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Electrical conductivity measurement of ferromagnetic metallic materials using pulsed eddy current method

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ABSTRACT

Pulsed eddy current testing (PECT) method for electrical conductivity measurement of ferromagnetic metallic materials is proposed. Based on time-domain analytical solutions to the PECT model of ferromagnetic plates, the conductivity and permeability are determined via an inverse problem established with the calculated and measured values of induced voltage. PECT method for conductivity measurement is verified by the four-point probe method on three carbon steel plates. In addition, the effects of the amplitude of pulsed excitation current and the lift-off of probe coils on measurement results are studied. PECT is an innovative, non-contacting method with good repeatability for electrical conductivity measurement.

1. Introduction

Electrical conductivity is an important parameter to characterize the conductivity property of metal materials. Electrical conductivity measurement is extremely useful for metal materials sorting, alloy materials identification, hardness and microstructure detecting, and heat treatment monitoring [1,2]. Therefore, an accurate, nondestructive testing on electrical conductivity of ferromagnetic metallic materials is of great significance.

Four-point direct-current potential drop (DCPD) measurement is a widespread method for measuring the resistivity of soil and semiconductor. It has the advantages of being simple device, convenient operation (without the need for calibration standards) and high accuracy. Similarly, four-point probe methods have been used to measure the electrical conductivity of metals [3–7]. In a typical four-point probe measurement, good electrical contact is required between the probe points and the conductor being measured. Firstly, excitation current is injected into the conductor via one pair of probe points; then, the potential drop between the other pair of probe points is measured through a voltmeter; finally, the electrical conductivity of the conductor can be calculated via a simple formula. A four-point alternating current potential drop (ACPD) method is proposed in Refs. [4,5] to measure the electrical conductivity of ferromagnetic metal plates. Instead of a direct current, a low-frequency alternating current in the frequency range of 1–100 Hz is used to determine the conductivity of a carbon steel plate and a spring steel plate respectively. It is indicated that below a certain characteristic frequency, the conductivity measurement results are independent of magnetic permeability. In addition, theory models of the four-point DCPD and ACPD measurement on conductive plates of arbitrary thickness are established in Refs. [6,7] respectively.

Although the four-point probe methods are able to measure the electrical conductivity of ferromagnetic metallic materials, there are several restraining factors for its practical application. Firstly, the non-conductive coating such as paint, oxidation and corrosion layer must be removed before testing because of the need for good electrical contact with the specimen. In addition, metal materials usually are good conductors, so a large excitation current is required to produce a sufficiently high potential drop signal. Due to the heating effects of the excitation current and the measurement errors of a weak potential drop signal, obvious errors are introduced to electrical conductivity measurement of metal materials using the four-point probe methods.

For non-ferromagnetic metal materials, sinusoidal eddy current testing (ECT) method can be used to measure the electrical conductivity precisely [5,8]. The electrical conductivity of the specimens can be obtained via calibrated standards, or an inversion problem using analytical expressions. The ECT method for conductivity measurement of non-ferromagnetic metals has been developed for decades, and it is a non-contacting detection method without pretreatment on the non-conductive coating of the test specimen. Unfortunately, in the ECT on ferromagnetic metallic materials, the electrical conductivity and magnetic permeability of the specimen cannot be separated unless at very low frequencies. In addition, the magnetic permeability is usually frequency dependence and related to the excitation field. Hence, the electrical conductivity of ferromagnetic metals cannot be

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easily measured using the ECT method. Pulsed eddy current testing (PECT) is an alternative method for inspecting the ferromagnetic metallic materials. The sinusoidal excitation current is replaced by a pulsed current, and the electrical conductivity, magnetic permeability and wall thickness of the test specimen could be determined by collecting the transient electromagnetic field. Currently, the PECT method has been developed mainly for detecting the wall-thinning corrosion of ferromagnetic containers and pipes [9–11]. A measurement method has been developed using the pulsed eddy current technique to determine the thickness or conductivity of metallic coatings (25–400 μm) on a metal substrate for the case when either the coating or substrate is magnetic [12]. Furthermore, the transient response, differential normalized response, magnitude spectrum and normalized magnitude spectrum of the PECT were carried out to decouple the influence of the conductivity and the permeability (varies from 1–1.63) of the test sample [13]. The numerical and experimental results reveal that conductivity effects are prominent in the rising edge of the transient response, while permeability effects can be reduced by normalization [13].

Since the superposition effects of the incident field and the reflection field from the conductor can be avoided in the pulsed eddy current field, the time-domain induced voltage in the PECT is significantly more sensitive to the wall thickness of ferromagnetic metallic plates, compared with the frequency-domain impedance change in the ECT [10]. Meanwhile, it is relatively easy to obtain a similar conclusion for the conductivity measurement: The time-domain induced voltage in the PECT is significantly more sensitive to the conductivity of ferromagnetic metallic plates. Therefore, this paper has tried developing a PECT method for electrical conductivity measurement of ferromagnetic metallic materials.

On the foundation of time-domain analytical solutions to the PECT model of the ferromagnetic plate, an inverse problem is established with the collected induced voltage signal to determine the electrical conductivity and magnetic permeability of the ferromagnetic plate. Then the inverse problem is solved through the Gauss–Newton method. In the section of experiments, the electrical conductivities of three different carbon steel plates are measured by the four-point probe method and PECT method respectively. Through the average value and standard deviation of the experimental measurement results, the detection capabilities of the measurement methods are compared. In addition, the effects of the amplitude of pulsed excitation current and the lift-off of the probe coils on detection results are studied. Finally, the PECT method proposed for measuring the electrical conductivity of ferromagnetic metallic plates is verified by experimental results.

