NDT&E International 74 (2015) 66–71

Contents lists available at ScienceDirect

NDT&E International

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

Elimination of liftoff effect using a model-based method for eddy current characterization of a plate

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ARTICLE INFO

Article history:
Received 6 December 2014
Received in revised form
3 April 2015
Accepted 15 May 2015
Available online 29 May 2015

Keywords:
Eddy current
Characterization
Metal plate
Liftoff effect
Model-based method

ABSTRACT

Model-based inversion method has been studied extensively for characterization of a metal plate in eddy current testing. However, few reports cover liftoff elimination. In this work, model-based inversion method is evaluated in terms of liftoff reduction. For better inversion accuracy, a complex yet accurate procedure is presented to do calibrations of coil parameters before use. The results from simulations and experiments demonstrate that model-based inversion method has an exceptional ability to compensate influence of large liftoff variations by considering it as an unknown variable to be determined.

1. Introduction

Conductivity and thickness of metal sheets are two important variables that play an essential role in product quality, process control, and cost control in many industries [1–4]. Currently, there are various methods available to measure them, such as ultrasonic, thermal, eddy current and four-point methods. Compared to others mentioned above, an eddy current method is preferable, because it is non-contact and relatively inexpensive. Additionally, an eddy current method is able to provide information about the metal sheet's conductivity and thickness simultaneously, which is a significant advantage.

So far, eddy current method has been employed for the measurement of electrical parameters for more than four decades. Generally, almost all commercial instruments require periodic calibrations. However, manufacture of perfect or satisfactory calibration standards remains a challenge [5]. For this reason, a model-based approach, which treats an inverse problem as an optimization problem, is highly desirable [5,6]. It would make use of an analytical or numerical model in order to compute coil impedances for a variety of possible combinations of parameter values. The set of parameters, for which the calculated result yields the best agreement with an experimental measurement in a least squares fit, would correspond to the parameters of the test object. The first step in developing such a method is to derive an accurate and efficient theoretical model for a coil above a conducting plate. In order to determine the unknown parameters from measured coil impedances, it is necessary to apply an optimization algorithm to minimize the difference between model-calculated and measured data.

In [7], a model-based approach was applied for the characterization of case depth of steel due to induction heating or case carburization. Similarly, this approach was utilized to determine the thickness and conductivity of three-layered plane conductors using an eddy current sweep technique [8]. In order to be more efficient, novel look-up-table and feature-based methods, which avoid iterative computations of a forward model, were proposed [9–14]. In [15], the investigation reveals that conductivity effects are prominent in the rising edge of the transient response, while permeability effects dominate in the stable phase, which is valuable for simultaneous measurement of permeability and conductivity using pulsed eddy current method with consideration of normalization techniques to remove influence of liftoff. Currently, research continues for new and robust signal features for the measurement of conductivity and thickness.

It is well known that problematic liftoff effects have always been one of the focuses for accuracy improvement in eddy current nondestructive testing [16,17]. However, few investigations using model-based approaches have addressed this problem. In addition, previous studies have demonstrated that measurement accuracy

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http://dx.doi.org/10.1016/j.ndteint.2015.05.007
0963-8695/

relies heavily upon the level of discrepancy between observed and predicted results [7,13–14]. This work aims to do research on liftoff elimination for model-based inversion method. For accuracy improvement, a complex yet accurate calibration procedure is presented to correct coil parameters. The remainder of this paper is organized as follows. In Section 2, an analytical model, which computes the coil impedance change, is formulated. Sections 3 and 4 provide a detailed description of the calibration and inversion procedures, respectively. Subsequently, Monte Carlo analyses were performed to verify the developed method and to evaluate its performances in Section 5. The feasibility and merits of the developed method in terms of liftoff elimination were confirmed by experiments in Section 6. Lastly, Section 7 provides a summary and outlines future work.

2. Theoretical formulation

Consider an air-core coil above two conducting layers with the axis perpendicular to the surface, as illustrated in Fig. 1.

The layer and substrate materials are assumed linear, isotropic and homogeneous. The values for the electrical conductivities and magnetic permeabilities of the layer and substrate are denoted by σ_1 and μ_1, and σ_2 and μ_2, respectively. The base of the coil is at a height z_1 above the surface, whereas the top of the coil is located at z_2. The important parameters of the coil are its inner and outer radii r_1 and r_2, and turns N.

