSTRON.

From the results of the fracture mechanics testing, it can be seen that the fracture toughness values differ with respect to the state of the material. The material in the normalized state (A) exhibits completely different properties than in the old (B) or deformed (C) state, as in the case of tightening the test tubes so in the case of examination of the fracture mechanics parameters. The fracture toughness values between the deformed and aging state are relatively small, which is why in the construction integrity analysis measured values for the aging and deformed state (B) can be considered relevant.

References


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Acknowledgments
This work is supported by the Elektroprivreda Crne Gore AD Nikšić (EPCG – a national energy company of Montenegro) – project: The program continuos monitoring condition metals for No3 pipe hydro-power plant Perucica, May 2011.
Electromagnetic acoustic transducers (EMATs) are presented as a good alternative to industrial applications due to their capability of operating in high-temperature metallic material thickness measurement [1-2]. They are superior to the piezoelectric transducers in some applications, where the coupling is not used, where the coating layer is unfavorable. However, EMATs have a relatively low signal-to-noise ratio (SNR) due to the poor transduction efficiency, the accuracy of thickness measurement by traditional time difference method is not high. This paper focuses on enhancing the accuracy of thickness measurement, the influence of edge detection is analyzed by finite element method, and super-heterodyne phase-sensitive detector is present to process the received signals, and thickness information could be acquired by the calculation of phase signals.

Edge detection is different from traditional shear wave thickness measurement, thickness is detected by the difference of multi-mode acoustic generated by the edge side. As shown in Fig.1, EMAT excites both shear vertical wave and Rayleigh wave at the edge side. According to the difference of wave velocity between the two, the thickness $D$ of the specimen can be solved by $D = \frac{(V_S \times V_R) \times \Delta T}{2(V_S - V_R)}$. Where $V_S$ is the velocity of shear vertical wave, $V_R$ is the velocity of Rayleigh wave, $\Delta T$ is the time difference between the shear vertical wave and the Rayleigh wave as shown in Fig.2.

Generally, $\Delta T$ is difficult to be obtained with high accuracy. Super-heterodyne phase-sensitive detector is to multiply the received signal with two local oscillation signals, where the phase difference of the two local oscillation signals is 90 degrees, then the product signals pass through the low-pass filter respectively, and the output will retain only the low-frequency terms ($I$ and $Q$) containing the received signal phase information, and the received signal phase $\Phi$ can be obtained by $\Phi = \arctan(I/Q)$, as show in Fig.2 and the $\Delta T = (\Phi_1 - \Phi_2)/2\pi f$.

The experiments are carried out, the thickness of specimen increases is from 30mm to 40mm, and $I_1$, $I_2$, $Q_1$ and $Q_2$ can be obtained by the EMAT detection as shown in Fig.3. The
Phase information of specimens with different thickness can be calculated as shown in Tab.1. The results show that the application of orthogonal phase-sensitive detection and edge detection in the inspection of metal thickness can denoise from the received signal and increase the measurement accuracy.

![Fig 2. (a). Received time domain signal and (b). Superheterodyne phase sensitive detection](image)

![Fig 3. (a). I and (b). Q in 30mm-40mm thickness measurement](image)

<table>
<thead>
<tr>
<th>Thickness(mm)</th>
<th>Theoretical value/degree</th>
<th>Phase sensitive detector value/degree</th>
<th>Relative error%</th>
</tr>
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<td>32</td>
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</tr>
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</tr>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>40</td>
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<td>1685.1</td>
<td>3.38%</td>
</tr>
</tbody>
</table>

References
Multi-source Effect in Electric Current Perturbation Testing for Ferromagnetic conductor

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Abstract

Electric current perturbation (ECP) owns the advantages of high inspection sensitivity and stability. It consists of establishing an electric-current flow in the material to be examined and then detecting localized perturbations of this current flow at discontinuities such as inclusions or cracks. Many previous studies have discussed the signal characteristics for different defects in non-ferromagnetic materials such as aluminum or Incoloy 901, and the frequency of the current and the defects form also have been analyzed. But almost none of them take the ferromagnetic materials into consideration. The ferromagnetic conductor carrying direct current produces not only magnetic leakage field but also current perturbation magnetic field in the space. To analyze the defect signals in different scanning paths, the distorted magnetic field generated by it are first analyzed theoretically. Then, the magnetic field distribution of the aluminum tube and steel tube are investigated by simulations. Finally, experiment signals of the circumferential defect are extracted in both type of tubes. The results show that, in ferromagnetic conductor, the testing signal is strengthened in the middle scanning path and reversed in the edge paths, which determines the signal source.

Inject current flows through the tube and creates a circumferential magnetic field. Because of the magnetic refraction, some flux lines break out of the surface into the air and generates MFL. The perturbed current also produces disturbed magnetic field in the space, as shown in Fig.1. The characteristic of component signals of the magnetic leakage field is different from that of the magnetic field arises from electric current perturbation. They are both picked up by the magnetic sensors, as shown in equation (1.1).

\[ \vec{B}(x, y) = \vec{B}_{MFL}(x, y) + \vec{B}_{ECP}(x, y) \]  

(1.1)

However, the main source of the signal on different paths various from each other. The MFL signals caused by the circumferential magnetization can enhance or weaken the ECP signal.

Fig.1 The source of the magnetic field distortion  
Fig 2. 3D FEM model and different path

In Fig.2, a 3D FEM was built in ANSYS. The surface crack (4 mm × 40° × 2 mm, length × angle × depth) was perpendicular to the current direction on the surface of steel tube, while the separation of the electric-current perturbation signals was based on the aluminum tube. Comparisons were made with simulation data for various sensor-scanning paths.

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Fig. 3 and Fig. 4 are, respectively, the current perturbation in XY plane and XZ plane. In figure 5(a), it can be seen that the $B_x$ signal is a “sunken” signal in aluminum tube while a “raised” signal in steel tube. The former owes to the current perturbation by the crack and the latter is created by the magnetic leakage field in addition with a disturbed magnetic field. From figure 6(a), both of the $B_z$ signal in aluminum tube and steel tube have the feature of twin peaks. Their difference is that the signal changes from positive to negative values in aluminum tube while this is opposite in steel tube. When the current is perpendicular to the crack, the signal component caused by MFL plays the dominant role. In figure 5(b) and 6(b), the $B_x$ and $B_z$ signals of steel tube are higher than that of aluminum tube. It is obvious that the magnetic leakage field have a negative impact on $B_x$ and $B_z$ signals and weaken the signals.

The signal mechanism of longitudinal crack on ferromagnetic materials based on electric current perturbation is more complex than non-ferromagnetic materials. In ferromagnetic conductor, the testing signal is strengthened in the middle scanning path and reversed in the edge paths, which determines the signal source.

References


Abstract

Capacitance imaging (CI) is a promising imaging technique that determines dielectric permittivity distribution of an object from external capacitance measurements. It has several advantages, which include low-cost, fast response, no ionizing radiation, and flexibility in electrode design[1, 2]. Coplanar capacitive sensors, apart from all benefits mentioned above, enable us to interrogate materials under test (MUTs) from only one side[3] due to its planar structure. It has proved to be highly useful when access to the MUT is limited. The performance of capacitive imaging relies on coupling between the MUT and interrogating electric field. An electric field generated from sensor electrodes can penetrate through the sample, causing an electric displacement to counter the applied field. Charge stored between the sensor electrodes is affected by displacement field, which changes the capacitance. In turn, the altered capacitance can be used to infer material properties of the MUT, such as permittivity and conductivity. Capacitive sensors consist of two electrodes patterned on an insulated substrate. These substrates are seen as driving and sensing electrode plates, where the driving electrode is subjected to a sinusoidal voltage input signal.

One of the challenging problems with CI is to reduce edge effect during the inspection of adhesive bonded structures as shown in Figure 1.

![Figure 1](image-url)  
**Figure 1.** Left: schematic design of MUT; Right: schematic diagram for the model to obtain capacitive tomography of a MUT

When the presence of adhesion is at the edge, the received signal is masked by the strong edge signal[4]. The electric field does not just exist between the sample and electrode plate, but also extends some distance away. This is known as a fringing field. This paper focuses on the effect of design parameters on sensor performance for samples with extremely low conductivity and low permittivity. Finite-element methods (FEM)[5] are used extensively for sensor modeling, sensitivity distribution analysis, and performance evaluation. The quality of the results from COMSOL based FEM simulation depends on model definition, as well as mesh generation and refinement[6]. In this research, sensitivity distribution will be studied and solved using the AC/DC module.

To obtain the sensitivity distribution within the volume of influence of a capacitive probe, a small perturbation with high relative permittivity $\varepsilon_r$ is introduced. Permittivity perturbation is modelled as polarization moment $\gamma \cdot P$ caused by electric field $\vec{E}_{dp}$ generated from driving electrode with $\gamma$ and $P$ representing volume of perturbation and polarization respectively. The presence of the dipole perturbation will change the signal on the sensing electrode. Since charge is fixed on the sensing electrode, capacitance variation is expressed as
\[ \Delta C = \frac{Q_s}{V+4V} - \frac{Q_s}{V} \]. Reciprocity theory on charge and electric potential provide us an effective approach to calculate \( \Delta C \) and the sensitivity distribution can then be defined as

\[ S = \frac{\partial \Delta C}{\partial \varepsilon_0 (\varepsilon_r - 1)} = -E_{D,V=1} \cdot E_{s,V=1} \]

With \( E_{D,V=1} \) and \( E_{s,V=1} \) representing electric field intensity when the applied voltage is 1 volt. The figure below shows the resulting distribution map within the adhesion layer when a capacitive sensor is placed at the centre of the MUT. Depending on the angles \( \theta \), according to the dot product, there can be regions where the sensitivity values are either zero, positive, or negative. The high sensitivity values are confined in a small area when strong coupling exists between the two electrodes. Due to the complexity of the actual probe geometry and the positions of the grounded electrodes/backplanes, the sensitivity distribution is much more complicated than the case shown in Fig. 2.

![Figure 2](image)

**Figure 2.** Left: Schematic diagram for the model to obtain the measurement sensitivity Right: measurement sensitivity distribution of the probe placed at the center of sample with 3mm lift-off distance.

Analysis on sensitivity distribution will provide us with rich information to optimize sensor design and image postprocessing. Therefore, it is critical to construct accurate sensitivity distribution during adhesion assessment. On the other hand, electrode geometry is the major factor which determines performance amongst all other design variables. Selection of sensor geometry should be considered circumspectly in order to reduce edge effect as well as enhance both the resolution and robustness of the obtained images. Overall, sensitivity distribution and design variables will be analysed to achieve high quality capacitive tomography.

**References**

HYBRID HYSTERESIS MODELS BASED ON A REGRESSOR APPROACH FOR THE CHARACTERISATION OF SOFT STEELS

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Abstract

The hysteresis curves of magnetic materials are rich in information with regard to the material microstructure, a fact that yields an indirect access to their mechanical and metallurgical properties. This indirect link is of particular practical importance for non-destructive characterization of industrial materials like steels, since it allows to assess the material state and to retrieve information about its structure or history by means of macroscopic magnetic measurements.

In a number of previous studies, it has been demonstrated that the main features of the hysteresis loops like the coercive field, the remanent magnetisation, the power losses, etc., can be used to monitor the recovery and recrystallization during the annealing of soft steel grades, such as low carbon (LC) or interstitial free (IF) steels [1][2]. An example of the annealing time effect, which in turn is determinant for the underlying metallurgical transformation, to the hysteresis data is shown in Fig. 1. In this figure, we can observe the shape changes of the B(H) loops as well as the correlation between the remanent magnetisation and the power losses associated to the hysteresis cycle with the coercive field. The linear correlation for the two cases is characteristic of the recovery process, whereas the existence of outliers at higher temperatures indicate the initiation of the recrystallization process.

Figure 1. (a) B(H) curves of a low carbon steel specimen after annealing at 300 °C for several annealing times. (b) Mr-Hc correlation. (c) Wt-Hc correlation.

In order to build theoretical models able of reproducing the experimental curves and extracting their basic features, one can resort to several successful parametric models of the literature, like the Jiles-Atherton model [3], the Preisach model with parametric distribution [4], or the Mel’gui model [5]. The main idea is, starting from the experimental datasets, to fit the given model of choice, a numerical procedure also known as model identification. The thus obtained parameters can be used then for extracting the features of interest, and, at a second level, to examine the correlation with the available microstructural-related data, such as the annealing conditions. Nevertheless, experience reveals that the several parametric models we have in our disposal do not perform equally well for the range of microstructures we wish to take into account. For the specific example of the data presented in Fig. 1, it turns out that whereas the Jiles-Atherton model reproduce the hysteresis curves for the lower annealing temperatures with a high accuracy, it is not very well suited for the steeper loops obtained by high-temperature annealing. The Mel’gui model, on the contrary, yields very satisfactory results for the latter case. A further disadvantage of the direct identification of certain models like the Jiles-Atherton or the

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Preisach model is also the relatively increased computational burden when several curves need to be identified.

To enhance the performance of the identification procedure and to overcome the above mentioned limitation a data-oriented approach can be devised. The main idea here is to interpret the B(H) curve as an abstract input-output relation, which will be used in order to train a regressor (gaussian process, kernel ridge regressor, etc.). Once the model has been trained any evaluation is carried out instantaneously, which makes the identification and the parametric studies very fast. Furthermore, choosing the best adapted parametric model for the creation of the training set offers a very straightforward approach for mixing different models and thus producing a generic hysteresis operator, which admits hysteresis characteristic values, common for all models, instead of model specific parameters. In Fig 2a is shown how two input subspaces for the Jiles-Atherton model and the Mel’gui model are mapped in a subspace composed by the remanent magnetisation and the coercive field. In Fig 2b and Fig 2c are compared the results obtained by identifying the regressor model using two datasets of the above mentioned LC specimen for two annealing temperatures.

![Figure 2](image)

(a) Mapping of two input subspaces of the Jiles-Atherton and the Mel’gui models to the M_r-H_c subspace (b) Identification results for a LC specimen subjected to 51s isothermal annealing at 300 °C. (c) Identification results for a LC specimen subjected to 51s isothermal annealing at 600 °C.

In this work, the above described procedure will be applied for the study of the effect of the annealing conditions to hysteresis datasets obtained from LC and IF samples. Feature extraction techniques will be also applied to study the correlation of the most significant features with pertinent physical parameters (magnetic and microstructural) of the considered materials.

