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Excitation current waveform for eddy current testing on the thickness of ferromagnetic plates

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ABSTRACT

Advantages of pulsed excitation current over conventional harmonic excitation for measuring the thickness of a ferromagnetic plate are studied. Compared with the sinusoidal voltage induced by harmonic excitation current, the time-domain voltage induced by pulsed current is highly more sensitive to the thickness. Quantitative proof of this conclusion is provided by solving the normalized derivatives with respect to the thickness. Furthermore, the effects of the time constant of pulsed current on the measuring sensitivity are examined, and an optimal range of the time constant is proposed. Finally, the theoretical model is verified by experimental results.

1. Introduction

Corrosion of ferromagnetic components is a kind of widespread damage in oil and gas, chemical, electric power, metallurgy and other related industries. For example ferromagnetic pipes and containers are widely used to transport and store liquid or gaseous corrosive media, and most components usually work under the conditions of high temperature and high pressure. As a result, corrosion of ferromagnetic components is unavoidable. Furthermore, wall-thinning defects usually caused by corrosion are potential hazards to safety, and may lead to pipeline leakage, explosion or other accidents. Therefore, to ensure safe operation, regular in-service nondestructive testing and evaluation for remaining wall thickness of ferromagnetic components are indispensable.

The eddy current testing (ECT) is a non-contact electromagnetic inspection method which can be used through the insulation and cladding. However, the conventional ECT method excited by time-harmonic current has rarely been used to measure the wall thickness of ferromagnetic components due to the limitation of its penetration depth. The pulsed eddy current testing (PECT) is an alternative method, and many researches in recent years have proved it an effective method for inspecting coated ferromagnetic pipes and containers [1–4]. Instead of time-harmonic excitation current, a pulsed current is used to induce a pulsed magnetic field outside the conductor, and then the wall-thinning corrosion of components can be evaluated by detecting this pulsed eddy current electromagnetic field. Unfortunately, few studies have been focused on the quantitative proof of advantages of the PECT method.

Analytical solutions to time-harmonic eddy current field have been developed perfectly. One classical method to solve axisymmetrical eddy current problems is developed in [5,6]. After that, Theodoulidis and Kriezis et al. obtain some modified expressions in the form of a series [7] rather than of an integral as in [5], by the truncated region eigenfunction expansion (TREE) method [8]. Furthermore, second-order vector potential (SOVP) is an effective tool to solve the non-axisymmetric eddy current field problems such as cylindrical and tubular conductors [9–13]. Closed-form expressions of the impedance change for a coil outside a conductive cylinder are solved by the SOVP formulation [9,10]. Furthermore, the model is extended to a cylindrical hollow pipe and solved analytically through the similar method [11–13].

On the basis of these analytical solutions for time-harmonic eddy current field, time-domain expressions for pulsed eddy current field can be calculated through the Laplace inverse transformation. The step response of the induced voltage across a coil above a half-space conductor has been derived from closed-form integral expressions, since its Laplace inverse transformation can be reduced to a standard form [14,15]. Moreover, rapid calculations for the transient eddy current response from a conductive plate are carried out by using the short and long time approximations in the Laplace inverse transformation [16,17]. Moreover, Jaeger and Lee

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et al. solve the time-domain pulsed magnetic field for enclosures and planar slabs by means of the residue theorem [18,19]. Based on this method, [20,21] propose an approach to solve the time-domain pulsed eddy current field for the conductive plate using the Heaviside expansion theorem.

Many simulations and experiments were designed to study the effects of the excitation current waveform on the detection signal in the PECT for ferromagnetic metallic materials [22]; however, little attention has been paid to study the theoretical foundations for excitation current waveform designing. On the basis of these analytical solutions mentioned above, the purpose of this paper is to compare the sensitivity of time-harmonic and pulsed excitation current for measuring the thickness of ferromagnetic plates. This paper is organized as follows. Section 2 describes the ECT model of a ferromagnetic plate. In Sections 3 and 4, the sensitivity to the thickness of the sinusoidal voltage induced by time-harmonic excitation field and the time-domain voltage induced by pulsed excitation field are calculated respectively. From analytical expressions, the potential advantages of pulsed excitation current for the thickness measurement are examined in Section 5. Furthermore, the optimal range of the time constant of pulsed excitation current is discussed in Section 6. Next, theoretical calculated results are compared with experimental results in Section 7. Finally, the conclusions are given in Section 8. This study presents that compared with the sinusoidal voltage induced by time-harmonic excitation current, the time-domain voltage induced by pulsed excitation current is much more sensitive to the thickness of ferromagnetic plates.

2. The ECT model of a ferromagnetic plate

The ECT model of a ferromagnetic plate shown in Fig. 1 is studied as an example in this paper. Generally, the ECT model of pipes could also be simplified to this plate model [1,2]. Respectively, d, σ and μ are the ferromagnetic plate's thickness, conductivity and permeability, where $\mu = \mu_0\mu_r$ (μ_0 is the permeability of vacuum, μ_r is the relative permeability). And the cylindrical coordinate system $O\rho\varphi z$ is established with the z-axis coinciding with the axis of the probe coil. The geometric parameters of the air-cored solenoid drive coil (subscript d) and pick-up coil (subscript p) are indicated in Fig. 1, and their values assigned in this paper are listed in Table 1.

