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TRANSIENT ELECTROMAGNETIC-THERMAL NONDESTRUCTIVE TESTING

PULSED EDDY CURRENT AND TRANSIENT EDDY CURRENT THERMOGRAPHY

YUNZE HE, BIN GAO, ALI SOPHIAN
AND RUIZHEN YANG

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Transient Electromagnetic-Thermal Nondestructive Testing focuses on two cutting-edge techniques used for Nondestructive Testing (NDT): Pulsed Eddy Current (PEC) and Transient Eddy Current Thermography (TECT).

These two electromagnetic nondestructive (EM NDT) techniques are a means to lower operation and maintenance costs and improve reliability and availability. Their advantages of high speed, high penetration, high sensitivity, wide spectrum, low cost, and easy quantification mean that they play an increasingly important role in: aerospace, renewable energy, marine science, railway, traffic control, civil engineering, and other industrial fields.

Coverage includes

- *Theory:* including the examination of multiphysics fields for (a) defect evaluation, such as parallel cracks, deep defects beneath the skin and (b) quantification, such as the analysis of thermal wave propagation for phase-based defect quantification
- *Methods:* including a variety of EM-thermal NDT techniques; time-domain, frequency-domain, and logarithm-domain defect evaluation methods; advanced algorithms, such as principal components analysis (PCA), independent components analysis (ICA), support vector machine (SVM), Blind Source Separation (BSS) and multidimensional tensor decomposition; and image reconstruction and enhancement for improving detectability
- *Applications:* including an analysis and evaluation of the variation in the properties of material including conductivity, permeability, and lift-off; experimental studies for real damage, including corrosion in steel, stress in aluminum, impact and delamination in carbon fiber reinforced polymer (CFRP) laminates, and RCF cracks in rail tracks

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Pulsed Eddy Current and Transient Eddy Current Thermography

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Preface

With a growing interest in safety and quality problems in aerospace, renewable energy, marine science, railway, traffic, civil, and other industrial fields, much attention has been devoted to the development of reliability-based or condition-based maintenance. Condition monitoring (CM), structural health monitoring (SHM), and nondestructive testing (NDT) techniques are the main means to lower the operation and maintenance (O&M) costs and improve reliability and availability. Transient electromagnetic–thermal (EMT)-related CM, SHM, and NDT techniques with advantages of high speed, great penetration, high sensitivity, wide spectrum, low cost, and easy quantification, are widely investigated and have become one of the most promising directions. In recent years, two transient EMT NDT methods—pulsed eddy current (PEC) and transient eddy current thermography (TECT)—have been the research hotspots. For example, in the Elsevier ScienceDirect database, PEC has been on a steady increasing phase in the past 10 years and TECT has been growing rapidly since 2011. Unfortunately, there are only a few books on PEC and TECT published in English, which hinders the spread and development of the technology and related research. In addition, there are more and more bilingual courses in many universities in China and non-English-speaking countries that would benefit from the availability of such a book. Many undergraduate and postgraduate students, as well as scientists and engineers, need a suitable book for their study and research on EMT NDT. Therefore, it is thought that it is the right time to publish a relevant book to meet the demand of readers.

This book is intended to solve several challenges in the physical principles, methods, techniques, and applications of PEC and TECT. *Theoretically*, multiphysics fields including EM induction, eddy current distribution, induction heating, heat conduction, thermal wave propagation, temperature field distribution, and infrared radiation are studied for defect evaluation and quantification; lateral heat conduction is used to detect parallel cracks; longitudinal heat conduction is used to detect deep defects, which are beyond the skin depth; thermal wave propagation is analyzed for phase-based defect quantification, and the physical–mathematical model is investigated to improve detection sensitivity and quantitative analysis. *Methodologically*, various EMT NDT techniques like eddy current pulse thermography (ECPT), eddy current step thermography (ECST), eddy current pulse phase thermography (ECPPT), and pulsed inductive thermal wave radar (PI-TWR) are investigated. Time-domain, frequency-domain, and logarithm-domain defect evaluation methods are described and analyzed; advanced algorithms, such as principal components analysis (PCA), independent components analysis (ICA), support vector machine (SVM), and multidimensional tensor decomposition are used, and image reconstruction and enhancement is used to improve detectability. In view of *applications*, material property variations including conductivity, permeability, and lift-off are evaluated; experimental studies for real damages including corrosion in steel, stress in aluminum, impact and delamination in carbon fiber reinforced polymer (CFRP) laminates, and RCF cracks in rail are abundant. The book is expected to fill the gap in the literature and provide a relatively comprehensive coverage of PEC and TECT, giving the readers detailed information in related theories, methods, and applications, and benefit readers in both academia and industry.