References
A FAST FORWARD SOLVER FOR SIMULATING EDDY CURRENT TESTING SIGNALS OF CRACK IN STRUCTURE OF CARBON FIBER REINFORCED POLYMER LAMINATE

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Abstract
In recent decades, carbon fiber reinforced polymer (CFRP) has growing applications in wide engineering fields, e.g., aerospace, transportation, renewable energy and other industries, due to its light weight and high specific mechanical properties compared with traditional metallic materials. However, carbon fiber composite materials have relatively low properties in the direction transverse to their reinforcing fibers, and notably low resistance to impact loads. Impact events are inevitable during the lifetime of a CFRP composite structure during fabrication, service and maintenance due to collisions of small object such as stones or tools. Such events may cause defects of fiber breakage and/or delamination, and severely degrade the loadbearing capacity of the structure [1]. A non-destructive testing (NDT) tool is necessary to detect the defects in CFRP laminates during both manufacturing and operation processes to ensure the structural integrity.

To date, the most commonly used NDT methods for inspection of CFRP material are ultrasonic testing, infrared thermography, X-ray and acoustic emission etc., but all of them have their limitations for NDT of CFRP both high accuracy and efficiency. Recently the high frequency eddy current testing (ECT) method is studied for application to inspection and quantitative evaluation of defects in CFRP materials. In the development of quantitative ECT technique for structure of CFRP materials, a high efficiency numerical code to simulate the ECT signals due to defect in anisotropic material is of great importance for probe optimization and defect reconstruction. Authors have developed an FEM-BEM numerical code base on the A-ϕ formulation for the ECT of CFRP material [2]. It can give good numerical results but needs large computer resources. On the other hand, though a fast solver for ECT of isotropic metallic material has also been developed, it cannot treat anisotropic material such as the CFRP laminate plate [3]. In view of these backgrounds, the aim of this paper is to develop a fast forward solver based on the conventional FEM-BEM code and the databases approach to solve the ECT problem for the anisotropic CFRP material, and to demonstrate its feasibility and efficiency through comparison with both the measured signals and the numerical results simulated with the full FEM-BEM code.

The paper is arranged as follows: First, the anisotropic numerical model and a derivation of formulation for the fast forward scheme based on the FEM-BEM hybrid scheme are presented by taking CFRP plate as example. Second, the fast forward scheme is implemented in the FEM-BEM hybrid code developed by authors for the CFRP material and the ECT signals of the crack in inspection target are calculated for comparison with those of the conventional FEM-BEM code. At last, an experimental system and ECT signals of artificial cracks in a CFRP plate are established and simulated to further prove the validity of the fast forward

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solver experimentally for ECT of practical anisotropic material. The conclusion remarks are given in the last section.

Fig. 1 shows the calibrated experimental signals and the simulated signals using the developed ECT fast solver and the updated full FEM-BEM method of the CFRP laminate plate, where the symbols Experiment, Full FEM-BEM and Fast FEM-BEM represent the calibrated experimental signals, the signals calculated with the full forward scheme and the updated fast scheme, respectively. The ECT signal values at the different scanning positions are compared. All of these signals show good agreement with each other, which means that the developed fast code has satisfactory simulation accuracy for laminated CFRP composite material. From the figures, we can see that there are some difference between the simulated results and the experiment. It is possible to say that the error comes mainly from the greater noise disturbance due to the smaller pick-up voltage, as well as the anomalous crack shape. As this milling cutter is a circular blade, the finished crack is not a regular rectangle but a trapezoid, which creates the larger difference from the simulated signals of the model with regular rectangle crack. The good agreement between the experimental results and the simulation demonstrated the validity of the proposed ECT fast forward solver of an anisotropic material. At the same time, for the simulation results shown in Fig. 9, the developed fast solver required only less than 1 minute.

![Comparison of experimental results and simulated results](image)

(a) Sample A  
(b) Sample B

Figure 1. Comparison of experimental results and simulated results

As conclusion, Comparison of the numerical results and the experimental results indicates that the proposed novel fast forward scheme can predict ECT signals accurately and over 100 times faster than the conventional FEM-BEM method.

References

Acknowledgments
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A0238 Efficient Analytical Model for Pulsed Eddy Current Evaluation of Tubes

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Abstract

The analytical model of pulsed eddy current (PEC) signals plays a critical role in exploring the physics of PEC testing. At present, PEC models are solved by inverse Fourier transformation on the basis of the truncated region eigenfunction expansion (TREE) method. In order to improve the efficiency, the piecewise cubic spline interpolation method is proposed to calculate the impedance change of harmonics after investigating partial derivatives of impedance change with frequency. Finally, the PEC analytical model of a tube is calculated, and the results are compared with those from finite element model to verify the correctness and efficiency of the proposed model. At the same time, it is found that the method is still applicable except for the conductivity when the other parameters are unchanged.

1 Introduction

The analytical model of PEC testing can reveal the relationship among the detection signal, probe and pipe parameters. It is very important for understanding the detection mechanism of the PEC and is the theoretical basis for improving the detection speed and accuracy. Li et al. [1] derived the double-coil impulse response model of multi-layer pipeline based on TREE method and found that it took 1500 summation terms to achieve the required accuracy in calculating the electromotive force and magnetic field intensity of the coil. When calculating the impulse response signal by the IFFT method, a large amount of harmonic magnitude needs to be calculated. Xie et al. [2] used the linear interpolation method in the finite element method to calculate 450 harmonic magnitude based on 30 interpolation nodes, and calculated the impulse response signal by IFFT method, which greatly improved the calculation efficiency.

Since the pipeline harmonic model based on the TREE method is computationally intensive, it is difficult to control its calculation accuracy. And the relationship between impedance change and frequency is nonlinear. The use of linear interpolation requires more interpolation nodes, otherwise, the interpolation error will be large. In this paper, a fast numerical calculation method for the analytical model of PEC signals is proposed. In order to solve the problem of low efficiency of generalized integral calculation, it is found that the generalized integral can be transformed into a definite integral by studying the characteristics of the integral function of the impedance change. On this basis, according to the variation of the integral function with the frequency, the piecewise cubic spline interpolation method is proposed to improve the calculation efficiency, and the correctness of the model is verified by finite element simulation.

2 Study of fast numerical calculation

The impedance change formula of the coil is

$$\Delta Z = \int_0^\infty 2j\omega\mu_0\mu_n^2 \frac{U_{\omega 12}}{U_{\omega 12}} \hat{k} d\alpha$$

$$\hat{k} = \int_0^{\infty} r I_1(\alpha r) dr$$

$$\hat{\theta} = \int_{z_1}^{z_2} \int_{z_1}^{z_2} \cos[\alpha(z - z_0)] dz_1 dz$$

Where $\omega$ is the excitation frequency, $\alpha$ is the integral variable, $\mu_0$ is the permeability of the vacuum, $\mu_1$ is the permeability of the pipeline, $U_{\omega 12}/U_{\omega 12}$ can be found in the reference [3].

As a measurable physical model, when the parameters are known, the result of the formula (1) must be a finite value. This means that the integral function in formula (1) must converge in the integral finite interval, and the generalized integral can be transformed into a definite integral.

For the convenience of calculation, the partial derivative curve of the integrand is shown in figures 1. It can be seen from figures 5 (left) that the real part curve of the partial derivative of the integrand can be divided into three segments. The piecewise interpolation interval for this case should be [0,1500Hz],
[1500Hz,5kHz] and [5kHz,50kHz].

**Fig. 1** Real part curve (left) and imaginary part curve (right) of the partial derivative of the integral function

### 3 Results and discussions

It is found that there are 16, 6, and 6 interpolation nodes in the interval [0, 1500 Hz], [1500Hz, 5kHz] and [5kHz, 50kHz], which means that the spacing of interpolation nodes is 100 Hz, 700 Hz and 9 kHz, respectively. Finally, 975 impedance changes are obtained by interpolation of 26 interpolation nodes on three intervals, which can meet the requirements of calculation accuracy. From Fig. 2 (left), it can be seen that the results obtained by interpolation with IFFT are in good agreement with the results of Comsol time domain calculation. Taking the Comsol time domain calculation results as a reference, the relative error of the interpolated IFFT results are shown in Fig. 2(right). It can be seen from Fig. 2(right) that the relative error at the peak is 1% and the relative error at the trough is 1.2%. This is mainly due to the fact that the energy of the PEC is mainly concentrated in the low-frequency band [18], while the relative error between the analytical impedance change in the low-frequency band and the finite element results is larger, resulting in a slightly larger relative error of the calculation results. In general, the analytical results are in good agreement with the finite element results, which show that the method proposed in this paper is effective and correct.

**Figure 2** The excitation signal of pulse voltage (left) and the response signal of current change (right)

### References


### Acknowledgments

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Characterization of Bearing Rings Using Pulsed Eddy Current Evaluation

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Abstract

Hardness is a critical index characterizing wear resistance of bearing rings. Pulsed current testing (PEC) has rich information and deep penetration compared with typical eddy current testing. In this work, PEC testing is applied to classify heat-treated bearing rings in terms of hardness. 11 bearing rings were prepared as samples, and the hardness were measured with an ultrasonic hardness gauge. From the experiments, it is found that the peak height of difference PEC signals allows for the sorting of the prepared samples. Specifically, the PEC signals from the unqualified and unheat-treated bearing rings exhibit positive peak height, whereas the PEC signals from the qualified samples have negative peak heights. Moreover, the peak height of PEC signals from the unqualified samples are much larger than those of the PEC signals from the unheat-treated bearing rings. It also comes to a conclusion that the decrease of rising time in PEC excitations suggests better sensitivity and reliability for sorting of heat-treated bearing rings.

Keywords: Bearing ring, heat treatment, hardness, pulsed eddy current

1 Introduction

Bearing is a basic part of a machine which dramatically affects the performance, life and reliability of a machine [1]. Unqualified bearing rings may occur in terms of hardness during the manufacturing process due to the imperfect heat treatment. Nondestructive testing of bearing rings after heat treatment is of great importance for ensuring quality. However, reliable and efficient identification of unqualified bearing rings in hardness is still an open problem.

Currently, there are ultrasonic, eddy current and magnetic methods available for hardness measurement in a nondestructive way. Ultrasonic hardness method is contact and inefficient, and would generate a slight indentation. Eddy current and magnetics methods are subject to misclassification, as there are multiple factors influencing the hardness like microstructure, carbon content, alloy composition, grain size and so on [2]. Recently, some researchers attempted to fuse two or more methods to improve accuracy and reliability. In this work, PEC testing is proposed to sort out heat-treated bearing rings in terms of hardness due to rich information. The results demonstrate that PEC testing is a promising candidate for accurate, efficient and reliable evaluation of bearing rings.

2 Experimental setup and samples

The PEC experimental setup includes a computer, signal generator (DG1022Z), data acquisition card (NI USB-6356) and probe. The pulse excitation signal from the signal generator is fed into to the probe. The data acquisition card communicates with the computer via USB interface.

11 fabricated bearing rings were fabricated as the samples in total. The samples were numbered from S1 to S11. The hardness of each sample was obtained by an Equotip 550 UCI ultrasonic hardness gauge, as listed in Table 1. The measured results show that the hardness of the qualified bearing rings is larger than that of the unqualified bearing rings, while the unheated bearing rings have a much lower hardness than the others.
### Table 1

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### 3 Results and discussions

With the developed PEC experimental setup, PEC signals were collected. After difference operations, the PEC difference signals from the samples were derived, as shown in Fig.1.

![Fig.1 PEC difference signals](a) 100 us (b) 10 us (c) 1 us

It is found that the PEC signals are quite different for qualified, unqualified and unheat-treated bearing rings. The PEC signals from the unqualified and unheat-treated bearing rings have positive peak height, whereas the PEC signals from the qualified bearing rings have negative peak height. It is also found that PEC evaluation of bearing rings could be improved in sensitivity and reliability by decreasing the rising time. The peak height of the PEC signals were derived, as shown in Fig.2. It comes to conclusion that PEC testing is feasible for nondestructive evaluation of heat-treated bearing rings.

![Fig.2 Peak height of the recorded PEC signals](Voltage/V)

### Acknowledgments

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### References


A0240 Fast Localization of Impact Damage on Woven CFRP based on Sparse Microwave Imaging

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Abstract

Microwave open-ended waveguide scanning has been proved to be a promising NDT technique for imaging of woven carbon fiber reinforced plastic (CFRP) with impact damages. However, the appearance of woven texture is opposed to an evaluation of impact damage on CFRP. Moreover, the typical C-scan is excessively time-consuming and therefore it is not effective for defect localization in large area. This work proposed a novel feature extraction and impact damage localization framework that mitigates woven texture effect and suitable for sparse measurement. First, a data set of full measurement of woven CFRP with impact damage is analyzed based on principal component analysis (PCA) to extract off-line statistical models of impact damage feature extraction with least influence of the woven texture. The sparse C-scanning process is simulated by stepped numbers of reduced sampling. In each sampling step, image reconstructed from the proposed feature is compared with image reconstructed from the classical feature (i.e., average magnitude over frequency). It is found in the results that the proposed method can accurately localize the impact damage with a smaller number of sparse sampling positions. In most cases, the impact area and its position can be identified by only 2% of full measurement.

Introduction

Woven carbon fiber reinforced plastic (CFRP) have been widely used in various engineering structures such as aerospace, automobile and civil engineering due to better stiffness to weight ratio property. Though, it is easily harmed by impact and dropped damage even at very low energy/velocity [1]. Microwave open-ended waveguide is a promising non-destructive testing (NDT) technique for woven and laminated composite imaging [2]–[4]. It clearly revealed both woven texture and impact damage on woven carbon composite [5], however, the appearance of woven texture diminishes an evaluation of impact damage, particularly, a tiny impact area caused by low impact energy. Moreover, the traditional area scanning process is tedious and thus is not effective for localizing damages in large area.

Recently, the microwave and millimeter-wave near-field imaging techniques based on sparse measurement has been introduced [4], [6]. It shows that the quality of the reconstructed images is equivalent to the original even with the sparse sampling rate of less than 20% [4]. However, the reconstructed images were simply generated from average magnitude over frequency or selective frequency and discarded useful information within its wide-band spectrum. In this paper, the PCA based feature extraction for impact damage is utilized for impact damage reconstruction. The proposed feature will be compared with traditional feature and evaluated through localization of impact damage based on sparse measurement.

