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Ferromagnetic material pulsed eddy current testing signal modeling by equivalent multiple-coil-coupling approach

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ABSTRACT

A multiple-coil-coupling model is proposed for ferromagnetic material pulsed eddy current testing signals in this paper. The model uses circuit-theory-based analysis to replace the field-theory-based analysis in pulsed eddy current testing modeling. A non-linear trust-region algorithm is developed to fit the practical signal. The eigenvalue for thickness quantification is selected as one of the fitted parameters and the algorithm is developed and verified by actual measured data. The model is simple and suitable for engineering application.

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1. Introduction

Pulsed eddy current (PEC) testing technique is characterized by its ability of in-service testing for the large corrosion of the ferromagnetic vessels and pipes without removing the wrapped coatings. Instead of single-frequency sinusoidal signal, its excitation is a step or square wave signal, which contains multiple frequency components.

Traditional single-frequency eddy current testing was first modeled by Dodd and Deeds whose work gave solutions of axially symmetric eddy current problems by vector potential analysis [1]. The representative researches for PEC modeling include the studies by Bowler and De Haan. Bowler and Marcus [2] calculated the PEC response to a conducting half-space when the excitation signal has exponential rising edge and made a comparison to the PEC response under ideal step excitation. de Haan and de Jong [3] gave solution of the transient induction voltage of a receiving coil over a plate with finite thickness. All these approaches are based on electromagnetic field theory such that these solutions are analytical and accurate but complex in form.

The method, which simplifies the eddy current testing system into a coil-coupling model (CCM), was first put forward by Loos in 1976 [4] and a revised version by Tan et al. [5]. The theory applies an equivalent current loop with finite dimensions to approximate the general eddy current effect of the specimen. The equivalent current loop can be modeled by an inductor and a resistor in series connection. Thus the traditional eddy current testing model is equivalent to an air-core transformer model [6]. The primary side of the transformer is the excitation circuit and the secondary side consists of an inductor and a resistor derived from the equivalent current loop. The key contribution of this method is transferring the field-theory-based calculation into circuit-theory-based calculation when solving traditional eddy current testing problems.

Lefebvre et al. [7] has successfully applied CCM based transformer model in non-ferromagnetic PEC testing signal modeling. Their research was proved for very thin non-ferromagnetic plate PEC signal modeling, the eddy current effects may be substituted by one equivalent coil with current flowing through it. However the research considered only the case of thin conductive plate (non-ferromagnetic) PEC testing.

Our research proves that CCM is not suitable for interpreting the ferromagnetic PEC signal behavior. Therefore, we present multiple-coil-coupling model (MCCM) for ferromagnetic PEC signal modeling. The experiment results show that the PEC signal fits well with the modified model.

2. Theory

2.1. CCM for single-frequency eddy current testing system

The key conception of CCM is to substitute the eddy current effects in the specimen by an equivalent current in the equivalent coil. To calculate the equivalent coil's dimensions, the equivalent current density is selected to be equal to the maximum eddy current density on the specimen surface.

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Assuming the outer radius of the excitation coil is r_{ex} and the skin effect depth of the excitation signal is δ [8], when the specimen's radial dimension r_s and thickness d satisfy the conditions

$$\begin{cases} r_s \geq 2.14 r_{ex} \\ d \geq 5.3\delta \end{cases} \tag{1}$$

The equivalent coil's dimensions have very little difference from the case in which the specimen has infinite radial dimension and thickness [5]. The calculated equivalent coil's dimensions are

$$\begin{cases} r_1 = 0.88 r_{ex} \\ r_2 = 1.38 r_{ex} \\ b = \delta \end{cases} \tag{2}$$

where r_1 and r_2 are equivalent coil's inner radius and outer radius, respectively, and b is the height of the equivalent coil. These dimensions are different from Loos's result, in which the equivalent current is the mean of the surface eddy current densities. The detailed calculation process can be found in [5]. In practical application, it is easy to satisfy $r_s \geq 2.14 r_{ex}$ by designing a small excitation coil. However the thickness of the specimen will not always satisfy $d \geq 5.3\delta$. Under condition

$$\begin{cases} r_s \geq 2.14 r_{ex} \\ d < 5.3\delta \end{cases} \tag{3}$$

the height of the equivalent coil can be calculated by

$$\int_0^{d/\delta} J_{0rex} e^{-\gamma} d\gamma = J_{0rex} b/\delta \tag{4}$$

and the solution is

$$b = (1 - e^{-d/\delta})\delta \tag{5}$$

when $\delta \to \infty$, $b \to d$, namely

$$\lim_{\delta \to +\infty} b = d \tag{6}$$

From the above discussion, when specimen has a limited thickness, the equivalent principle is still feasible but the equivalent coil's height is less than the skin effect depth and plate thickness. Thus the single-frequency eddy current testing system can be equivalent to the mutually coupled coils shown in Fig. 1(a) (detection coil is not shown) and modeled by the equivalent circuit shown in Fig. 1(b). The detection coil circuit can be ignored if the excitation coil is also applied as the detection coil.

