Sensors and Actuators A 238 (2016) 251–265

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Gradient-field pulsed eddy current probes for imaging of hidden corrosion in conductive structures

Yong Li[a], Bei Yan[a], Da Li[a], Yili Li[a], Deqiang Zhou[b,*]

[a] Research centre for inspection and evaluation of nuclear structural integrity, State key laboratory for strength and vibration of mechanical structures, School of Aerospace, Xi'an Jiaotong University, ShaanXi, Xi'an 710049, China
[b] School of Mechanical Engineering, Jiangnan University, Wuxi 214122, China

ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form
21 December 2015
Accepted 21 December 2015
Available online 29 December 2015

Keywords:
Electromagnetic non-destructive evaluation
Pulsed eddy current
Gradient field
Corrosion
Analytical modeling

ABSTRACT

Pulsed eddy current testing (PEC) has been found advantageous over other non-destructive evaluation (NDE) techniques particularly in detection and characterization of subsurface defects in conductive structures. The measurement of net magnetic field for acquisition of transient signals is normally employed in traditional PEC during inspection of conductors. In this paper, PEC in conjunction with gradient field measurement is investigated in an effort to enhance the inspection sensitivity to hidden corrosion in conductors and accuracy of corrosion imaging. Closed-form expressions of gradient field and its sensitivity to hidden corrosion are formulated via the extended truncated region eigenfunction expansion (ETREE) modeling. A series of simulations are subsequently conducted to analyze the characteristics of gradient field signals and inspection sensitivity to hidden corrosion. Following this, experiments of Gradient-field PEC (GPEC) for evaluation and imaging of hidden corrosion are carried out. Through theoretical and experimental investigation, it has been found that the GPEC probe is advantageous over that based on traditional PEC in terms of inspection sensitivity and accuracy of corrosion imaging.

1. Introduction

Among various types of defects, hidden corrosion has posed a more severe threat to the integrity of the crucial metallic and stratified components/structures of such mechanical apparatus as airplanes, pipeline, pressure vessels, etc. It is one of the critical causes resulting in structural failure, and can barely be detected or even assessed by using common Non-destructive Testing and Evaluation (NDT&E) techniques such as visual testing (VT), eddy current testing (ECT) [1], ultrasonic testing (UT) [2], etc. In light of this, pulsed eddy current technique (PEC) has been investigated and found efficient and advantageous over other NDT&E methods in detection and characterization of subsurface defects within in-service conductors [3]. Conventional PEC utilizes mostly magnetic field sensors (ratiometric-output sensors) such as Hall devices to measure the transient signal of net magnetic field which has correlation with defects in layered conductors under inspection [4]. Li et al. [5] realized a PEC probe consisting of a pancake coil and Hall device to investigate transient magnetic field responses to multilayered structures. Sophian et al. [6] employed giant magnetoresistance (GMR) sensors to obtain the PEC signals to detect, characterize and identify typical defects including cracks, large-area surface/subsurface corrosion within conductors. Xie and Chen et al. investigated the forward and inverse problems of PEC inspection of hidden corrosion in steam-generation pipes in nuclear power plants [7].

However, PEC probes are subject to technical drawbacks in terms of relatively low signal-to-noise ratio, sensitivity to subsurface defects in layered conductors and accuracy in defect sizing, etc. In light of this, optimization of PEC probes has been carried out over years, which was focused on modification of field-excitation modules (namely excitation coils) [8,9], utilization of high-sensitivity field sensors/devices [10–12] and rearrangement of deployment and mode of sensors and excitation coils [13,14]. Whereas, the proposed measures enhancing the performance of PEC probes were based on measurement of net magnetic field in lieu of gradient field.

Gradient-field measurement (GFM) has been proved efficient and effective in measurement of field perturbation resulting from variation in not only strength but also distribution of magnetic field. Therefore, GFM is preferred in such fields demanding high-sensitivity quantification of magnetic field as medical science and military, etc [15]. Valentino et al. [16] adopted a couple of GMR sensors for measurement of

* Corresponding author.
E-mail address: zhoudeqiang@jiangnan.edu.cn (D. Zhou).