Methodology and Results

The framework for impact damage feature extraction and localization is depicted in Figure 1, composed of two stages. The first stage is to learn offline modelling for impact damage feature extraction based on PCA. Once the impact damage feature model is chosen, the second stage perform online sparse measurement following by SAR image reconstruction based on selected feature and localisation of the impact damage. The comparison at various numbers of
measurement between typical SAR image feature (i.e., average magnitude) and our proposed PCA method is shown in Figure 2. It can be seen in the reconstructed images based on PCA feature clearly reveal the impact area with the number of measurements from only 18 positions (0.3% of full measurement). While the impact location of the image reconstructed by average magnitude feature is varying due to appearance of the woven texture. Moreover, due to less influence of texture, the PCA images simply render an area of single impact damage, which its centre location is located by the centroid of its cluster.

Figure 1. The framework for impact damage feature extraction and localization

![Figure 1. The framework for impact damage feature extraction and localization](image-url)

Figure 2. The reconstructed images using average magnitude, PCA and clustered PCA at various numbers of spare measurement

References

NATURAL CRACK EVALUATION BASED ON NOVEL YOKE STRUCTURED ELECTROMAGNETIC THERMOGRAPHY

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Abstract

Eddy current pulsed thermography (ECPT) [1][2] is a multi-physical coupling NDE technique which combines the well-established inspection techniques of eddy current, magnetism and infrared thermography. The configuration of ECPT system determines the direction and magnitude of the electromagnetic filed, thereby affecting the detection results [3][4]. This paper proposes a novel yoke structured eddy current pulsed thermography (ECPT) system for micro fatigue cracks inspection on irregularly shaped metallic materials. The proposed detection model provides a region of interest with a relatively uniform magnetic field. The detectability and thermal contrast of omnidirectional micro fatigue cracks are enhanced remarkably. In addition, the configuration has advantages of dramatically increasing portability and efficiency for detecting complex workpiece since the detection is completely in the open view of the infrared camera. Experimental studies have been conducted on natural fatigue cracks in order to validate the reliability and efficiency of the proposed sensing structure.

The novel yoke structure of ECPT system is proposed and illustrated in Fig. 1. Specifically, the excitation structure is made of open-view yoke and copper helix coil. At the same time, the infrared camera is positioned normal to the surface of the conductive material. The proposed detection model is a hybrid of magnetic flux, eddy current and infrared radiation which enables the detection more efficient. For the defect detection in electromagnetic thermography, the high frequency magnetic flux is used to induce eddy current and generate heat in the sample. Thus, the frequency has a great impact on the induction heating when the amplitude of the magnetic flux density is limited within a range. The excitation frequency in this model is typically chosen as several hundred kHz to generate intense eddy current in the sample. The displacement current density at this frequency is negligible. After setting the boundary conditions on the surface of the conductor, the distribution of electromagnetic field can be solved using the finite element method. When a defect exists in the ROI, the uniform eddy current will be destroyed. Specifically, the highest current density will be concentrated in tips and bottom of the notch. Fig. 2 shows the eddy current path around the crack.

Figure 1. The new configuration of ECPT system. Figure 2. Eddy current path around crack.
The sample with complex geometry and the detection results are shown in Fig. 3. The shape of the crack is a small cylinder, the radius and the height of which is both 0.5mm. Fig. 3 (b) is the result of defect-free surface. Fig. 3 (c) and (d) are the results of defective surface of 45# steel and 316# stainless steel, respectively. With the high thermal contrast, the performance of the detection using the proposed excitation configuration is validated.

![Image](image1.png)

Figure3. The detection model of the sample with complex geometry and the results. (a)The sample and the crack. (b)~(d) The temperature distribution on steel without crack, 45# steel with a crack, 316# stainless steel with a crack.

The screw sample with anomalous shape is shown in Fig. 4 (a), and the natural fatigue cracks are mainly concentrated at the root of the screw as marked by the red oval. Due to the cracks are close to the edge or hide in the root, the diagnosis is inconvenient and difficult to be performed by using conventional configuration of ECPT system. The crack in the root of screw is shown in Fig. 4 (b) and (c). As can be illustrated that the crack is extremely narrow and irregular. The verification experiments are performed by using the proposed novel configuration model to detect the fatigue cracks in the root of screws, and the thermal images are captured by the infrared camera as shown in Fig. 4 (d) and (e), respectively. The results illustrate that the cracks are detected with high temperature contrast and the crack shape are clearly visible.

In this paper, an efficient excitation structure of eddy current pulsed thermography system is proposed. The theoretical derivative model of the excitation structure is developed. The detection results of natural cracks on the surface of several metallic materials are investigated.

![Image](image2.png)

Figure4. The experimental sample and the detection results (a) screw (b)(c) the cracks in the root of screw (d)(e) detection results

References


The effect of grain and grain boundary microstructure on domain wall motion and magnetic Barkhausen noise under tensile stress

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Abstract:

Magnetic Barkhausen noise (MBN) is an effective electromagnetic method for stress measurement of ferromagnetic objects. The microstructure (such as grain and grain boundary) affect the activity of MBN signal, which can further interface the results of stress measurement. In this paper, the relationship between domain wall motion and the time characteristic of MBN during the magnetization process in different location is analyzed to evaluate the effect of microstructure on time characteristic of MBN. In addition, the difference of these magnetic parameters in different locations is highly affect by the tensile stress. The proposed work has potential for interpretation the effect of microstructure on MBN under tensile stress by studying DW motion, which can be further applied for enhancing accuracy on stress measurement.

Key words: magnetic Barkhausen noise, stress measurement, grain, grain boundary

Introduction:

Since stress concentration is the main cause of fatigue failure and micro defects, different electromagnetic methods have been applied in non-destructive testing (NDT) for stress measurement [1]. As a non-destructive method, magnetic Barkhausen noise (MBN) is applicable to ferromagnetic materials, which are composed of small order magnetic regions called magnetic domain [2-3]. The microstructure of a magnetic material interferes with the movement of magnetic domain walls, which can further affect the activity of MBN signal [4]. In this paper, the micro-macro magnetization process in different location is analyze to evaluate the effect of microstructure on time characteristic of MBN under tensile stress. In addition, the difference of these magnetic parameters in different locations is highly affect by the tensile stress.

Design and Results:

MBN signal and DW structure of the silicon steel sheet are captured by MBN detection device and a longitudinal MOKE microscopy as shown in Figures 1. The diameter of MBN probe is 10mm. Applied magnetic field is in stress direction. To obtain DW and MBN signal, the magnetization frequency is 0.5 Hz.

![Experimental set-up for MOKE and MBN observation](image)

Figure 1. Experimental set-up for MOKE and MBN observation

Figure 2 show DW motion in different location of the sample under tensile stress. The microstructure of grain boundary can affect the distribution of magnetic domain, the behavior of DW motion and magnetization process around the grain boundary under tensile stress. When the
tensile stress is 121 MPa, the strength of external magnetic field required to make material achieve saturation magnetization, is significantly bigger in S1-gb12 than this in S1-g1 and S1-g2.

As grain boundary can affect the magnetization process, which lead to the different MBN behavior [4]. From Figure 3, the MBN signal is much larger in S1-gb12 than these in S1-g2 and S1-g1 under stress. The difference of the time characteristic of MBN in different locations increase with tensile stress. These phenomena are consistent with the results shown in Figure 2.

<table>
<thead>
<tr>
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<th>121 MPa after demagnetization</th>
<th>18 MPa after demagnetization</th>
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<tr>
<td></td>
<td>0.15 kA/m</td>
<td>0.30 kA/m</td>
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<td>S2-g1</td>
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<td></td>
<td>0.71 kA/m</td>
<td>0.68 kA/m</td>
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<td>S2-gb12</td>
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<td>S2-g2</td>
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Figure 2. The magnetic domain of sample 2. The sizes of magnetic domain images are 8.14 mm × 6.94 mm.

Figure 3. MBN signal in different location under tensile stress: (a) g1; (b) gb12; (c) g2.

**Reference**


RECONSTRUCTING THE 3-D SIZES OF DEFECTS WITH MAGNETIC FLUX LEAKAGE TESTING SIGNAL

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Abstract

Magnetic flux leakage testing (MFLT) is highly efficient and easy to operate, has shorter test time and strong noise resistance, requires simple equipment, and is effective in detecting deep defects. Thus, it is an important nondestructive testing technology that has been extensively used to find metal-loss defects in critical ferromagnetic structures and components, such as rail tracks, pipelines, and tubes. Ensuring the equipment’s safety is greatly significant to reduce the accident rate and to protect the ecological environment. However, the current MFLT technology is mainly used to locate defects in ferromagnetic components and inadequate for quantitatively evaluating defect size. MFLT is influenced by the length, width, and depth of a defect and thus provides useful information about the size of the defect. Therefore, determining the size of a defect by using MFLT signals conceives great potential.

Evaluating defect size by using MFLT signals is a typical back-stepping problem. Current methods mainly include statistical analysis [1-2], neural network [3], and iterative method [4]. Statistical analysis correlates the dimension parameters of simple and regular defects with the characteristic parameters of MFLT signals by using several algorithms. Neural network method sets up the mapping function between the dimension parameters of defects and the characteristic parameters of MFLT signals. These two methods can be used to determine the sizes of simple and regular defects and inadequate in quantifying complex defects. Meanwhile, the iterative method applies iterative algorithm to estimate the dimensions of a defect according to the governing equation between MFLT signals and defect parameters [5-7]. The method allows the calculation of changes in the dimensions of a defect with a governing equation in real time and thus preparing samples and training data in advance is unnecessary. The solution for defect size is promising, especially for the quantitative evaluation of the sizes of defects with complex shapes.

The sizing of a three-dimension arbitrary defect, by using MFLT signal, is a hot and difficult issue of MFLT. The key factor of the iterative method is the establishment of a governing equation, which correlates the dimensions of a defect with an MFLT signal. This study intends to explore a three-dimensional qualitative method for characterizing arbitrary defects by using MFLT signals. First, we derived the governing equation correlating the depth field of a defect with an MFLT field signal. Second, we designed the reconstruction algorithm and set up a reconstruction program. Third, the validity and accuracy of the reconstruction algorithm was verified through an experiment.

Fig. 1 shows the schematic diagram of a physical model, which illustrates the correlation of defect dimensions with the MFLT signal. In this model, an arbitrary defect is located at the center of a continuous structure. After being magnetized by a magnetic field of $H_y$, along the $y$-direction of the structure, magnetic charge with density of $\rho$ is distributed inside the structure.

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The magnetic charge distribution is blocked by the defect, discontinuous around the defect, and influenced by the defect’s depths in different points. We name the depths in all points as depth field \( \{d_i\} \) because the depth of \( d_i \) varies with source point \( r_i' \). \( \{B\} \) is the tested data matrix of MFLT signal at all field points \( r_j \), and \( h \) is the lift-off of the test sensor, which is equal to the distance in \( z \)-direction between the field point \( r_j \) and the top surface of the structure.

![Fig. 1. Physical model of the defect correlation with MFLT signal](image)

**References**


**Acknowledgments**

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QUANTITATIVE EVALUATION AND IMAGING OF LOCALISED THICKNESS LOSS IN GFRP WITH $K_a$-BAND MICROWAVE OPEN-ENDED WAVEGUIDES

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Abstract

Glass Fibre Reinforcement Plastic (GFRP) is extensively used in industrial fields as aerospace, marine, construction and medicine, etc [1]. In harsh and severe environments, the thickness loss which normally occurs in in-service GFRP due to collision, is one of the typical GFRP defects [2]. It causes serious threats to the integrity and safety of GFRP. Therefore, it is indispensable to conduct quantitative evaluation of the thickness loss in GFRP with Non-Destructive Testing (NDT) techniques such as ultrasonic testing [3] and acoustic emission [4]. Complementary to these methods, microwave NDT has been found to be one of the promising techniques in GFRP evaluation. In this paper, the microwave NDT for quantitative evaluation and imaging of the Localised Thickness Loss (LTL) in GFRP is intensively investigated. A 2D Finite Element Model (FEM) with the $K_a$-band open-ended waveguide [5, 6] and GFRP sample subject to LTL is set up and applied for analysis of field characteristics and testing signals. Following that, an experimental investigation is conducted to further study the feasibility of microwave NDT with the $K_a$-band open-ended waveguide for LTL imaging.

In consideration with the particular propagation characteristics of the microwave in TE$_{10}$ mode, the 3D FEM is further simplified into a 2D model in order to improve simulation efficiency. The schematic of the 2D model is presented in Figure 1. In simulations, the scattering parameters including $S_{11}$ and $S_{21}$ in conjunction with the Nicolson–Ross–Weir (NRW) algorithm [7], are used for: (1) calculation of the equivalent permittivity of the Material Under Test (MUT); and (2) analysis of the correlation between the equivalent permittivity and LTL depth. The monotonic relation of the computed equivalent permittivity of the MUT with LTL depth is portrayed in Figure 2.

In parallel, the experimental system is built up for investigation of LTL imaging. The system is shown in Figure 3. The imaging results of the LTL with the fixed diameter of 10mm

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and depths of 2mm, 4mm and 6mm are shown in Figure 4 with the red solid lines depicting the real LTL profiles. It can be found from Figure 4 that the LTL in the GFRP sample can be readily detected by the $K_a$-band open-ended waveguide.

**Figure 3. Experimental set-up**

**Figure 4. Imaging results of LTL**

In summary, the $K_a$-band open-ended waveguide of microwave NDT is investigated for the quantitative evaluation and imaging of LTL in GFRP. Through the 2D FEM-based simulations and experimental investigation, the feasibility of the $K_a$-band open-ended waveguide for LTL evaluation and imaging is identified.

**References**


**Acknowledgments**

The authors would like to thank the Natural Science Foundation of China (Grant No. 51777149, 51477127), National Key R&D Program of China (Grant No. 2017YFF0209703), and Fundamental Research Funds for the Central Universities of China (Grant No. XJJ2018027) for funding this research.
EDDY CURRENT TESTING OF THE LIGHTNING STRIKE PROTECTION LAYER IN AEROSPACE COMPOSITE STRUCTURES

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Abstract

Metals, especially aluminum and titanium, were extensively used to construct aerospace structures decades ago. Since 1990s, carbon fiber reinforced polymer (CFRP) composites have been increasingly used due to its high strength-to-density ratio and resistance to corrosion. Nowadays, composites can be the major part of the aircraft. For example, the Airbus A350 XWB is made of more than 50% composites while the Airbus NH90 comprises 90% composites [1]. One of the main drawbacks of changing the aerospace structure from electrical conductive metal to semi-conducting composite is the vulnerability to lightning strike damage [2]. Lightning strikes, with current up to 200 kA, could cause fiber breakage, resin deterioration and delamination in composites. In order to protect the composite structure, a lightning strike protection layer, in the form of metal mesh, is commonly incorporated in the composite to dissipate currents [3].