The equivalent coil's dimensions depend on the excitation frequency such that the DC resistance and inductance of the equivalent coil are all frequency dependent. If the excitation signal contains more than one frequency, the circuit in Fig. 1(b) should not be directly applied.

2.2. Modified CCM for PEC testing system

2.2.1. Ideal PEC system

Let us consider a PEC system, which includes an excitation coil, a detection coil and a plate specimen with $r_s \geq 2.14 r_{ex}$ and infinite thickness. An ideal step current excitation is exerted to the excitation coil.

The step signal can be expressed as

$$x(t) = Au(t) \tag{7}$$

where $u(t)$ is the Heaviside function and A is the amplitude. Its Fourier transform can be written as

$$X(\omega) = A(\pi Dirac(\omega) - i/\omega) \tag{8}$$

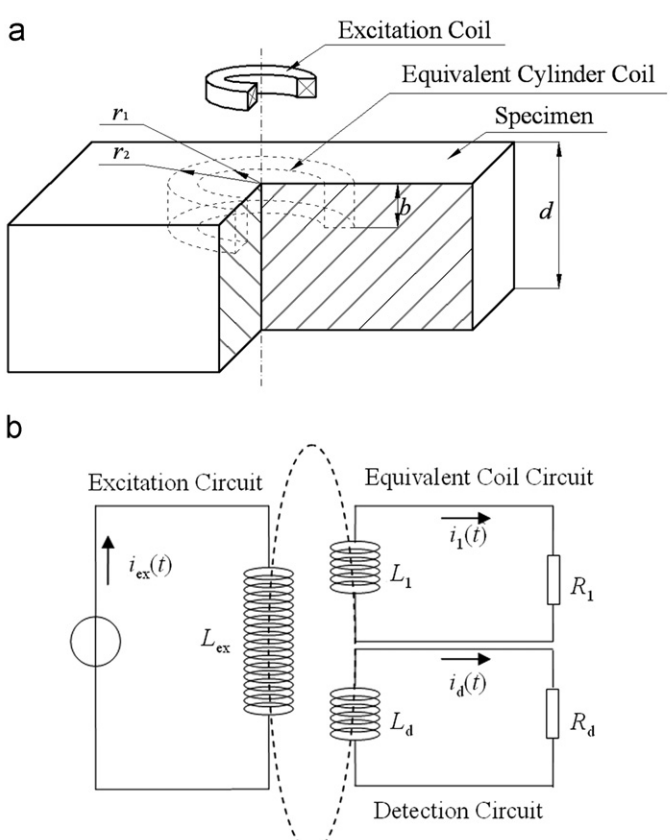

Fig. 1. (a) Equivalent CCM and (b) equivalent circuit model for single-frequency eddy current testing system.

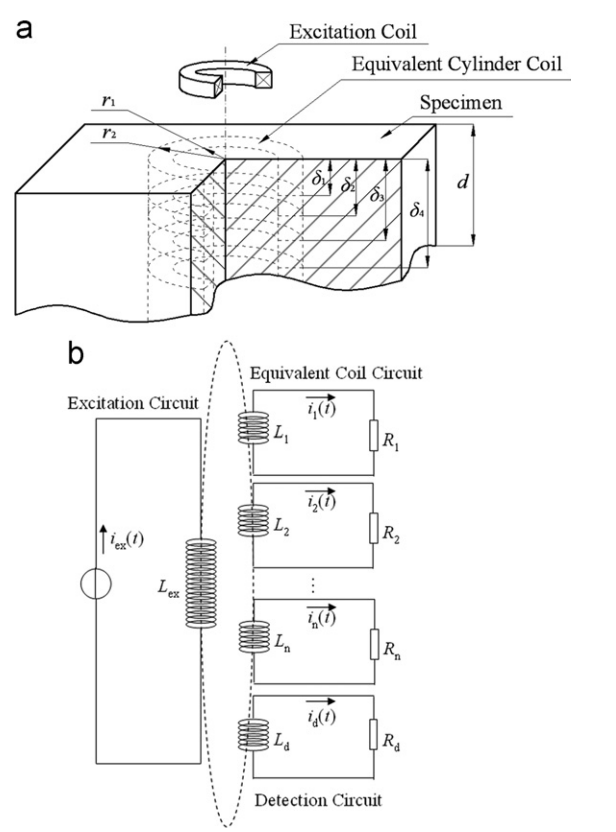

Fig. 2. (a) Equivalent MCCM and (b) equivalent circuit model for pulsed eddy current testing system.

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