Chapter 1 introduces the classification of NDT and the classification of transient EMT NDT techniques. The book mainly consists of three parts. Part I is related to PEC. In Chapter 2, a PEC technique where a magnetic sensor is used for sensing the magnetic field is introduced. The usages of signal processing and feature extraction using PCA and wavelets on PEC signals are also presented. In Chapter 3, the influences of material properties on PEC responses are investigated and normalization technique is used to reduce the lift-off effect. Subsequently, two time-domain features representing electrical conductivity and magnetic permeability are extracted. These features are utilized to measure stress in aluminum alloys, to detect defects in honeycomb sandwich structures, to evaluate low-energy impact defects in CFRP, and to characterize atmospheric corrosion on steel. In Chapter 4, the directional PEC probe design providing uniform eddy current is presented. The PEC feature extraction techniques are then studied in both time and frequency domains. PEC frequency response optimization is investigated and used in combination with PCA to eliminate the lift-off effect and interlayer air gap and to classify defects in multilayer structures. The optimized SVM is used to build the classifier model and predict the types of defects.

Part II, which includes Chapters 5–12, is related to TECT and its methods for defect evaluation and characterization. In Chapter 5, basic concepts and classifications for active thermography and eddy current thermography are introduced. Chapter 6 is focused on defect evaluation based on longitudinal and lateral heat conduction of ECPT. Subsurface defects, parallel cracks, and natural oblique cracks in rail are evaluated. Chapter 7 is focused on ECST. Two characteristic features representing separation time were extracted from temperature responses and their monotonic relationships with defect depth were obtained for subsurface quantification. Chapter 8 introduces ECPPT for metal materials through numerical and experimental studies. Two characteristic features, namely blind frequency and minimum phase, were extracted from differential phase spectra. Based on their linear relationships with defect depth, both features can be used to measure defect depth. This chapter also experimentally demonstrates the advantages of phase information to reduce or enlarge the effect of surface emissivity variation. Chapter 9 presents volume heating thermography (VHT) and inside heating thermography (IHT) for advanced composite materials through these electromagnetic excitations. Several specific VHT/IHT methods have been developed in the forms of both (square) pulse and step analysis in the time domain and phase analysis in the frequency domain. Chapter 10 presents eddy current volume heating thermography (ECVHT) and phase analysis for delamination and impact inspection in CFRP. Chapter 11 presents PI-TWR by introducing cross correlation (CC) matched filtering in ECPT. The results illustrate a significant improvement in the dynamic range, depth resolution, emissivity variation reduction, and detectability of subsurface defects and inside delamination. Chapter 12 proposes through coating imaging (TCI) based on ECPPT. The experimental results illustrate that ECPPT has a greater potential for corrosion detection, sizing, and monitoring than laser profilometry, PEC, and microwave waveguide. Finally, power function is suitable for demonstrating development of early stage (in 6 months) marine atmospheric corrosion like it does for long-term corrosion.

Part III, including Chapters 13–16, is related to the physical–mathematical model-based ECPT for defect evaluation. Chapter 13 constructs a physical–mathematical time-dependent partition model to analyze the whole thermal transient process and considers characteristic times for separating Joule heating and thermal diffusion into four different stages. Chapter 14 proposes an unsupervised method for defect diagnosis with ECPT. The proposed method is fully automated and does not require manual selection of the specific thermal frame images for defect diagnosis by the user. The core of the method is a hybrid of a physics-based inductive thermal mechanism with a signal processing-based pattern extraction algorithm using sparse greedy based principal component analysis (SGPCA). Chapter 15 develops a physics-based multidimensional spatial–transient–stage tensor model to describe the thermooptical flow (TOF) pattern for evaluating contact fatigue damage in a helical gear. It indicates that the proposed methods are effective tools for gear inspection and fatigue evaluation. In Chapter 16, we generate a physics–mathematical modeling and mining route in the spatial-, time-, frequency-, and sparse-pattern domains. This is a significant step toward realizing the deeper insight in ECPT and automatic defect identification. This renders ECPT a promising candidate for the highly efficient and yet flexible nondestructive testing and evaluation (NDT&E) technique.