http://dx.doi.org/10.1016/j.sna.2015.12.026
0924-4247/

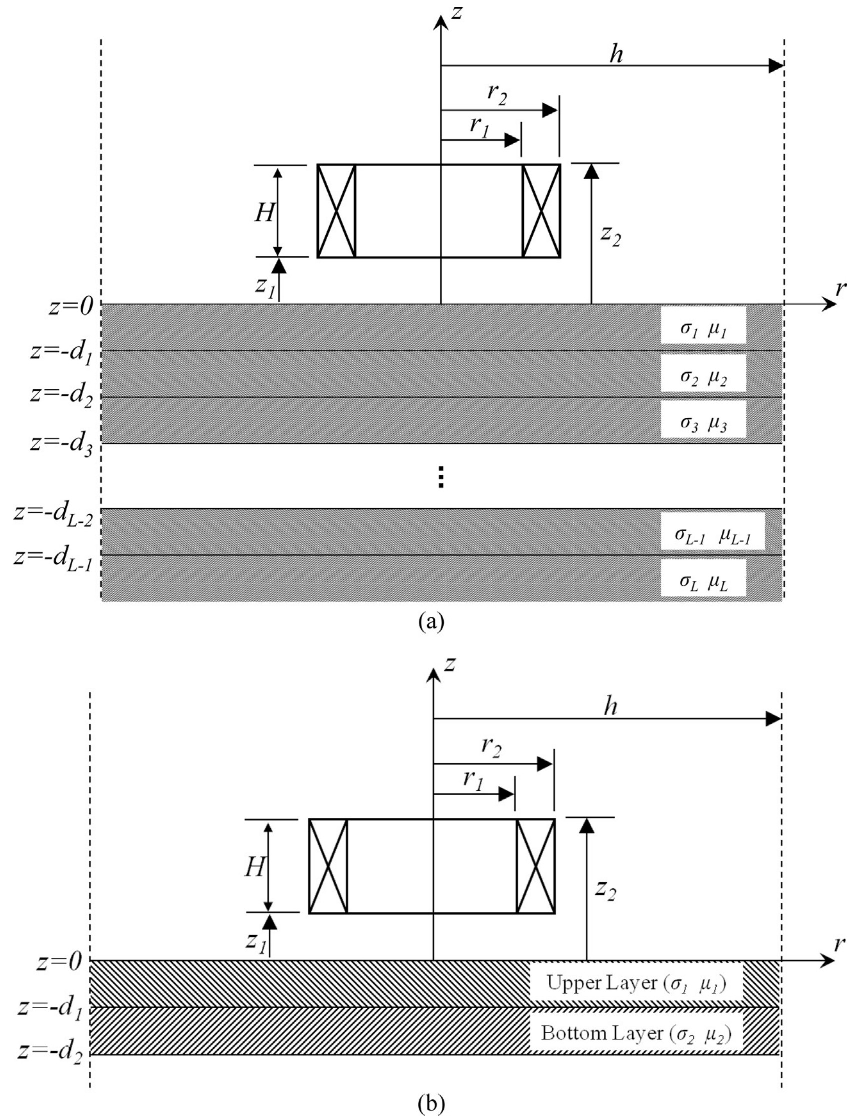

Fig. 1. A 2D axi-symmetric model of GPEC of a stratified conductor with: (**a**) L layers; (**b**) 2 conductive layers.

gradient field in EC-based detection and imaging of defects in riveted structures of aircrafts, which has shown the advantages of GFM over measurement of net magnetic field in defect imaging. Li et al. [17] investigated GFM-based PEC (GPEC) for evaluation of subsurface material degradation and found that the transient signal of gradient field had higher sensitivity to subsurface material degradation than that of net magnetic field. Whereas, GPEC and its probes are still demanding more intensive investigation involving: (1) the elaborated theory of gradient field underlying GFM; (2) theoretical and experimental analysis of GPEC sensitivity to hidden corrosion; and (3) evaluation and imaging of hidden corrosion by using dedicated GPEC probes, etc.

In this paper, GPEC probes for evaluation and imaging of hidden corrosion are investigated via the theory and experiment. The closed-form expressions of the gradient field response and its sensitivity to hidden corrosion are formulated based on the extended truncated region eigenfunction expansion (ETREE) [18]. The signal characteristics and sensitivity of GPEC are analyzed via simulations. Following this, the comparison in sensitivity and imaging of hidden corrosion between GPEC and PEC is conducted through experiments.

2. Theory

2.1. Field formulation

Different from the conventional PEC, the modeling of GPEC probes is focused on the formulation and analysis of the gradient field instead of net magnetic field. As shown in Fig. 1, suppose that a cylindrical GPEC probe (with the inner and outer radii of r_1 and r_2, height of H and liftoff of z_1, $z_1 = z_2 - H$) is placed over a stratified conductor comprising a number of flat conductive layers with upper surfaces locating individually at $-d_n$ ($n = 0, 1, 2, 3\ldots L$-1 whilst $d_0 = 0$), different conductivities (σ_n, $n = 1, 2, 3\ldots L$) and relative permeabilities (μ_n, $n = 1, 2, 3\ldots L$). The GPEC probe consists of an excitation coil generating primary/incident field to induce eddy currents in the conductor and a sensing element picking up transient signals of the gradient field at an arbitrary position whilst $z \geq 0$. The excitation coil is supplied with a transient current $I(t)$ in rectangular waveform which is taken as the excitation source. The solution region is truncated with the radial