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Thickness measurement of metal pipe using swept-frequency eddy current testing

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ABSTRACT

Swept-frequency eddy current measurement of pipe thickness is studied in this paper. First, suitable frequency range of swept-frequency eddy current testing is determined by comparing sensitivities of relative reactance change with respect to pipe thickness and other parameters at different frequencies. Based on analytical solutions to pipe eddy current field, Levenberg–Marquardt algorithm and variable transformation, a method for solving inverse eddy current problem is developed. Finally, several inversion calculations are carried out and the results are close to the truth values. The low errors reveal that the method presented in this paper is appropriate.

1. Introduction

Corrosion would lead to a pipe wall thinning, which is of great danger. Eddy current testing (ECT) is a typical non-contact nondestructive testing method and is considered to be a powerful approach for the nondestructive testing of pipe wall thinning. Lookup table method is often used for pipe thickness gauging [1,2]. However, the table is usually constructed based on a mass of experiments on standard specimens, and it is only suitable for special specimen testing. Researchers use features of eddy current testing signals, such as zero crossing time of induced voltage [3], peak frequency of inductance changes [4], zero crossing frequency of resistance change [5], time-to-peak of differential pulsed eddy-current testing signals [6], to gauge thickness of metal pipe or plate. This method is available when some parameters of the specimen, e.g., conductivity, have been determined beforehand and the measurement result is impressionable.

Essentially, pipe thickness measurement using eddy current method is an inverse problem of pipe eddy current field. Optimization methods are already applied to gauge thickness of metal plate. Thickness and conductivity measurement is carried out by using least square algorithm in [7]. Ren and Lei [8] use the Powell algorithm to solve eddy current inverse problem of three-layered plates and determine the thickness of each layer. Chen and Lei present an inverse method to determine the relative variation of the wall thickness of ferromagnetic plates in [9]. Additionally, optimization methods are also effectively used for crack reconstruction and imaging [10–12]. The works above demonstrate optimization methods can be used in pipe thickness measurement by ECT. Nowadays, some significant pipe eddy current problems have been studied analytically, such as curved spiral coils [13,14], arbitrarily positioned probe coil [15], etc. The authors' group also proposed vital analytical solutions to pipe eddy current field [16–18]. The solutions are benefit to solve the inverse problem of pipe eddy current field by optimization methods.

By using swept-frequency ECT and the Levenberg–Marquardt (L–M) algorithm, this paper presents a method to estimate the thickness of pipe. The configuration is shown in Fig. 1, where an air-cored excitation solenoid coil C is placed outside to an infinite long pipe of inner radius r_i, thickness t, conductivity σ, relative permeability μ_r. The central axis of the coil is normal to the long axis of the pipe. Parameters to be determined in the inverse problem are the coil lift-off l, t, r_i, μ_r and σ, which are usually unknown in practice. In this paper, only the inductive reactance changes are used in the inversion calculation, because the real part of the impedance changes of coil are easily affected by temperature in experiments, and the interference may result in undesirable errors.

This paper is organized as follows. The reasonable frequency range of the swept-frequency eddy current testing is discussed in Section 2. In Section 3, the constraints of the inverse eddy current problem are eliminated by using a square root transformation and then an inverse algorithm based on L–M algorithm is developed. Section 4 presents several inversion calculation examples.

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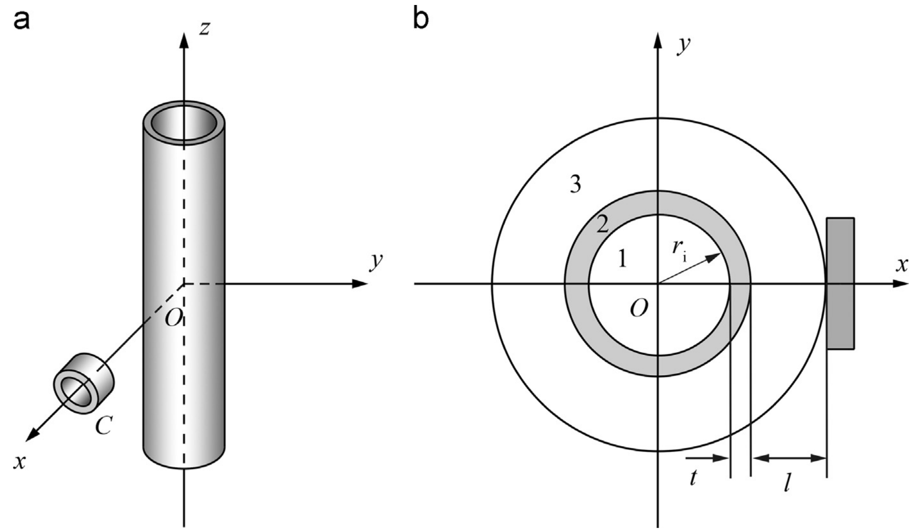

Fig. 1. (a) 3D diagram and (b) top view of an excitation coil and a metal pipe with their axes are normal to each other.