The lightning strike protection layer could be damaged by huge current or corrosion and lose the ability to protect the composites. In order to guarantee its functionality, its integrity must be inspected. Eddy current testing (ECT) is an efficient technique for detecting defects in both metal [4] and composite [5]. Therefore, it is implemented to inspect the breakage of lightning strike protection layer in this paper. The sample and the ECT probe are shown in Figure 1. The ECT probe consists of an excitation coil outside and a coaxial sensing coil inside. In order to tune the resonant frequency of the coils, the inductances of the two coils were measured when they were in air. A capacitor of 3.9 pF was connected to the excitation coil in series and a capacitor of 1.5 nF was connected to the sensing coil in parallel. A resistor of 10 Ω was also added to the excitation circuit in series to measure the excitation current. The excitation signal, with frequency of 150 kHz and peak-to-peak amplitude of 1.8 V, was generated by an arbitrary function generator and was amplified by a power amplifier. The layup of the sample is shown in Figure 2. It consists five layers of CFRP material, each layer is with thickness of 0.8 mm. Copper tapes, with thickness of 100 µm, were adhered onto the surface of the third layer to simulate a section of the metal mesh.

Figure 1. Experimental setup.  
Figure 2. Layup of the sample.

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The probe was driven by a two-axis positioning system to make a scan above the sample in an area of 81 mm × 81 mm with steps of 1 mm. At each location, the peak-to-peak amplitude of the sensing coil voltage was acquired by an oscilloscope and were send to a computer. Eddy current testing signals are prone to be influenced by lift-off changes. To reduce the influence of lift-off on the scanning result, the output voltage of the sensing coil obtained at the starting point were subtracted from the values at the other three corners of the scanning region. The differences were used to form a baseline matrix of 81 × 81 points by interpolating linearly from the corners. The final result, which is shown in Figure 3(a), was obtained by subtracting the baseline matrix from the output voltages of the sensing coil. As a comparison, a photo of the metal mesh is shown in Figure 3 (b). Three artificial breakages were made in the copper tapes with different widths. From the ECT results in Figure 3(a), it can be seen that the locations and dimensions of the copper tapes were accurately imaged, and at the junctions of two tapes, the ECT signals have larger perturbations. Furthermore, all the three breakages were successfully detected, and the perturbation increases with the width of the breakage.

![Figure 3](image_url)

**Figure 3.** (a) ECT scanning result; (b) a photo of the metal mesh with breakages.

**References**


**Acknowledgments**

This work was developed at Instituto de Telecomunicações and it was supported by the Portuguese Science and Technology Foundation (FCT) under projects UID/EEA/50008/2019 and PTDC/EEI/EEE/30723/2017. The supports are gratefully acknowledged.
QUANTITATIVE EVALUATION OF CONDUCTIVITY DISTRIBUTION INSIDE STRESS CORROSION CRACK WITH ELECTROMAGNETIC NDE METHODS

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Abstract: This paper presents a study on the distributed electrical conductivity of stress corrosion crack (SCC) aiming to improve its sizing precision when using electromagnetic non-destructive testing (ENDT) techniques. Numerical investigations were carried out to clarify the influence of crack conductivity on NDT signals of the direct current potential drop (DCPD) and the eddy current testing (ECT) method respectively. In addition, experiments of the DCPD and ECT method were also conducted for specimens with artificial SCCs. Inversion schemes, consisting of efficient forward simulator and a deterministic optimization algorithm, were proposed and implemented for reconstruction of electrical conductivity and size of SCC from both the DCPD and ECT signals. The reasonable reconstruction results from measured NDT signals proved the validity of the inversion schemes. The conductivities distribution obtained in this work reveals that the crack conductivity is larger in crack tip area, which gives a good reference to enhance the sizing accuracy of SCC from ENDT signals by updating its numerical model to a crack of distributed conductivity.

Introduction

Stress corrosion crack (SCC) inevitably occurs in key structural components such as those of nuclear power plants (NPPs) as a result of residual stress and water environment. Much attention has been paid to the non-destructive testing (NDT) and quantitative evaluation of SCC in order to ensure the structural integrity of NPPs. Electromagnetic NDT methods, such as eddy current testing (ECT), are studied for sizing of this type of natural crack. However, the sizing precision is still not satisfied due to its complex profile, especially the unknown conductivity distribution in SCC region \cite{1-2}. In this paper, the quantitative assessment methods for local conductivity inside SCC were developed and implemented with two typical electromagnetic NDT techniques. The experimental signals of direct current potential drop (DCPD) and eddy current testing (ECT) were measured to reconstruct the distributed conductivity of practical SCCs by addressing the proposed inversion schemes.

Quantitative Assessment of Conductivity inside SCC with ECT Method

The ECT technique, as a conventional NDT method to measure the electrical conductivity of metallic materials, has been widely applied in many industrial fields, but is not available directly for measurement of conductivity inside the SCC region. In this work, a strategy was put forward to evaluate SCC conductivity layer by layer in crack depth direction through inversion of ECT signals of the same probe and frequency. The ECT signals of layer in different depth were measured separately by scanning the ECT probe along the crack length direction for the specimen plate with its top layers were removed by grinding machining, which were calibrated and utilized as the target signals for reconstruction of SCC conductivity. An inversion scheme, consisting of a fast forward solver and the particle swarm optimization

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(PSO) algorithm was proposed and adopted to reconstruct the conductivity of SCC. The detailed results will be presented in the full paper.

**Conductivity Distribution Reconstruction in SCC Region Based on DCPD Signals**

A novel strategy to measure the local conductivity around a real SCC was proposed based on DCPD technique. To get the distributed conductivity inside a SCC, two specimen plates each with a SCC in its center region were fabricated and cut into groups of thin slices to measure DCPD signals and to evaluate the local conductivity through an inverse analysis slice by slice. A 4-probe DCPD experimental system was constructed as shown in Figure 1(a) to conduct DCPD measurements and gain the signals due to SCC. A typical DCPD signal measured with the measurement system at a scanning line is shown in Figure 1(b). To reconstruct the local conductivity from measured DCPD signals, a numerical inversion scheme was proposed and implemented. The DCPD forward simulator with multi-medium element was updated for efficient calculation of DCPD signals of a conductive crack with complex boundary profile and the conjugate gradient optimization method was adopted for the conductivity reconstruction.

![Figure 1. (a) Schematic diagram of the experimental system for DCPD signal measurement, (b) Measured potential drop signals of the scanning line located in the 1.5 mm SCC depth](image)

**SCC Conductivity Evaluation Based on Feature Signals of Magnetic Flux Density**

A strategy for the local conductivity estimation was also proposed by inversion of the measured magnetic flux density signals due to excitation coil. The advanced MME method, different with that utilized in DCPD method, was approached and updated at first to improve the simulation model of SCC. Then the signals of magnetic flux density were measured for the sliced SCC specimens by using an experimental system developed by authors. Finally, several feature parameters of the magnetic flux distribution were suggested and extracted to determine the conductivity inside SCC through inverse analysis.

**References**


**Acknowledgments**

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ELECTROMAGNETIC NDT METHODS FOR EVALUATION OF STEEL SPECIMENS AFTER TENSILE TESTING

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Abstract

The tensile testing techniques are frequently used [1] to obtain the mechanical properties of materials. In this research changes (deformations) observed in the material at different level of loading were evaluated using selected electromagnetic methods. The short version of the contribution presents results achieved using measurements of residual magnetization. All measurements were made using a computerized universal NDT system. The residual magnetization of the sample is measured by a transducer containing a magnetic field sensor (HMC5883L [2]). In order to obtain complete information about the flux distribution, an AMR (Anisotropic Magneto-Resistive) three axis sensor was utilized. Simultaneous measurements of all three magnetic field components enhance the capability to detect changes in the material regardless a different orientation.

In order to evaluate performance of the electromagnetic system, a set of experiments were carried out. The first experiment was done using 9 tensile samples made of the carbon steel S355J2G3. The photo of the samples and the dimensions are presented in Fig. 1. For each sample a different level of the stress was applied, as it is shown on a tensile stress-strain curve (Fig. 2).

Figure 1. The tensile samples made of the carbon steel S355J2G3 (all dimensions in mm)

Figure 2. The tensile stress – strain curve achieved for S355J2G3 samples (0-8 – the sample numbers)

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The samples after the tensile test were demagnetized and then magnetized in a solenoid. The residual magnetization was measured in case of all samples by scanning the sensor in \( x \) and \( y \) axis direction. Then scanning step in \( x \) direction is 0.5 mm and in \( y \) direction is 1 mm. Example of the measurements achieved for the selected samples are shown in Fig. 3. The measured signals (\( B_x, B_y, \) and \( B_z \) components) were further processed (Fig. 3 - right) in order to enhance changes caused by the material deformations.

Influence of various factors (e.g. magnetization current, time since magnetization) on the achieved signals was investigated, and it will be presented in the full version of the paper. All the achieved signals were analyzed and relationships with the stress and strain were explored. Several different parameters (Fig. 4) were proposed to identify conditions of the sample. The parameters were evaluated and it was proved that they enable to identify level of the applied stress. Results of this evaluation as well as the results obtained using other testing methods will be provided in the full version of the paper.

![Figure 3](image1.png)

Figure 3. The original signal (\( B_x \) [p.d.u]) (left) and signal after processing (right) achieved in case of the sample S0 (top), S4 (middle) and S6 (bottom).

![Figure 4](image2.png)

Figure 4. Plot of the stress-strain curve and selected parameters of the measured signals.

References
MAGNETIC PROPERTY CHANGED BY INTERACTION OF IMMUNO-MAGNETIC NANO-PARTICLE WITH BACTERIA CELL

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Abstract

Foodborne pathogens have greatly impacted global public safety and health. Infectious diseases from foodborne, such as Salmonella infection, are the cause of death to approximately 155,000 people per year as reported by the World Health Organization [1]. Recently, several developing and developed countries are affected from foodborne disease. In the United States Alone It was reported that about 48 million cases suffered particularly diarrheal and invasive diseases from food consumption. The 14 most caused diseases include Salmonella enterica, Clostridium botulinum, Campylobacter spp., non-typhoidal Pathogenic Escherichia coli and norovirus [2].

Immuno-magnetic nanoparticles (IMNPs) are well-known several biological applications including contrast agent for magnetic resonance imaging (MRI), bacterial detection, drug delivery, hyperthermia, and magnetofection. IMNPs have been used for capture and concentration of target bacteria [3]. In foodborne detection, IMNPs are generally able to concentrate the target bacteria in any solution without enrichment processes which can helper to reduce the processing time and cost for conventional detection methods. Besides the benefits of IMNPs as described above. The magnetic properties change of IMNPs should be focused by detecting the change when IMNPS captured the target bacterium cell.

The previous research [4] found that the magnetic properties of IMNPs would be changed by capturing with bacterium cell, and concluded that a coercively force and retentively from B-H curve related to the captured bacterium cell concentration. The maximum variation of coercively force from B-H curve was 25 Oe which was quite low which could be the effect from any IMNPs preparation steps before using the IMNPs to detect the target cell. To convince the feasible of develop the bacteria detection test kit based on the electro-magnetic responding sensing in next development research, all steps in the IMNPs preparation and capturing process should be studied for improve the test kit development.

This research explored the realistic mechanism of IMNPs which lead to the change of the magnetic properties in the bacteria detection process. The research hypothesis was determined that the variation of magnetic properties could be from an atom and electron condition in IMNPs molecule. The synchrotron XAS with high sensitivity and resolution, could discover the information of the atomic structure and electronic transfer of IMNPs throughout three surface modifications and the bacteria capturing steps for observing the effects of each step. The change of magnetic properties were approved by the vibrating sample magnetometer (VSM).

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Figure 1. XAS Energy absorbant Spectrum of IMNPs –Salmonella capturing protocol

References


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An electromagnetic acoustic transducer for generating and receiving torsional mode guided waves

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Abstract

A new electromagnetic acoustic transducer (EMAT) to generate and detect torsional waves is provided based on Lorentz force and magnetostrictive effect. The transducer consists of several rectangular coils which are vertical to the pipe’s surface and a set of magnets oriented perpendicularly to the pipe. To confirm that the T(0,1) mode guided waves could be generated by the transducers, the experiment is performed. The velocity and spectrum of the experiment data are compared with the theory to verify the guided waves mode. The T(0,1) mode is confirmed by the velocity and the non-disperse characteristic of the wave.

Key words: torsional wave; EMAT; non-contact transducer; guided waves

1. Introduction

Recent years, the technology of guided waves has been applied to nondestructive testing (NDT) of pipelines because the technology can inspect over long distance from a single position \cite{1-2}. The advantage of the technology of EMAT generated guided waves compared with the piezoelectric technology is non-contact needed for measurement. The first torsional wave mode T(0,1) is preferred because the branch is non-dispersive and favorable for signal processing. EMATs have been applied and studied by many researchers \cite{3-4}. The Kwun’s transducer consists of a nickel strip and a solenoid coil surrounding the strip \cite{5}. The strip is bonded circumferentially to a pipe and a permanent magnet is rubbed on the nickel strip for premagnetization. The Kim’s transducer consists of several pieces of nickel strips which are attached to the test specimen with the alignment angle 45° \cite{6}. In addition, the Kim’s transducer needs to be bonded circumferentially to the pipe. Kwun also used a drawbar nose piece insert the pipes to generate the torsional wave which coupled the torsional wave to the tube through the mechanical contacts formed at the tip area. In general, their methods of generating torsional waves using EMATs need contact with the specimen. In other word, some coatings need to be removed at the position of transducers and sensors to inspect the coated pipes which will weaken the overall performance of the coatings. The sensors for detecting torsional waves also need to contact the rod or tube directly. Due to these characteristics, the application of the technology has been limited.