2. Time-domain solutions to the PECT model

2.1. The PECT model for ferromagnetic metallic plates

As shown in Fig. 1, the PECT model of a ferromagnetic metallic plate is studied as an instance in this paper. Respectively, the electrical conductivity, magnetic permeability and wall thickness of the measured ferromagnetic metallic plate are denoted as σ, μ and d, where $\mu=\mu_0\mu_r$ (μ_0 is the permeability of the vacuum, μ_r is the relative permeability of the metallic plate). A cylindrical pick-up coil (subscript p) and a drive coil (subscript d) both of height h are positioned perpendicularly above the plate. l_o is the lift-off between the probe coils and the upper surface of the plate. The parameters of the air-cored probe coils are listed in Table 1. A cylindrical coordinate system $O\rho\varphi z$ is established, with the z-axis being coincident with the central axis of the probe coils. Using the TREE method (truncated region eigenfunction expansion) proposed in Ref. [14], the solution region of the PECT model could be truncated by a magnetic insulation boundary on the surface $\rho=b$, as shown in Fig. 1. In order to obtain a sufficient

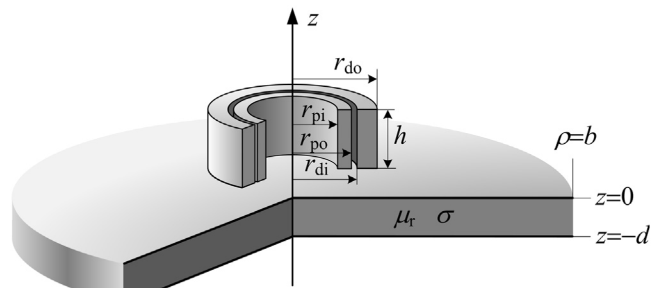

Fig. 1. The PECT model of a ferromagnetic metallic plate detected by two cylindrical air-cored coils.

Table 1
Parameters of the cylindrical air-cored probe coils.

Parameters	Drive coil	Pick-up coil
Number of turns N	149	863
Height h (mm)	15.0	15.0
Inner radius r_i (mm)	22.3	20.0
Outer radius r_o (mm)	24.4	22.1

calculation accuracy, the boundary b should be set nearly 10 times larger than the radius of the probe coils.

2.2. Time-domain analytical expressions of the induced voltage

The magnetic vector potential $\boldsymbol{A}$ in axisymmetric eddy current field as shown in Fig. 1, just have a circumferential component A_φ, i.e. $\boldsymbol{A}=A_\varphi \boldsymbol{e}_\varphi$. A classical method is proposed in Ref. [15] to obtain the closed-form expressions of the magnetic vector potential by the separation of variables. Rather than an integral form as in Ref. [15], approximate expressions in a series form are achieved by the TREE method [14] and the finite Hankel transformation [16], respectively. Then, through the Laplace inverse transformation, time-domain solutions to the pulsed eddy current field could be derived from the frequency-domain solutions. Concretely, the Laplace inverse transformation for a metallic plate can be calculated via the Heaviside expansion theorem [16,17]. Finally, across the pick-up coil, the time-domain voltage $u_{ec}(t)$ induced by the eddy current in the plate, can be derived as [10].

$$u_{ec}(t)=i'(t)*\frac{32\pi}{\sigma d b^2}\sum_{i=1}^{+\infty}\frac{C_d(\lambda_i)C_p(\lambda_i)}{\lambda_i^2 J_0^2(b\lambda_i)}\sum_{k=1}^{+\infty}\frac{\xi_k^2}{\Gamma_{ki}}e^{-\frac{t}{\tau_{ki}}} \quad (1)$$

where $i'(t)$ denotes the time derivative of the pulsed excitation current, and "$*$" denotes the convolution operation, $f_1(t)*f_2(t)=\int_0^t f_1(\tau)f_2(t-\tau)d\tau$; λ_i is the i-th positive root of the first-order Bessel function, $J_1(b\lambda)=0$; ξ_k denote the k-th positive root of the transcendental equation, $\left[\tan\xi+2\xi/(\mu_r\lambda_i d)\right]\left[\cot\xi-2\xi/(\mu_r\lambda_i d)\right]=0$. In addition, the coefficient, $\Gamma_{ki}=4\xi_k^2+2\mu_r\lambda_i d+(\mu_r\lambda_i d)^2$, and the time constant, $\tau_{ki}=\mu\sigma d^2/\left(4\xi_k^2+\lambda_i^2 d^2\right)$; the coil coefficients $C_d(\lambda_i)$ and $C_p(\lambda_i)$ are given in Refs. [16,17].

Commonly, the relative permeability of ferromagnetic metals satisfies, $\mu_r >> 1$, hence, the time-domain induced voltage in Eq. (1) has been simplified as [10]

$$u_{ec}(t)\approx u_p(t)=\frac{8\pi^3 I_0}{\sigma\mu_r^2 d^3}\sum_{i=1}^{+\infty}\frac{C_p(\lambda_i)C_d(\lambda_i)}{\lambda_i^4 J_0^2(b\lambda_i)b^2}e^{-\frac{\pi^2}{\mu_0\sigma\mu_r d^2}t} \quad (2)$$

where I_0 denotes the amplitude of the pulsed excitation current. From Eq. (2), it can be observed that the time-domain induced voltage of the PECT on ferromagnetic metallic plates can be rewritten as

$$u_{ec}(\sigma,\mu_r,d,t)\approx u_p(\sigma d,\mu_r d,t) \quad (3)$$