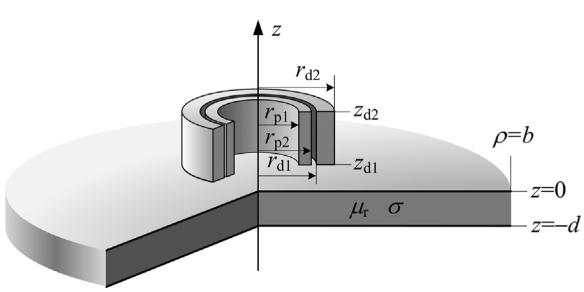

Fig. 1. The eddy current testing model of a ferromagnetic plate.

Table 1
Parameters of the drive coil and pick-up coil.

Parameters	Drive coil	Pick-up coil
Number of turns, N	174	1025
Length ($z_2 - z_1$) (mm)	25.0	25.0
Inner radius r_1 (mm)	20.9	20.0
Outer radius r_2 (mm)	22.2	20.8

3. Excited by time-harmonic current

3.1. Expressions for the mutual impedance

Following the TREE method, the solution region of the ECT model presented in Fig. 1 could be truncated by imposing a magnetic insulation boundary at the cylindrical surface $\rho = b$, which is set far from the coil to approximate an infinite domain [7]. When the drive coil carries a time-harmonic excitation current $I_0 e^{-j\omega t}$, (with $\omega = 2\pi f$, being the angular frequency), the mutual impedance, $Z(j\omega)$, is defined as the phasor ratio between the induced voltage across the pick-up coil and the excitation current. As is known that the mutual impedance of the total field $Z(j\omega)$ can be divided into two parts: $Z_{\text{in}}(j\omega)$, the mutual impedance in air produced by the incident field, and $Z_{\text{ec}}(j\omega)$, the mutual impedance change produced by the eddy current induced in conductors. The mutual impedance in air, Z_{in}, can be given as [7]

$$Z_{in} = j\omega L_{in} \tag{1}$$

where

$$L_{in} = \frac{4\pi\mu_0}{b^2}\sum_{i=1}^{+\infty}\frac{C_0(\lambda_i)}{\lambda_i^3 J_0^2(b\lambda_i)} \tag{2}$$

where λ_i is the ith positive root of the first-order Bessel function $J_1(b\lambda) = 0$, and the coil coefficient of the incident field is

$$C_0(\lambda_i) = \frac{N_d N_p \chi(r_{d1}, r_{d2})\chi(r_{p1}, r_{p2})(e^{-\lambda_i h} + h\lambda_i - 1)}{(r_{d2} - r_{d1})(r_{p2} - r_{p1})h^2} \tag{3}$$

where $\chi(x_1, x_2) = \int_{x_1}^{x_2} xJ_1(\lambda_i x)dx$; and $h = z_{d2} - z_{d1}$, is the length of the probe coil. As the probe coil placed above the ferromagnetic plate, the mutual impedance of eddy current field is given by [20]

$$Z_{ec} = j\omega\frac{2\pi\mu_0}{b^2}\sum_{i=1}^{+\infty}\frac{C_d(\lambda_i)C_p(\lambda_i)}{\lambda_i^3 J_0^2(b\lambda_i)}\alpha(j\omega, \lambda_i) \tag{4}$$

in which the coil coefficient of eddy current field is

$$C(\lambda_i) = \frac{N\chi(r_1, r_2)(e^{-\lambda_i z_1} - e^{-\lambda_i z_2})}{(r_2 - r_1)(z_2 - z_1)} \tag{5}$$

and the plate coefficient is defined as

$$\alpha(j\omega, \lambda_i) = \frac{[(1 - \mu_r^2)\lambda_i^2 + j\omega\mu\sigma](e^{-2\gamma_i d} - 1)}{(\gamma_i + \mu_r\lambda_i)^2 - (\gamma_i - \mu_r\lambda_i)^2 e^{-2\gamma_i d}} \tag{6}$$

with $\gamma_i = \sqrt{\lambda_i^2 + j\omega\mu\sigma}$.

In order to study the sensitivity of the mutual impedance to the thickness, we formulate the partial derivative of $Z(j\omega)$ with respect to the thickness d. From Eq. (1), it is evident that $\partial Z_{in}/\partial d = 0$, hence, we have

$$\frac{\partial Z}{\partial d} = \frac{\partial Z_{\text{ec}}}{\partial d} = j\omega\frac{2\pi\mu_0}{b^2}\sum_{i=1}^{+\infty}\frac{C_d(\lambda_i)C_p(\lambda_i)}{\lambda_i^3 J_0^2(b\lambda_i)}\frac{\partial\alpha}{\partial d} \tag{7}$$

where

$$\frac{\partial\alpha}{\partial d} = -\frac{8\gamma_i^2\mu_r\lambda_i[(1 - \mu_r^2)\lambda_i^2 + j\omega\mu\sigma]e^{-2\gamma_i d}}{\left[(\gamma_i + \mu_r\lambda_i)^2 - (\gamma_i - \mu_r\lambda_i)^2 e^{-2\gamma_i d}\right]^2}.$$

3.2. Sensitivity of the mutual impedance to the thickness

In most cases, the amplitude $A(\omega)$ and phase $\varphi(\omega)$ of the sinusoidal voltage induced by time-harmonic excitation current can be measured directly. Therefore, in order to study the sensitivity of the sinusoidal induced voltage to the thickness, the normalized derivatives of the amplitude $A(\omega)$ and phase $\varphi(\omega)$