2. Transducer structure

Figure 1 shows the schematic of the structure of the designed transducer. The transducer includes two coils, several pieces of permanent magnet, a connector, a cover board and a shell. The shell is made up of non-ferromagnetic materials. The shell with a V shape bottom can mount on the specimen which need not contact with the specimen directly. The permanent magnets are placed in a cubical hole of the center of shell. The coils are placed at the both sides of the permanent magnets with the same current direction. Both the coils are connected the connector. When the transducer is taken as a transmitter, the pulse is imported by the connector. When the transducer is taken as a receiver, the induced signal is exported by the connector. There is a cover board to protect the coils and the permanent magnets on the top of the shell. When the transducer is mounted on the pipe as a transmitter, the length of the coils is parallel to the axis of the pipe and its plane is vertical to the pipe’s surface. If the pulse is imported the coils, there will induce the AC magnetic field with the circumferential direction in the pipe which bases on the law of electromagnetic induction. The permanent magnets will induce the DC magnetic field with the radial direction in the pipe. There will generate the torsional mode guided waves in the pipe which bases on Lorentz force and Wiedemann effect. In the same way, when the transducer is taken as a receiver, the coils can induce the torsional mode guided waves in the pipe which bases on the law of electromagnetic induction and Matteucci effect.

![Figure 1 Schematic of the transducer structure](image-url)
3. Experiment setup

In the experiment, approximately the 3.2m long, 38mm outside diameter, and 5mm wall pipe was used as the specimen. The transmitting transducers were placed at the left end of the pipe and the receiving transducer was placed at approximately 1800 mm from the left end of the pipe respectively. The transmitting transducers made up of two transducers which were mounted on the pipe face to face. The rectangular transmitting coils were made of 30 turns of No.24 gauge wire, approximately 60mm length and 30mm width. The length of the coils is parallel to the axis of the pipe. The permanent magnets include four Nd-Fe-B permanent magnets. The size of permanent magnet is 10 mm (H) * 40 mm (L) * 30 mm (W). The receiving transducer is made up of one transducer. The difference from the transmitting transducers is the receiving coils which are made of 60 turns of No.37 gauge wire. Figure 4 illustrates the schematic diagram of the transducers setup on the specimen. The data that was obtained using a pulse excitation, in this case at 60 kHz, is given in figure 2(a) and the short-time Fourier transform of the signal is shown in figure 2 (b).

![Image](a) Time domain waveform (b) Time-frequency domain waveform

Figure 2 Data taken from a 3.2m long, 38mm OD, 5mm wall steel pipe at 60 kHz

The first signal in the figure is the initial tone-burst pulse applied to the transmitting coil which was electrically leaked to the receiving coil from the air at velocity of light. The second signal, occurring at approximately 0.556ms from the initial pulse, was the signal detected when the transmitted elastic wave passed through the receiving coil. The third signal is the end-reflected signals. The end-reflected signal is the one detected during the return trip of the elastic wave after reflection from the end of the pipe near the receiving coil. This wave travels with a velocity of approximate 3237m/s (1.8m/0.556ms). Judging from the velocity based on the group velocity dispersion curve, this wave could be the lowest-order torsional mode or the second longitudinal mode. The magnitude of the signal at each point in frequency and time is represented by the color scale. Red represents the maximum amplitude and blue the minimum. Figure 2 (b) clearly shows that the energy of each pulse is up to the excitation frequency 60 kHz. The non-dispersive characteristic of the first branch of the torsional wave is revealed by the straight vertical lines in the time-frequency plane.

4. Conclusions

A new EMAT to generate and detect torsional waves is provided in the paper. The transducer consists of several rectangular coils which are vertical to the pipe’s surface and a set of magnets orient perpendicularly to the pipe. The T(0,1) mode guided waves could be generated by the transducers which is confirmed by the velocity and the non-disperse characteristic of the wave. However, there are other modes existences in the wave generated by the transducers. More work should be focused on the signal processing, the improved design of the transducers and the placement of the bias magnet field to obtain purer T(0,1) mode guided waves.

Acknowledgements

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References

Abstract: A non-contact laser ultrasonic B-scan system was established to detect the surface defects of 316L stainless steel samples prepared by SLM process in different lengths. According to the influence of SLM technology on material residual stress, samples were simulated to observe the surface wave propagation station. Then, according to the principle of surface wave diffraction at defects, B-scan images of surface cracks with different lengths were obtained, which realized the quantitative detection of surface defects. In order to further improve the signal-to-noise ratio (SNR) and improve the accuracy of imaging detection, variable mode decomposition (VMD) is used to decompose the collected ultrasonic signal, and the imaging detection of surface length defects is realized clearly and accurately. The experimental results show that this imaging detection method can effectively avoid the influence of SLM processing technology on wave velocity in different directions, and the imaging accuracy after VMD is 30% higher than that of 10-fold average method.

1. Introduction

Additive manufacturing is a novel technology of high importance for global sustainability of resources. However, there are some shortcomings, such as poor surface quality of formed parts and easy to appear micro-cracks, which affect the performance of materials. Laser Ultrasound (LU), as a new non-destructive testing technology, not only inherits the advantages of traditional ultrasonic testing, but also realizes non-contact excitation and detection [1]. The Canadian National Research Council (CNRC) used laser ultrasound combined with SAFT (synthetic aperture focusing) to detect the shallow surface defects of 718 Alloy and TC4 titanium alloy [2]. D. Cerniglia used B scan to detect the sandwich defects of the added material parts, which confirmed the feasibility of using laser ultrasound for imaging detection of the AM material [3].

In addition, in the signal detection, the complexity of the internal structure of the material makes the measured signal have greater noise interference. Therefore, it is necessary to de-noise the ultrasonic signal. VMD (Variational Mode Decomposition) is a recently proposed time-frequency analysis method, which can better separate the components of complex multi-component signals, and is very suitable for the extraction of non-linear and non-stationary characteristics of ultrasonic signals [4].

2. Theory and simulation

Surface wave will reflect and diffract when it interacts with defects during propagation, as shown in Fig. 1. Combined with the time delay of the surface wave received with or without defect, further quantitative detection of the defect length can be realized.

Sample simulation model was established based on SLM technology. It can be seen that the wave velocity of the cladding layer in the axial direction is different from that in the horizontal direction. As shown in Fig. 2, B scan mode can ensure the excitation and acceptance in the same horizontal direction and avoid the influence of the wave velocity in the direction.

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3. Experiment

Fig. 3 is a laser point B-scan system. The processing method of the sample is SLM, and the material is 316L stainless steel. Three groove defects were machined on the surface, which are 2 *0.5 *1 mm, 0.8 *0.5 *1 mm and 6 *0.5 *1 mm, respectively. They are in different lengths. As shown in Figure 4. In order to verify the advantage after VMD, the imaging results are compared with the original signal after ten times average. The result is shown in Fig. 5. After VMD processing, the accuracy is improved by nearly 30%.

4. Conclusion

In this paper, the quantitative detection of different surface length defects of 316L steel by SLM process is carried out, and a completely non-contact laser ultrasonic B-scan detection platform is built, which avoids the influence of directional wave velocity and achieves fast scanning imaging. In order to further improve the SNR and the accuracy of the imaging results, VMD decomposition of the collected ultrasonic signal is applied, which makes the signal more stable and realizes the visual quantitative detection of defects clearly and intuitively. In addition, the VMD de-noising imaging results are compared with the 10-fold average results. The results show that the laser ultrasonic testing technology has high sensitivity to the surface defects of the sample, and can effectively determine the location and length of the defects. The imaging accuracy after VMD is about 30% higher than that of the 10-fold average signal.

5. Reference


Magnetic measured theory and experiment research of three-dimensional residual stress for ferromagnetic components based on piezomagnetic effect

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In the manufacturing process of pressure vessels and pipes, after hot and cold processing (such as cold rolling, welding), residual stress generally exists in the vessels or pipes. And the static load strength, fatigue strength and stiffness of ferromagnetic components will be affected. At present, there are many non-destructive measuring method of residual stress, such as X-ray method, neutron diffraction method, magnetic method, ultrasonic method and so on. However, the X-ray equipment is large, the person who use it need to be protected. The ultrasonic method is greatly affected by the coupling condition \(^{[1,2]}\). Compared with them, more advantages are appeared in the magnetic method. Because the ferromagnetic materials are very sensitive to microstructure and stress changes, the magnetic method can measure the residual stress by measuring the characteristic magnetic field variation of the structure surface \(^{[3,4]}\). The magnetic method is flexible. It is fast in obtaining information, and can test various kinds of materials and reach any measuring point. The surface of the tested material does not need any treatment. It can be used for contact and non-contact measurement. So the magnetic method has great application advantages in the detection and evaluation of residual stress of ferromagnetic components.

When the stress is applied to ferromagnetic components, the permeability of the component will change, it is known as the piezomagnetic effect. Because of the magnetic anisotropy of ferromagnetic materials, the permeability changes of the components are inconsistent in all directions, which are related to the stress. Therefore, the piezomagnetic effect can be used to detect the residual stress of ferromagnetic components. At present, the research of magnetic residual stress measurement methods is based on two-dimensional plane stress theoretical models, such as mathematical models of different types of sensors and so on \(^{[5]}\). However, quantitative detection theory of three-dimensional residual stress exists some difficulties. Especially for thick structural parts, if the surface residual stress is only known in the weld zone or zone closed to the weld, and the internal residual stress distribution is not clear, the fatigue cracks would occur in the interior. Therefore, it is necessary to study the theory and Experiment of the magnetic method for three-dimensional residual stress of ferromagnetic components based on magnetic anisotropy.

On the basis of the theory of magnetic circuit analysis, by loading periodic sinusoidal current, this paper studies the mathematical relationship between plane stress and induced voltage based on nine-pole sensor, and analyzes the influence of air gap on the results of magnetic measurement. Moreover, an approximate linear relationship model is established between the magnetic properties changes of materials and the sum of plane stresses under the exciting field which is perpendicular to the two-dimensional plane \(^{[6]}\). These models can be used to calculate the three-dimensional residual stress distribution of ferromagnetic components. The schematic diagram of the theoretical model is shown in figure 1.

![Fig.1 Theoretical model of the magnetic measured method for three-dimensional residual stress](image)
In fig. 1, it is assumed that the nine-pole magnetic sensor is placed on the surface of the weld. There is residual stress in the weld area, and the distribution of magnetic permeability is not uniform. This reflects the distribution (size and direction) of residual stress in the weld area. The theoretical model only provides the relationship between the primary stress difference (σx − σy) and the induced voltage U. The states of the stresses at the measured points are obtained need shear stress difference method. Then the exciting magnetic field in the x direction is applied, and the maximum flux density Bm is approximately linear with the main stress sum. After the linear relationship is used, the stress σ1 in the direction of vertical plane stress will be obtained. Combined with the skin effect of ferromagnetic materials, the interior three-dimensional residual stress model of thick ferromagnetic components can be further obtained.

Then, based on the theoretical model, a three dimensional residual stress testing platform of ferromagnetic components is constructed. The test platform is mainly composed of test specimen, excitation device, nine-pole magnetic sensor (see fig. 2), U-type magnetic sensor, collecting and processing device of detection signal. Among them, the exciting device is used to generate magnetic field, the nine-pole magnetic sensor is used to analyze the size and direction of plane stress, the U-type magnetic sensor is used to load the magnetic field in the x direction, and the collecting and processing device is used to obtain the induced voltage signal and flux density value.

Fig. 2 A nine-pole magnetic sensor

Finally, calibration experiments are carried out on the test platform, and calibration coefficients under different conditions are measured. Using the test platform, we also verify the theoretical model of magnetic measured method for three-dimensional residual stress of ferromagnetic components. The results show that the modified theoretical model can be used to measure the three-dimensional residual stress of ferromagnetic components at the measured points.

Reference:
Development of an omni-directional PPM EMAT for plate inspection

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Abstract

Electromagnetic acoustic transducer (EMAT) has been widely applied in non-destructive tests for structural health monitoring. Due to the non-dispersive characteristic of the SH₀ mode propagating plate structure, this mode has certain advantages in non-destructive testing of plate structure. This paper proposes an omni-directional shear horizontal mode EMAT, which uses fan-shaped periodic permanent magnet (PPM) and spiral coils, in order to realize the excitation of omnidirectional SH₀ mode based on Lorentz force effect. The experiment proves that the omni-directional shear horizontal mode EMAT can excite a single SH₀ mode in the aluminum plate, and it has good frequency response characteristics. The omni-directional test shows that the developed omni-directional PPM EMAT can excite SH₀ mode propagating along 360 degrees.

Figure 1. Working principle of the transducer

Figure 2. Lorentz force simulation diagram of the transducer

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MICROWAVE SENSOR BASED ON COPLANAR WAVEGUIDES FOR DIELECTRIC CHARACTERIZATION

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Abstract

This paper presents a novel microwave sensor based on the coplanar waveguide (CPW) for characterizing the complex permittivity of an unknown dielectric sheet. By combining the advantages of symmetry and IDC configuration, the interference was suppressed with minimum errors, and the sensing resolution has been further improved. To analyze the sensing capability of the proposed sensor, the presented sensors which configured in three different fingers of IDC unit as depicted. The sensitivity of the sensor to variation in frequency and amplitude has been estimated by modulating the dielectric permittivity of MUT.

Microwave sensors can be used for determining the dielectric characterization of materials. This characteristic make it very useful in agricultural, industrial, scientific, and biomedical applications over the past several decades [1-4]. According to Debye theory, the dielectric parameters are strongly-dependent on the frequency at which the material would be used [5]. Therefore, significant microwave measurement sensors including resonant and non-resonant methods have ensued in characterizing the complex dielectric properties of the material at RF and microwave frequencies. Recently, researchers found that the sensitivity of dielectric sensors can be increased by virtue of CPW geometries, as both the center strip and side-plane conductor are printed on the same surface of the substrate, which makes them capable of possessing less dispersive, weaker cross-sensitivity, and minimize the possible fringing effect as compared with other planar configurations. As a result, the CPW-based circuits gradually considered as an attractive candidate for dielectric sensing.

In this research, a novel symmetric coplanar waveguide sensor has been developed for determining the complex permittivity of thin dielectric materials. The proposed sensor consists of two identical CPW divider sections loaded with pairs of IDC units. The operating principle of the sensor follows on perturbation theory caused by symmetry disruption when exposed to the MUT. The sensor presents real-time response and high sensitivity, which makes it a good candidate for determining the permittivity of materials in different ranges of frequency band.

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Figure 1. The simulated electric-field concentration near IDC unit at 4.5GHz.