Discussions on the influence of frequency dependence of magnetic permeability are shown in Section 5. Conclusions are given in Section 6.

2. Selection of the frequency range

A reasonable frequency range is of great importance for the swept-frequency ECT. The range could be determined by analyzing sensitivities of the relative reactance change with respect to the unknown parameters at different frequencies. Following [16], the relative reactance change of the excitation coil C is

$$\frac{\Delta X(l,t,r_i,\mu_r,\sigma)}{X_0} = \text{imag}\left\{-\frac{j\omega 4\pi^2}{X_0\mu_0 l^2}\int_{-\infty}^{\infty}\sum_{m=-\infty}^{\infty}\alpha^2 C_s(\alpha,m)D_{ec}(-\alpha,-m)d\alpha\right\}, \quad (1)$$

where ΔX is relative reactance change of the excitation coil, X_0 is coil reactance in air, C_s is the coil coefficient which depends only on the coil geometry, D_{ec} is a coefficient which has relationships with C_s and parameters of pipe. The expressions of C_s and D_{ec} could been found in [16]. Thus, the sensitivities of the relative reactance change vs. l, t, r_i, μ_r and σ are

$$\begin{cases} S_{Xl} = \frac{1}{X_0}\frac{\partial \Delta X}{\partial l} \\ S_{Xt} = \frac{1}{X_0}\frac{\partial \Delta X}{\partial t} \\ S_{Xri} = \frac{1}{X_0}\frac{\partial \Delta X}{\partial r_i} \\ S_{Xm} = \frac{1}{X_0}\frac{\partial \Delta X}{\partial \mu_r} \\ S_{Xc} = \frac{1}{X_0}\frac{\partial \Delta X}{\partial \sigma} \end{cases}. \quad (2)$$

Based on Eq. (2), sensitivity curves at different frequencies (500 Hz, 1 kHz, 5 kHz, 10 kHz and 50 kHz) are plotted, as shown in Fig. 2. A single-layer coil of 43 turns is used in the calculation, and its radius and height are 10 mm and 7.2 mm, respectively. The basic values of l, t, r_i, μ_r and σ are 1.2 mm, 1 mm, 14 mm, 100 and 5 MS/m, respectively. Fig. 2(a) demonstrates that the relative reactance change is more sensitive to the lift-off at low frequency. Fig. 2(b) indicates that the change of thickness leads to a visible variation of the relative reactance change when thickness is less than 2 mm at low frequency, and the sensitivity vs. thickness decreases rapidly when frequency increases. Fig. 2(c) shows that the absolute sensitivity vs. inner radius at low frequency and high frequency is greater than that at middle frequency. It can be seen from Fig. 2(d and e) that the relative reactance change is more sensitive to relative permeability and conductivity at high frequency. So, test at high frequency is conductive to gauging inner radius, relative permeability and conductivity and the low frequency benefits the lift-off, thickness and inner radius gauging. Therefore, in order to solve the inverse problem accurately, sufficient observed reactance changes at both low frequency and high frequency are needed so that the detected signals have adequate sensitivities to all the five unknown parameters.

3. The inversion procedures

In the inverse pipe eddy current problem, an optimal values of $\mathbf{v}=[l,\ t,\ r_i,\ \mu_r,\ \sigma]^T$ should be determined by minimizing the least square error function between estimated relative reactance changes $\mathbf{X}_{est}(\mathbf{v})=[X_{est1}(\mathbf{v}),\ X_{est2}(\mathbf{v}),\ \dots,\ X_{estN}(\mathbf{v})]$ and observed relative reactance changes $\mathbf{X}_{obs}=[X_{obs1},\ X_{obs2},\ \dots,\ X_{obsN}]$. The cost function can be written as

$$\min_{\mathbf{v}\in\mathbb{R}^5} f(\mathbf{v}) = \frac{1}{2}\sum_{f=1}^{N}\frac{\left[X_{estf}(\mathbf{v})-X_{obsf}\right]^2}{X_{obsf}^2}, \quad (3)$$

$$\text{s.t.}\begin{cases} l>0 \\ t>0 \\ r_i>0 \\ \mu_r>0 \\ \sigma>0 \end{cases}, \quad (4)$$

where N is the number of frequency used for the optimization. $X_{obsf}(\mathbf{v})$ is experimental relative reactance change at any frequency and $X_{estf}(\mathbf{v})$ is relative reactance change calculated by Eq. (1) at the same frequency. Eq. (4) indicates the inverse problem is constrained. The constraints would lead to an increase of difficulty to solve the problem.

It can be seen from Eq. (4) that the five unknown parameters are all greater than zero. So, the parameters can be supposed to be sums of a positive infinitesimal and a square of a real number [19], as:

$$\begin{bmatrix} l \\ t \\ r_i \\ \mu_r \\ \sigma \end{bmatrix} = \begin{bmatrix} x_1^2+\xi_0 \\ x_2^2+\xi_0 \\ x_3^2+\xi_0 \\ x_4^2+\xi_0 \\ x_5^2+\xi_0 \end{bmatrix}. \quad (5)$$