Since coil excitation frequencies for ECT range from a few Hz to several MHz, the displacement current is negligible. In the late 1960s, Dodd and Deeds [18] formulated the eddy current field for a coil in the form of multiple improper integrals, causing some difficulty for numerical computation. In [19], the authors presented an improved model using the TREE method and reflection and transmission theory of electromagnetic waves. The modified formulation of the impedance change for coils above stratified conductors becomes

$$\Delta Z = \frac{j2\pi\omega\mu_0 N^2}{(r_2-r_1)^2(z_2-z_1)^2}\sum_{i=1}^{\infty}\frac{\chi^2(\lambda_{0i}r_1,\lambda_{0i}r_2)}{\lambda_{0i}^7\left[\rho J_0(\lambda_{0i}\rho)\right]^2}\left(e^{-\lambda_{0i}z_1}-e^{-\lambda_{0i}z_2}\right)^2 R_0' \tag{1}$$

where

$$\chi(\lambda_{0i}r_1,\lambda_{0i}r_2) = \int_{\lambda_{0i}r_2}^{\lambda_{0i}r_1} xJ_1(x)dx,$$

$$R_0' = \frac{R_0+R_1 e^{-2\lambda_{1i}d_1}}{1+R_0R_1 e^{-2\lambda_{1i}d_1}},$$

$$R_m = \frac{\mu_{m+1}\lambda_{m,i}-\mu_m\lambda_{m+1,i}}{\mu_{m+1}\lambda_{m,i}+\mu_m\lambda_{m+1,i}} \quad m=0,1$$

$$\lambda_{n,i} = \sqrt{\lambda_{0i}^2+j\omega\sigma_n\mu_n} \quad n=1,2$$

In the above expressions, μ_0 is the magnetic permeability of free space, the eigenvalue λ_{0i} is the i-th positive root of Bessel function $J_1(\lambda_0\rho)$, $J_1(x)$ is Bessel function of the first kind of first order, μ_m and σ_m are the permeability and conductivity of the m-th layer, ω refers to angular frequency of the excitation, $j^2=-1$, and $r=\rho$ is the position where the artificial magnetic insulation boundary is placed.

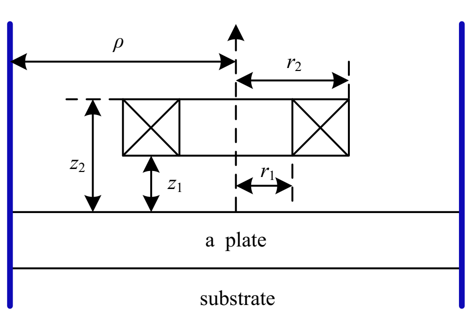

Fig. 1. Air-core coil over layered conductors.

Eq. (1) is used to calculate the impedance change of a coil due to layered conducting plates. For the case of an isolated coil in air, the impedance is written as follows [19]:

$$Z_0 = \frac{j4\pi\omega\mu_0 N^2}{(r_2-r_1)^2(z_2-z_1)^2}\sum_{i=1}^{\infty}\frac{\chi^2(\lambda_{0i}r_1,\lambda_{0i}r_2)}{\left[(\lambda_{0i}\rho)J_0(\lambda_{0i}\rho)\right]^2\lambda_{0i}^5}\left[\lambda_{0i}(z_2-z_1)+e^{-\lambda_{0i}(z_2-z_1)}-1\right] \tag{2}$$

3. Calibration

The inner radius of the coil was obtained by measuring the dimensions of the former, using a digital caliper, before the coil was wound. The outer radius and height of the coil were measured before the coil was enveloped. The self-inductance, stray capacitance and resonant frequency of the enveloped coil were measured using a Wayne Kerr WK65120B impedance analyzer, and DC resistance was measured using a multimeter. The measured parameters of the coil are given in Table 1.

For model-based inversion, accuracy is adversely affected by discrepancies between theoretical calculations and experimental measurements. To the authors' knowledge, mainly two types of factors contribute to these discrepancies. The first is that a coil is typically modeled as an ideal inductor, neglecting effects of stray capacitance mainly due to adjacent turns and AC resistance due to skin effects [20]. The second is that outer radius of a coil and liftoff distance are difficult to measure directly and accurately. Therefore, it is necessary to perform calibrations in order to improve inversion accuracy by narrowing the gap between predictions and measurements.

Harrison et al. [21] introduced an equivalent circuit which incorporated the coil's non-ideal behavior, shown in Fig. 2. R_0 and L_0 are the DC resistance and inductance of the coil respectively. ΔZ_c denotes the impedance change due to induced eddy current in a sample. R_s and C_s represent resistance and self-capacitance. C_L is the capacitance resulting from the lead connected to the coil. For completeness, an unspecified circuit network RC is drawn to represent entire non-ideal probe behaviors except for the major components R_s, C_s and C_L. For sake of simplicity, a total lumped parameter Z_p is defined to represent the whole factors above that do not incorporated in the presented theoretical model.

The approach of Harrison et al. uses the equivalent circuit to estimate how much the coil impedance has been altered, and then subtracts this change from the measurements. Following the method described in [21], the corrected impedance change due to a plate is

$$\Delta Z_c = Z_c - Z_0 \tag{3}$$

Table 1
Coil parameters.

Parameters	Value
Inner radius r_1/mm	2.22
Outer radius r_2/mm	2.90
Number of turns N	206
Height /mm	3.70
Stand-off /mm	0.80
Self-inductance L_0/mH	0.159
DC resistance R_0/Ω	7.75
Resonant frequency f_r/MHz	1.35