Figure 2. The simulated scattering parameter of S21 for different MUTs. (a) Relationship between the magnitudes and the real part of the complex permittivity; (b) and the imaginary of the complex permittivity.

References


Acknowledgments

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A Method to Distinguish Plastic Deformation and Stress State of Materials based on the Combination of Magnetic Barkhausen Noise and Magnetic Parameters

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Abstract

Since the discovery of Magnetic Barkhausen Noise, a large number of scholars have shown that Magnetic Barkhausen Noise is can be used for stress measurement because it is sensitive to stress and has a good correspondence with the stress state of materials\textsuperscript{[1]}. The basic method of stress measurement by the Magnetic Barkhausen Noise is that the calibrated specimen with residual stress eliminated was used for tensile and compression experiments firstly, and the Magnetic Barkhausen Noise-stress calibration curve was established when the material was in the elastic phase of tensile and compression. During field testing, the measured Magnetic Barkhausen Noise was compared with the calibration curve, and the stress value of the material was obtained. However, as the Magnetic Barkhausen Noise is an electromagnetic signal released by the microscopic domain movement during the ac magnetization of ferromagnetic materials, the material composition, microstructure, heat treatment state, stress, fatigue and plastic deformation degree will all affect the Magnetic Barkhausen Noise signal\textsuperscript{[2]}. Therefore, in the process of stress measurement by Magnetic Barkhausen Noise method, if the influence of these factors is not considered, the measurement results will be greatly deviated or even wrong.

The tested parts and calibrated specimens, under the condition of ignoring fatigue, creep, etc., can be considered to have the same material composition, metallurgical and heat treatment state, but the measured parts from the base material to the molding process are often processed by turning, milling, drilling, grinding, etc., and these processing methods are compulsory material removal methods, which will inevitably cause local plastic deformation of the material. Some scholars have shown that plastic deformation can also affect the Magnetic Barkhausen Noise signal. Therefore, plastic deformation is an important factor that can not be ignored when using the Magnetic Barkhausen Noise to test the stress of the forming parts.

This paper combines other electromagnetic signals to eliminate the interference of plastic deformation to the stress measurement by Magnetic Barkhausen Noise method because of the different responses of different electromagnetic signals to different damage of material. As shown in figure 1, three kinds of steel Q235, Q345 and 20# were respectively tensile tested when these specimens undergoes elastic, elastoplastic, plastic deformation, strengthening stage. Step loading method was adopted in the experiment. The signal of Magnetic Barkhausen Noise and hysteresis loop was measured when the stress of each step was stable. After the material was stretched to the plastic deformation stage, the stress was unloaded to zero and then measured, and then continue to measure after the stress was loaded, and measuring order is 1, 2, 3...N. As shown in figure 2, the relation curve of Magnetic Barkhausen Noise with stress and plastic deformation is obtained in the experiment, and the relation curve of coercive force with stress and plastic deformation is obtained through the hysteresis loop measured as shown in figure 3. As shown in figure 2, when a certain value is measured (assumed to be A), the material may be at the tensile elastic stage at point A\textsubscript{1}, or at

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the position of $A_2$ at the tensile elastic-plastic stage, or at the position of $A_3$ at the tensile strengthening stage. Therefore, it would be wrong to directly compare the stress value with the calibration curve of the material at the elastic stage. At this time, the measured $A$ value of $A_1/A_2/A_3$ can be distinguished by combining with the coercivity value $B_1/B_2/B_3$ measured in figure 3, so as to accurately measure the stress of the material. Therefore, combining with the change rule of coercivity of materials, the plastic deformation of materials can be distinguished and make the stress measured by Magnetic Barkhausen Noise more accurate.

![Figure 1. Schematic diagram of the measurement sequence](image)

![Figure 2. Magnetic Barkhausen Noise and stress, plasticity curve](image)

![Figure 3. Coercivity and stress, plasticity curve](image)

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Research on Early Fatigue Damage Evaluation Method of Ferromagnetic Materials based on Multi-Source Information Fusion

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Abstract

Fatigue damage of materials is a process of gradual accumulation, including crack initiation, crack growth and sudden fracture finally. Under the condition of alternating load, fatigue is always a process in which it accumulates from a point inside or on the surface of the material, causing the initiation of microcracks, and then gradually extends to the surroundings. Therefore, monitoring the accumulation of fatigue degree on the whole thickness of the material, the growth rate of microscopic cracks, and the changes of different depth layers during the service of the material is helpful to better evaluate the fatigue condition of the material.

At present, in the way of electromagnetic detection, many scholars have adopted different methods to study fatigue, most of which are to detect the variation of signal and fatigue degree under a single excitation frequency. Due to yield effect, the ac electromagnetic signal of fixed frequency can only be used to detect the material surface with certain thickness, but the weakest strength of material may be in any position on the surface of the material or inside the material, so in the fatigue evaluation, the crack growth during the whole fatigue fracture process of the material may not be detected by using a certain fixed frequency. In addition, the dislocation, slip and microscopic holes in the microscopic lattice of the material during the fatigue process may also cause changes in the electromagnetic characteristics of the material, and thus cause changes in electromagnetic detection signals. However, different electromagnetic detection signals have different sensitivity to such changes in the electromagnetic characteristics, and thus have different sensitivity to fatigue.

The Magnetic Barkhausen Noise is sensitive to the micro-structure changes of ferromagnetic materials because it is the electromagnetic signal released by the microscopic domain movement. In addition, the magnetic parameters (coercivity, strength of remanence) can well reflect the electromagnetic characteristics of materials.

In this paper, low cycle fatigue experiments were carried out on two materials, Q235 and Q345. As shown in figure 1, The Magnetic Barkhausen Noise signal and hysteresis loop signal under multi-frequency excitation conditions were measured, and the changes of microstructure and macroscopic electromagnetic properties during fatigue were monitored. By adopting multi-frequency excitation to obtain fatigue changes at different depths under the surface of the tested component, more fatigue information can be obtained. The experimental results show that the fatigue degree of materials is well correlated with the regression value through information fusion and linear regression analysis of parameters extracted from multi-frequency Magnetic Barkhausen Noise and hysteresis loop. So the multi-source information fusion method can be used to evaluate the fatigue state of materials correctly.

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Figure 1. Multi-source information fusion fatigue test results

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Irregular Eddy Current Testing of Micro-Cracks on Relay Contacts

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Abstract
At present, riveting contact crack of relay is mainly tested by optical detector or by manual visual inspection off-line. Testing of optical detector is precise, but it cannot complete 100% inspection, and with low efficiency. The results of manual visual inspection are influenced by subjective factors of worker, and the labor cost and work intensity is high. Neither of the methods can find the inner cracks.

Eddy current testing has many advantages, such as faster detection speed, smaller blind area of surface and near-surface, and higher sensitivity. At present, the eddy current detection technology based on impedance plane analysis can only achieve a depth of 30 μm for the detection sensitivity of metal cracks. However, for the tiny cracks in the riveting contact of relay, the detection sensitivity is less than 10 μm, so the conventional eddy current detection method cannot meet the detection requirements. In order to detect microcrack of relay riveting contact, the paper proposes an irregular eddy current detection method using variable amplitude of excitation signal and spectrum analysis of detection signal. In order to test relay contact micro-cracks of relay contact by irregular eddy current, work-pieces without defects were firstly made as the standard specimen with the same material and structure of relay riveting contact. Testing probe was placed on the specimen surface with the transformer vortex excitation signal (FIG. 1). The spectrum/phase characteristic curve is analyzed by signal spectrum, as shown in FIG. 2 (1). Then this curve can be set to calibration curve A, and the area is set as eligible surrounding the calibration curve (dotted line), while outside the area as alarm area.

Then, the probe is placed above the relay contact to be tested, and the spectrum/phase characteristic curve B of the relay contact is also obtained on the eddy current instrument. The signal curve B is compared with calibration curve A. As shown in FIG. 2(2), If curve B is in the qualified area and basically consistent with the calibration curve A, it can be determined that the tested relay contact has no micro-crack defects. As shown in FIG. 2(3), if the two curve deviate and the curve B enters the alarm area, it can be judged that there are tiny cracks in the relay contacts under inspection, and the instrument sends alarm signal of unqualified products.

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In order to verify the effectiveness and reliability of unconventional eddy current testing for micro-cracks in relay contacts, this paper designs an EEC-22D eddy current equipment specially designed for testing metal semi-finished products and metal component materials, as shown in FIG. 3. The instrument is suitable for testing electric riveting parts, matrix structure of steel materials, surface hardness, depth of hardening layer, strength and material confusion.

In order to ensure the stability of point-type eddy current probe detection, this paper designs a feeding device for automatic detection, as shown in FIG. 4. It is mainly composed of automatic transfer device, automatic loading and discharging device, automatic sorting device, etc. The transmission speed of the transmission device is stable and the error is within 5%. In order to meet the requirements of eddy current testing of relay contacts of different types and sizes, the speed of transmission device can be adjusted so that one machine can be used for many purposes and the scope of use of the instrument can be expanded.

Through testing experiments, it is found that the relay contact microcrack detection system designed in this paper can realize the rapid quality detection of the measured contact. At present, the average detection time of the designed system is less than 0.5 seconds for a single workpiece, and the maximum daily detection time is more than 50,000 products. The cracks with a width of more than 3 microns can be detected successfully by this system.

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Fast sorting of automobile seat parts by heat-treated states based on multi-channel eddy current testing method

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Abstract
With rapid development of industry, testing requirement of parts is increasing. At present, sorting of automobile seat parts by heat-treated states on the production line is mainly conducted by manual inspection.

Non-destructive testing of auto seat parts is characterized by high labor intensity, tedious process, low efficiency and human error. Due to the slow speed of manual testing, only sampling inspection can be adopted, and it will reduce the work efficiency of product testing and increase the error rate. In view of the current status of automobile seat parts detection, the paper proposes a multi-channel eddy current detection method to rapidly separate and identify the heat treatment state of automobile seat parts.

Eddy current method for hardness testing of parts is based on the principle of electromagnetic induction. The hardness of conductive material workpiece is non-destructively evaluated by measuring the changes of induced eddy current in the workpiece. The eddy current testing can be non-contact testing and does not need coupling medium, removing the oil and protective layer on the surface of the parts under the condition of detection; The detection signal is electrical signal, so the detection results can be digitized and compared.

In order to ensure the stability and rapidity of rapid sorting automobile seat parts by heat-treated state, the paper designs a rapid sorting testing platform for automatic multi-channel real-time testing, as shown in Figure 1. The rapid sorting and testing platform can be embedded into the production line body and carried by a non-standard rack. The up-and-down movement of the probe mounting plate is controlled by lifting cylinder on the detection platform. When the part tray to be tested reaches the detection position, the probe will automatically move down to the position that fits the workpiece. To meet the requirements of the eddy current testing for car seats of different models and sizes, the probe mounting plate can be replaced so as to coordinate with the detection and positioning of different parts.

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The sorting system is equipped with 16 probes, depending on the type of car seat. If the number of heat-treated parts to be tested is less than 16, the working mode of detection probe can be switched, and the probe to be tested is set to be effective, and the remaining probes are not tested or detected but the signal is not processed. If the eddy current signal is consistent in the qualified zone during the test, it means that the heat treatment of the specimen is normal. Otherwise, it can be judged to the unqualified hardness and marked the unqualified. In the actual test figure shown in Figure 2 and Figure 3, the red sign represents unqualified products, and the green sign represents qualified products. A statistical report will be issued after each batch of products are tested. If an unqualified product is detected, there will be an alarm prompt and the hardware outputs alarm signal for processing.

The fast sorting system based on multi-channel eddy current testing has been used in some manufacturers. Through practical use, it is found that the system can complete the 16 stations in the whole experimental platform within 4s, and can save all measurement data and signal images, which facilitates the follow-up product quality tracing and provides necessary data support for production process adjustment. It can stabilize the test and output the test result according to the production beat, and store the test result in the local computer, which is convenient for users to check at any time. The system is with anti-interference ability, and can reliably distinguish parts by heat treatment state.

It is found in the field that it is fast, non-contact and easy to realize automation, which can give full play to the advantages of non-destructive testing, realize the automation and informatization of automobile seat production, reduce production cost, improve testing efficiency and effectively eliminate the hidden danger of automobile safety.

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Abstract

Electromagnetic methods have a wide range of uses in monitoring and inspection of ferritic steel structures due to the influence of stress and microstructure on magnetic properties. Practical applications in this area are motivated by the increasing importance of monitoring to ensure safe and cost-effective operation of structures. Moreover, there is a drive towards the use of sensor technology that can not only detect cracks and material loss, but also evaluate material property changes and early microstructural deterioration due to stresses and fatigue.

In this regard, we consider here the use of the transient potential drop (TPD) method [1,2] where a pulsed current is used as the excitation source and the response is a transient voltage that is sensitive to the variation of electromagnetic properties with depth in the material. Physically, this is due to diffusion of the injected current into the material [3].

To interpret measured signals in terms of material properties, an essential step is the physical modeling of the sensor response, a process that is greatly simplified by assuming linear material properties. However, in ferromagnetic materials, non-linear effects may be prominent depending on the magnitude of the exciting field [4]. While these effects complicate the analysis, they may also be exploited to provide additional information on the state of the material.

In this work we have studied applications of such effects by measurements on metal rods (Figure 1) assuming axial symmetry of the injected current. An advantage of this arrangement is that, in the linear case, simple analytical modeling of the transient response is possible [3]. We have initially validated the basic theory which can be used for characterization of metal rods (for brevity the details are omitted here). Further, we consider measurements on carbon steel where effects due to non-linear and hysteretic magnetization are observed.

Figure 1: Potential drop measurement on a metal rod. A current \( I \) is delivered via wires attached to the ends of the specimen and the surface voltage, \( V \), is measured between electrodes in contact with the specimen.

A simple and inexpensive setup is used in the experiments and consists of an arbitrary waveform generator (AWG), which feeds a drive current amplifier, and a PC oscilloscope to record the waveforms of the drive current and the transient potential drop.

An example of a transient measurement is given in Figure 2. Due to the skin effect, the transient voltage features a characteristic peak whose magnitude increases with increasing permeability of the material [1]. As a basic example of the characterization of non-linear effects, Figure 3 shows that the ratio of the peak voltage to the steady state (DC) value increases with increasing magnitude of the drive current. Thus, the peak voltage is not proportional to the magnitude of the drive current as expected in the linear case, but increases

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due to a higher effective permeability. In this figure we have also included data obtained for a plastically deformed sample, showing that plastic deformation reduces the permeability and the non-linear dependence due to an increase in the number of dislocations acting as pinning sites for magnetic domain walls [5].