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Yunze He, Bin Gao, Ali Sophian, Ruizhen Yang
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Abbreviations

ACFM	Alternating current field measurement
ADC	Analog-to-digital converter
AHT	Abnormal heating thermography
APG	Accelerated proximal gradient
BOB	Bottom of bottom
BOT	Bottom of top
BPT	Burst phase thermography
BSS	Blind source separation
CC	Cross correlation
CCMF	Cross correlation matched filtering
CFRP	Carbon fiber reinforced plastic
CM	Condition monitoring
DAC	Different absolute contrast
DAQ	Data acquisition
DF	Diff frequency to zero
DFT	Discrete Fourier transform
DL	Digital level
DWT	Discrete wavelength transform
EC	Eddy current
ECLT	Eddy current lock-in thermography
ECPPT	Eddy current pulsed phase thermography
ECPT	Eddy current pulsed thermography
ECSPPT	Eddy current square pulsed phase thermography
ECSPT	Eddy current square pulsed thermography
ECST	Eddy current step thermography
ECT	Eddy current testing or eddy current thermography
ECTRT	Eddy current time-resolved thermography
ECVHT	Eddy current volume heating thermography
EDM	Electrical discharge machine
EIS	Electrochemical impedance spectroscopy
EMAT	Electromagnetic acoustic transducers
EMNDT	Electromagnetic nondestructive testing
EMT	Electromagnetic–thermal
EVD	Eigenvalue decomposition
FD	Fault diagnosis
FEM	Finite element modeling
FFT	Fast Fourier transform
FMT	Frequency modulated thermography
FN	False negative

FP	False positive
GFRP	Glass fiber reinforced plastic
GMR	Giant magnetoresistive
IC	Independent components
ICA	Independent component analysis
IHT	Inside heating thermography
IR	Infrared
LHC	Lateral heat conduction
LLT	Laser lock-in thermography
LOI	Lift-off point of intersection or lift-off invariance
LST	Line scanning thermography
LT	Lock-in thermography
MAE	Magnetoacoustic emission
MBN	Magnetic Barkhausen noise
MCMC	Markov chain Monte Carlo
MFL	Magnetic flux leakage
MP	Matching pursuit
MT	Modulated thermography
MUT	Materials under test
MWT	Microwave thermography
NC	Normalized contrast
NDE	Nondestructive evaluation
NDT	Nondestructive testing
NDT&E	Nondestructive testing and evaluation
NMF	Nonnegative matrix factorization
OF	Optical flow
O&M	Operations and maintenance
OMP	Orthogonal matching pursuit
PC	Principal components
PCA	Principal component analysis
PEC	Pulsed eddy current
PI-TWR	Pulsed inductive thermal-wave radar
POD	Probability of detection
PPI	Preprocessed image
PPMM	Physics–mathematical pattern modeling and mining
PPT	Pulsed phase thermography
PSO	Particle swarm optimization
PT	Penetration testing or pulsed thermography
PTFE	Polytetrafluoroethylene
QEC	Quantitative error curve
RBF	Radial basis function
RCF	Rolling contact fatigue
RFID	Radio frequency identification
ROC	Receiver operating characteristic
SeHT	Selectively heating thermography
SFPM	Spatial–frequency pattern mining
SGPCA	Sparse greedy based principal components analysis
SHM	Structural health monitoring

SHT	Surface heating thermography
SNR	Signal-to-noise ratio
SPPT	Square pulse phase thermography
SPT	Square pulse thermography
SSFPM	Sparse spatial–frequency pattern mining
SSIM	Structural similarity
SSTPM	Sparse spatial–time pattern mining
ST	Step thermography
STPM	Spatial–time pattern mining
SVD	Singular value decomposition
SVM	Support vector machine
TBET	Tone burst eddy current thermography
TCH	Through coating heating
TCI	Through coating imaging
TC-PCT	Truncated correlation photothermal coherence tomography
TECT	Transient eddy current thermography
TN	True negative
TOB	Top of bottom
TOF	Thermooptical flow
TOT	Top of top
TP	True positive
TRT	Time-resolved thermography
TSR	Thermographic signal reconstruction
TWR	Thermal-wave radar
TWRI	Thermal-wave radar imaging
UT	Ultrasonic Testing
VBSPCA	Variational Bayesian sparse principal components analysis
VHLT	Volume heating lock-in thermography
VHPPT	Volume heating pulse phase thermography
VHPT	Volume heating pulse thermography
VHST	Volume heating step thermography
VHT	Volume heating thermography
WT	Wind turbine