![Normalized voltage/current vs. time](image1)

**Figure 2:** Transient potential drop measurement on a carbon steel rod (10 mm diameter). An exponentially rising drive current (amplitude 100 mA) is used as the source.

![Peak to DC ratio vs. current](image2)

**Figure 3:** Dependence of the normalized peak voltage on the magnitude of the injected current pulse, indicating the non-linear magnetic response. Data is shown for two similar samples, where one has been plastically deformed in uniaxial tension.

In addition to the above we have investigated the effects of heat treatment (annealing), which enhances the non-linear dependence, and hysteretic effects where transient measurements can be used to sense magneto-mechanically induced magnetization.

Applications include the use of potential drop probes for inspection of components as well as structural health monitoring by use of permanently installed sensors.

**References**


Magnetic field and stress-induced magnetic domain reorientation and its correlation with Barkhausen Noise

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Abstract

We investigate magnetic field and stress-induced magnetic domain reorientation and its correlation with Magnetic Barkhausen Noise (MBN). The magnetic domain dynamics and MBN of grain-oriented transverse and longitudinal electrical steels are studied by using time-resolved and quantitative magneto-optical imaging. Time evolutions of magnetic domain dynamics show that 180° domain wall (DW) and 90° DW reorganization generate peaks in MBN measurement for longitudinal and transverse electrical steel, respectively. In-plane vector magnetization imaging reveals complicated domain arrangement processes in transverse electrical steel due to locally varying stress induced magnetic anisotropy.

1. Introduction

MBN is an electromagnetic phenomenon originating from the irregular and irreversible motion of the DWs under external magnetic field excitation. The induced sudden fluctuations in the magnetization are linked to the interaction between DW dynamics and microstructural obstacles like dislocations, precipitates, phases, grain boundaries (GBs) and related micro stresses\textsuperscript{[1-3]}. The MBN has been used as a non-destructive testing technique for stress evaluation and microstructural characterization.

The imaging of magnetic domains in magnetic materials is essential to obtain an understanding of the underlying mechanisms of magnetization reversal\textsuperscript{[4,5]} and the related electromagnetic Nondestructive Evaluation techniques (ENDE)\textsuperscript{[7,8]}. Synchronous measurements of macroscopic magnetization properties, including MBN, and magnetic magnetic domain wall (DW) dynamics in the magnetic material, and also taking into account stresses and anisotropy, mark a crucial step forward to reveal physics of MBN, metal magnetic memory (MMM) and other ENDE methods.

2. Experiment

The imaging of magnetic domains with varying plane of incidence through a single objective lens is attainable with an adapted polarizing or materials microscope.\textsuperscript{[4, 5]} The setup allows for imaging with a spatial resolution down to approximately 200 nm. Imaging of in-plane magnetic domains with the longitudinal Kerr microscopy works best with high numerical aperture (NA) objective lenses. The principle ray diagram of an advanced MO imaging setup with different kinds of illumination sources and detection schemes is sketched in Fig. 2(a). The general scheme of operation is described in detail in Ref\textsuperscript{[4]}. Interchangeable light sources include high-power light emitting diodes (LEDs) and laser. Both allow for imaging with temporal resolution, for the laser down to nanosecond time scales. Using multiple illumination sources concurrently, the simultaneous imaging with two different MO effects is possible. Yet, this requires a way of separating the image paths for observation. This is achievable by the application of two synchronized cameras\textsuperscript{[6]} or an image-splitter, where the divided image is then captured by a single camera\textsuperscript{[6]} (Fig. 1(b) and 1(c)).
3. Results

3.1 Magnetic domain under demagnetizing state

Figure 2 shows static magnetic domain images obtained in the demagnetizing zero-field state with zero stress.

![Static magnetic domain images](image)

**Fig. 2.** Static magnetic domain images with the magneto-optical sensitivity along the \( y \)-direction (a) and \( x \)-direction under demagnetizing state at \( \sigma = 0 \) MPa (a) sample 1, (b) sample 2.

3.2 Barkhausen Noise under different tensile stress

Figure 3 shows MBN envelopes versus applied magnetic field for the ascending branch of the magnetization reversal in dependence of the applied mechanical loading in sample S1 and S3. With different applied tensile stress, envelopes of MBN distribution are obtained for comparison.
Fig. 3. Barkhausen Noise envelope under different tensile stress amplitudes for the ascending magnetic fields (a) sample 1; (b) sample 2.

3.3 Magnetic domain dynamics by time-resolved magneto-optical imaging

Figure 4 shows the time evolution of magnetic domain states at three AC excitation field values at a given tensile stress of $\sigma = 0$ MPa, $\sigma = 40$ MPa and $\sigma = 90$ MPa. Time-resolved magneto-optical imaging shows that domain reorganization from 180° DW formation and annihilation generates characteristic double peaks in MBN measurements for longitudinal electrical steel. In contrary, 90° DW formation and regular movement generates characteristic double peaks for transverse electrical steel.

Fig. 4. Time evolution of magnetic domain state with the magneto-optical sensitivity along the y-direction at different applied tensile stress amplitudes of $\sigma = 0$ MPa, $\sigma = 40$ MPa and $\sigma = 90$ MPa for sample 1 and sample 2.

4. Discussion

4.1 Quantitative evaluation of dynamic magnetization response images

Essentially, vectorial magnetic domain observation is merely possible by imaging methods that provide a signal being proportional to the magnetization $\mathbf{M}$ of the observed magnetic materials and offer as well the possibility of separating different components of $\mathbf{M}$ individually. Fig. 5 shows the static $x$-component and $y$-component of magnetization by applying simultaneously mechanical stress and a bias field. At zero stress, the domain walls firstly move along perpendicular magnetic field direction, which generates MBN activity. With mediate
excitation field, magnetic domain moments gradually rotate to the magnetic field direction via magnetic domains reorganization. With further magnetic field increasing, the Bloch domain walls move, which generates large MBN activity. With increasing the tensile stress, the magnetic moment is more or less rotated to magnetic field direction via magnetic domain reorganization. The Bloch wall movement is occurred at low field, this enhanced the MBN activity.

Fig 5. Quantitative static magnetization response images along x-direction and y-direction magento-optical sensitivity at different applied tensile stress amplitudes of $\sigma = 0$ MPa, $\sigma = 40$ MPa and $\sigma = 90$ MPa for sample 1.

Acknowledgments

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Reference

Analytical model for velocity induced fields of pulsed eddy current testing at high-speed

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Abstract

Pulsed eddy current testing (PECT) is a viable method for rail inspection because of its advantages of relatively high inspection speed and ability of surface defects detection, and it has been employed in rail inspection [1]. Whereas, the velocity induced eddy current generated due to the relative motion between the probe and metal is the main obstacles for PECT at the high-speed. Thus to improve the detection accuracy, the velocity induced fields of PECT should be studied. Attempts have been made to study velocity induced fields. Du [2] built a 3-D transient finite element model based on T-Ω formulation to analyze velocity induced fields of magnetic flux leakage (MFL) testing at high speed. Li [3] investigated the eddy currents and their characterizations in high-speed MFL inspection systems by using numerical simulations. While the investigation on the velocity effect for the PEC is inadequate, and the analytical model which is a useful tool to reveal the essence and predict the signal has seldom been used. Thus the purpose of this paper is to obtain the solution of the pulsed eddy current testing at high-speed by using the Galilean transformation.

Firstly, the model of rail inspection using PECT at high-speed is conducted. The rail is approximated by a ferromagnetic metallic plate. And the TR probe which can be used to reduce the lift-off effect [4] is used in this paper. Then the model is given in Fig. 1, in which (x’, y’, z’) is the rail coordinate system, (x, y, z) is the probe coordinate system, and the detection velocity of the probe is v. Furthermore, to simplify the calculation, two regions of interest are created, in which R₀ is the air region between the bottom of the coil and the interface of the rail, R₁ is the region of the rail, and the relative magnetic permeability and electrical conductivity of the regions.

![Fig. 1 A TR probe over the rail.](image)

Secondly, the solution of the model in the rail coordinate system is deduced. The solution can be obtained by using the SOVP formulation $W'$, and $W'$ satisfies the 3D scalar Laplace and Helmholtz equations[5]:

$$\frac{\partial^2 W'_a}{\partial x'^2} + \frac{\partial^2 W'_b}{\partial y'^2} + \frac{\partial^2 W'_a}{\partial z'^2} = k^2 W'_{a,b}$$

where, $W'_a$ is the transverse electric (TE), $W'_b$ is the transverse magnetic (TM) potential, $k^2= j\omega \mu_0 \mu_r \sigma$, $j$ is the imaginary unit, $\mu_0$ is the permeability of vacuum, $\omega$ is the angular frequency of the harmonic excitation current.

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By applying the separation of variables method and satisfying the interface conditions, \( W_a \) and \( W_b \) can be solved:

\[
W_a^{(i)}(x',y',z') = \frac{1}{4\pi^2} \times \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{|x-y|} \left[ e^{ik_1'x} + (k_1\mu_1 - \lambda)/(k_1\mu_1 + \lambda) e^{-ik_1'x} \right] \mathcal{C}(\xi') e^{ik_1'y} e^{ik_1'z} \, dk_1 dk_1',
\]

\[
W_b^{(i)}(x',y',z') = \frac{1}{4\pi^2} \times \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} 2k_1\mu_1 (k_1\mu_1 + \lambda) e^{-ik_1'x} \mathcal{C}(\xi') e^{ik_1'y} e^{ik_1'z} \, dk_1 dk_1',
\]

\[
C(\xi') = \mu_0 n N l / (r_{2T} - r_{1T}) / k_2^2 x (1 - e^{-k_2^2}) \text{Int}(k_2 r_{1T}, k_2 r_{2T})
\]

where, \( W_{a,b}^{(i)} \) means \( W_{a,b} \) in region \( i \) (i=0,1); \( \lambda^2 = k_2^2 + k_1^2 \), and \( k_1, k_2, k_3 \) are the eigenvalue in the direction of \( x' \), \( y' \) and \( z' \), respectively; \( n \) is the number of the coil turns; \( \text{Int}(x_1, x_2) = \int_{x_1}^{x_2} x J_1(x)dx \), and \( J_1(x) \) denotes the first-order Bessel function. Furthermore, by using the equations \( E' = -j\omega A' = -j\omega \nabla \times W' \) and \( B' = \nabla \times \nabla \times W' \), the field \( E' \) and \( B' \) can be deduced.

Although \( B' \) and \( E' \) are both determined by the induced eddy current and velocity induced eddy current, as the rail coordinate system coincides with the inertial coordinate system, the effect of the velocity on the field cannot be analyzed directly, thus solutions in the probe coordinate system are necessary.

The solutions in the probe coordinate system can be obtained by using the Galilean transformation. The Galilean transformation is defined as:

\[
\mathbf{r}' = \mathbf{r} - \mathbf{v} t' = t \quad \nabla' = \nabla - \frac{d}{dt} - \mathbf{v} \cdot \nabla
\]

Furthermore, the field \( E \) and \( B \) in the probe coordinate system can be calculated from \( E' \) and \( B' \) in the rail coordinate system with the relationships \( B' = B, \ E' = E + \mathbf{v} \times \mathbf{B} \). Then the solution of induced voltage in the probe coordinate system is obtained:

\[
\Delta U = \int E \cdot ds = \int \left( E' - \mathbf{v} \times \mathbf{B}' \right) \cdot ds = \frac{N}{l_i(r_{2R} - r_{1R})} \int \left( -j\nu e \nabla \times W'^{(i)} - \mathbf{v} \times \nabla \times \nabla \times W'^{(i)} \right) dx dy
\]

References


Acknowledgments

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Multi-Channel IoT-based Ensemble-Features Fault Diagnosis For Machine Condition Monitoring

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Abstract. This paper proposes a multi-channel internet of things (IoT)-based industrial wireless sensor network (IWSN) with ensemble-features fault diagnosis for machine condition monitoring and fault diagnosis. In this paper, the rolling bearing is taken as an example of monitored industrial equipment due to its wide use in industrial processes. The rolling bearing vibration signals are measured for further processing and analysis. On-sensor node ensemble feature extraction and fault diagnosis using BP(Back propagation network) are then investigated to address the tension between the higher system requirements of IWSNs and the resource-constrained characteristics of sensor nodes. A two-step classifier fusion approach using Dempster-Shafer theory is also explored to increase diagnosis result quality. Four rolling bearing operating in cage fracture, rolling ball spalling, inner ring spalling and outer ring spalling are monitored to evaluate the proposed system. The final fault diagnosis results using the proposed classifier fusion approach give a result certainty of at least 95.75%, proving the feasibility of the proposed method to identify the bearing-fault patterns. This paper is conducted to provide new insights into how a high-accuracy IoT-based ensemble-features fault diagnosis algorithm is designed and further giving advisable reference to more IWSNs scenarios.

Keywords. IoT, wireless sensor networks (WSNs), fault diagnosis, BP network, Dempster-Shafer theory

1. Introduction

Machine fault diagnosis is becoming increasingly important to meet the higher demand of safety, reliability and efficiency in many industrial areas. [1, 2]. As the key components of machinery, the rolling bearings have been widely applied in most industrial sectors, [3]. Due to artificial errors, material defects, and inadequate operations of the bearing, various incipient defects of rolling bearings may occur, and potentially lead to a series of unforeseen damages [4]. Hence, bearing-fault diagnosis is of paramount significance to improve the availability, increase the operating efficiency, and ensure the safe operation of the mechanical system [5].

Generally, bearing fault diagnosis depending on on-line monitoring vibration signal of critical devices includes three stages: signal processing, feature extraction, and classification recognition [6]. Currently, in many industrial fields, bearing fault diagnosis relies on the wired systems, which features as high reliability, but expensive maintenance cost, time-consuming [7]. Alternately, the wireless sensor networks (WSNs) have many inherent advantages including less weight, distributed operation, ease installation and relatively low-cost manufacturing, which make them as a promising approach for fault diagnosis [8].

Till now, numerous researchers have yielded some achievements on the IWSN [9-11]. Our previous work demonstrated a new multi-channel MEMS-based Low-Power Wide-Area Network (LPWAN) incorporating LoRa with NB-IoT for machine vibration monitoring [12]. In addition, compared with wired monitoring systems, WSN monitoring systems have constrained resources, including limited radio bandwidth, computational ability, and battery energy. Therefore, a key question to be addressed in this work is how to achieve these higher system requirements using resource-constrained IWSNs. The on-sensor feature extraction and fault diagnosis is a promising alternative approach to raw data transmission, which can reduce the quantity of transmitted data, save node energy, and prolong node lifetime. To date, this topic is a relatively unexplored area for IWSNs.

In many applications, it is difficult to capture all the required information for device fault diagnosis through a single sensor, particularly for sensors working in harsh industrial settings. For IWSN fault diagnosis systems, the situation is even worse because the noise and interference will impact the quality of communication in the IWSNs and further increase the uncertainty of the diagnosis results. In recent years, data fusion techniques have been investigated to enhance measurement accuracy by combining the data from different sensors. Data fusion can also effectively reduce the amount of information and data that need to be processed and transmitted and then save the resources and energy of the measuring or processing units. A number of induction motor fault diagnosis systems using different data fusion techniques, such as the Bayesian method [14] and fuzzy data fusion [15], have been reported. Dempster–Shafer theory is another promising data fusion technique for fault diagnosis, which does not need the knowledge of the prior probability and conditional probability relationships of data. This method has been successfully used on induction motor fault diagnosis [16], diesel engine cooling system condition monitoring [17], and railway track circuit fault diagnosis [18]. However, all of the aforementioned cases are based on wired sensor systems. Using

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Dempster–Shafer data fusion together with WSNs for condition monitoring and fault diagnosis has not previously been reported.

In this paper, the following design strategies have been adopted to explore the applicability of data fusion for fault diagnosis in WSNs.

1) We propose a new IoT-based Ensemble-Features WSN for machine fault diagnosis. A local-processing distinct ensemble-extraction algorithm in time-domain is presented, which contributes to the low power consumption, low cost, and covering all the typical characteristics of vibration signals in time-domain.

2) We also extend the previous WSN data fusion by applying Dempster–Shafer theory to for industrial condition monitoring and fault diagnosis.

The remainder of this paper is organized as follows. The system architecture and implementation methodology is briefly introduced in Section II. The experimental evaluation of the proposed system is given in Section III. Finally, Section V presents the overall conclusions.

2. System and Architecture and implementation

The architecture of the proposed rolling bearing condition monitoring and fault diagnosis system with two-classifier data fusion is illustrated in Fig. 1. This star topology WSN consists of multi-channel sink node and multiple end nodes. One sensor node measures the vibration on the head of the motor, while the other sensor node monitors the stator current signal. IEEE 802.15.4 and LoRa protocols are used for the radio.

End nodes can sleep between sampling, processing, and data transmission steps. The signal conditioning, data acquisition, feature extraction, and local fault classification functions were carried out on the sensor nodes, while decision level data fusion was achieved on the multi-channel sink node. The diagnosis result was displayed on the centralized computer. The details of each section of the system are given hereinafter.

2.1. The LoRa-based Multi-Features Extraction Sensor Node (LMESN) and sink node

As is shown in Fig.1, the LMESN is mainly consisted of data acquisition unit, wireless communication unit, wireless unit, power module. The core of data acquisition unit is TI ADS8688AT chip having 16-bit resolution Analog-to-Digital Converter (ADC) and conversion rate of up to 100 kHz. With regard to the data sensing unit, the ADXL345 micro-electromechanical systems (MEMS) accelerometer with 12-bit resolution of measurement ranging from ±2 g to ±16 g and 3.9 mg/LSB sensitivity is integrated into the LMESN. The collected data are sent to the local-processing feature extraction unit for performing the feature extraction of vibration signal. As for the wireless communication, a low-power RF chip Silicon SX1278 based on LoRa protocol, which can offer a theoretical maximum transfer speed of 500 kbps. The SX1278 in wireless unit is connected to STM32F407 processor through SPI ports for exchanging commands and transmitting wireless data. Our previous work has proposed a multi-channel sink node integrated multiple LoRa modules and NB-IoT modules for machine vibration monitoring[12].
2.2. Feature-extraction Design

As shown in Fig.2, the architecture of the rolling bearing is consisted of the rolling ball, cage, inner ring and outer ring. In this respect, \( D \) is the bearing pitch, \( d \) is the diameter of rolling ball and \( \alpha \) is the angle between the forced direction of rolling ball and the inner and outer vertical lines. Four common faults of the rolling bearing are F1="cage fracture,” F2="rolling ball spalling,” F3="inner ring spalling,” and F4="outer ring spalling” respectively.

![Structure of a rolling bearing](image)

This stage extracts the relevant fault features for further fault diagnosis from the raw digital data stream. Considering the resource constraints of the sensor node, a simple set of fault features are employed in this system. The time-domain characteristic parameters mainly include dimensional parameters (mean value, peak value, root mean square value, square root amplitude) and non-dimensional parameters (tolerance index). The 12 most frequently occurring frequency components(20480 samples within one fast Fourier transform (FFT) window) were counted and selected as the fault features in the frequency domain. These fault features will be used to classify the healthy rolling bearing. The definition of these parameters is shown in Table 1.

Stator current signal is employed to identify motor load changes. Motor load changes or faults will affect the load torque of the motor. Continuous monitoring of the amplitude of the stator current signal can be used to find the abrupt change of load due to load side faults such as a broken connection shaft. In addition, periodic load torque changes with the rotational speed can affect the stator current signal spectrum and produce the current harmonics. In this paper, the load changes are tested by the modulation of a resistor connected to a generator used as a load, which is not a cyclic load variation, and do not give other current harmonics. Therefore, for the stator current signal, only peak-to-peak amplitude and variance value in the time domain are selected as fault features. The selected fault features in this experiment are summarized in Table I.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Dimensional parameters</th>
<th>Non-dimensional parameters</th>
<th>Frequency Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>Peak value ( x_p = \max { x_i } )</td>
<td>Kurtosis index ( \beta = \frac{\sum_{i=1}^{n} x_i^4}{N} )</td>
<td>( f_p ), ( f_{p1} ), ( f_{p2} ), ( f_{p3} ), ( f_{p4} ), ( f_{p5} )</td>
</tr>
<tr>
<td>Dimensional</td>
<td>Mean value ( \mu = \frac{\sum_{i=1}^{n} x_i}{N} )</td>
<td></td>
<td>( f_p ), ( f_{p1} ), ( f_{p2} ), ( f_{p3} ), ( f_{p4} ), ( f_{p5} )</td>
</tr>
<tr>
<td>parameters</td>
<td>Root mean square value ( x_{rms} = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{N}} )</td>
<td></td>
<td>( f_p ), ( f_{p1} ), ( f_{p2} ), ( f_{p3} ), ( f_{p4} ), ( f_{p5} )</td>
</tr>
<tr>
<td></td>
<td>Square root amplitude ( x_r = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{N}} )</td>
<td></td>
<td>( f_p ), ( f_{p1} ), ( f_{p2} ), ( f_{p3} ), ( f_{p4} ), ( f_{p5} )</td>
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</table>

<table>
<thead>
<tr>
<th>Current</th>
<th>Dimensional parameters</th>
<th>Non-dimensional parameters</th>
<th>Frequency Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>Peak value ( x_p = \max { x_i } )</td>
<td>Kurtosis index ( \beta = \frac{\sum_{i=1}^{n} x_i^4}{N} )</td>
<td>( f_p ), ( f_{p1} ), ( f_{p2} ), ( f_{p3} ), ( f_{p4} ), ( f_{p5} )</td>
</tr>
</tbody>
</table>

Table 1. Nine dimensional and non-dimensional parameters
2.3. Neural Network Classifier

After the signal measurement and feature extraction, the next step is fault diagnosis. In this paper, a BP neural network was employed on the sink node as the local fault classifiers. As shown in Fig. 2, the neural network has several hidden layer neurons and five output layer neurons, corresponding to five rolling bearing working conditions, i.e. The log-sigmoid function, defined herein, is used as the hidden layer and output layer neuron activation function. The output range of this function is $(0, 1)$

$$\text{log sig}(n) = \frac{1}{1 + \exp(-n)} \quad (1)$$

For the vibration or current signal, the inputs of the neural network were the 21 fault features $(x_1, x_2, \ldots, x_{21})$ extracted as described earlier (12 frequency features, 9 time-domain features). The output range of the neural network was $(0, 1)$, which indicates the probability of the relevant bearing condition having happened. For example, if the motor is a healthy one, the corresponding ideal output of the neural network classifier will be $\{1, 0, 0, 0, 0\}$. The training error goal of the neural network was set at 0.01. The neuron weights were obtained by offline training of the neural network and then embedded in the local classifier on the sensor node for online primary fault diagnosis.

Dempster–Shafer theory assigns a belief mass to each element of the power set. Shown as (1), a basic belief assignment (BBA), called $m$ in the following, is a function mapping from $2\Theta$ to $[0, 1]$, provided that the sum of all basic belief masses is equal to one and the mass of null set is zero:

$$m : 2^\Theta \to [0, 1] \text{ if } \sum_{A \in \Theta} m(A) = 1 \text{ and } m(\emptyset) = 0 \quad (2)$$

According to (2), the sum of all basic belief masses is equal to one. Therefore, the outputs of neural network classifier $y(B_i)$ need to be normalized as follows:

$$m(B_i) = \frac{y(B_i)}{\sum_{j=1}^{4} y(B_j)} \quad (3)$$

where $B_i, i = 1, 2, 3, 4$, denotes the four previously described operating conditions of the rolling bearing. The results of the normalized $m(B_i)$ can be used for further decision level classifier fusion.

2.4. Decision Level Fusion

Data fusion processes are often categorized as data level fusion, feature level fusion, or decision level fusion, depending on where the fusion takes place. Decision level fusion combines the primary recognition results from each sensor or data sources and gives a more accurate and certain decision. It utilizes the computing capability of individual low-level sensors and reduces the communication throughput. Therefore, in this paper, decision level fusion by Dempster–Shafer theory was selected to combine the outputs of the three local neural network classifiers.

3. Experimental Verification

To evaluate the performance of the proposed bearing fault diagnosis method, a series of experiments are conducted. The experimental setup is shown in Fig.4. Four LMESNs nodes are installed on a Drivetrain Diagnostics Simulator (DDS) for implementing to acquire vibration signal of rolling bearing. Then, the processed vibration signals are sent to the sink node. Additionally, the sampling frequency of the system is configured to the value of 10.24 kHz, coupling with sampling length set to 20480. The rotating speed of the testing bearing is set to around 1310 r/min.
In this section, to investigate the influence of the number of hidden layer nodes and (non)dimensional parameters on the fault classification accuracy, we make a detailed comparative analysis under dimensional parameters \((x_p, \pi, x_{\text{rms}}, x_r)\), non-dimensional parameters \((C_f, W_s, I, L, \beta)\) and the combination parameters \((x_p, \pi, x_{\text{rms}}, x_r, C_f, W_s, I, L, \beta \text{ and } f)\) respectively, as hidden layer nodes are set to 5, 6, 7, 8, 9, 10. As is shown in Fig. 5 (a), the average classification accuracies under the dimensional parameters are below 65%, due to the distinct differences between 4 dimensional parameters for 5 bearing states in Table III. In contrast, it is seen from Fig. 5 (b) that all average fault classification accuracies under the non-dimensional parameters are above 80%. Due to the non-dimensional parameters are the radios of two different dimensional parameters, and so the above increase of fault classification accuracy indicates that the non-dimensional features not only include the information of dimensional features, but also could better reflect the actual information of bearings. As is shown in Fig. 5(c), it is noted that the average fault classification accuracies under the combination of the dimensional and non-dimensional parameters are nearly close to 95%, proving that this combination for fault classification accuracy outperforms the dimensional parameters or non-dimensional parameters. Additionally, we can see from the three figures that the classification accuracy can reach the highest level as the number of hidden layer nodes reaches 7. It's also worth mentioning from Fig. 5 (c) that the classification accuracies of five bearing state degree recognition are achieved with 97.27% (Normal), 96.44% \((F_1)\), 97.21% \((F_2)\), 95.97% \((F_3)\) and 97.96% \((F_4)\), respectively. Nevertheless, it cannot continuously guarantee a high and stable accuracy rate when the number of hidden layer nodes exceeds 7. The reason is the few hidden layer nodes \((P.5 \text{ and } P.6)\) contributes to inaccurate training, while the excessive hidden layer nodes \((P.8, P.9 \text{ and } P.10)\) result in too long learning time, larger training error and worse generalization ability. In conclusion, the hidden layer node \(P.7\) is the optimal node for the proposed BPNN, which can reach the highest classification accuracies.

In short, the above comparison analysis results have proved that the selected nine dimensional and non-dimensional parameters with representative ability of extracted features can provide a more reliable and stable fault classification accuracy for bearings. In addition, the fault classification accuracies can attain the best performance when the hidden layer node of BPNN is 7.

![Fig.4 Wireless experimental test for rolling bearings based on DDS system](image)

![Fig.5. Average fault classification accuracies with different hidden layer nodes of BPNN under different parameters (a) under dimensional parameters \((x_p, \pi, x_{\text{rms}}, x_r)\) (b) under the non-dimensional parameters \((C_f, W_s, I, L, \beta)\) (c) under the combination parameters \((x_p, \pi, x_{\text{rms}}, x_r, C_f, W_s, I, L, \beta \text{ and } f)\)](image)

### 4. CONCLUSION

In this paper, we proposed a local-processing multi-features fault diagnosis algorithm based on the BP neural network (BPNN) for is proposed in this paper. We actualize the LMESN in wireless communication for acquiring vibration signals of bearings. In addition, dimensional parameters and non-dimensional parameters of vibration signals are extracted as the input vector of the designed BPNN. The feasibility and performance of the proposed method has been verified by a set of comparison experiments on a bearing. Furthermore, considering the key importance of the hidden layer nodes and different number of characteristics to the fault classification accuracy, we conduct many experiments with different hidden layer nodes under different number of characteristics and prove that the average classification accuracies of five bearing state degree recognition under the dimensional and non-dimensional parameters reach the highest level (Normal: 97.27%, \(F_1\): 96.44%, \(F_2\): 97.21%, \(F_3\): 95.97%, and \(F_4\): 97.96%) when the hidden layer nodes of BPNN P is 7.
REFERENCES


