Impedance Characteristics and Analysis of Liftoff Distance Effect using Polynomial Approximation on Eddycurrent Nondestructive Testing

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Abstract—**Development of eddy current testing makes possible for the inspection of the conductivity variations, inspection of surface and beneath the surface of conductivity materials and liftoff property to characterize nonconductive materials.This paper deals with impedance analysis and analyzes liftoff distance effect using numerical method on eddy current testing. The focus of this paper is to first characterize impedance values under measurement with ferrite pot core probe in eddy current testing. Pot coreshaping probe used in this work offers a number of advantages, including self-shielding, space efficiency, convenience, good temperature stability and low losses. In addition, utilization of pot core shaped probe makes the edge effect on test sample avoidable. Secondly, a liftoff distance effect using a polynomial model is introduced and can be mitigated on zero of liftoff distance effect for measured data. This research allows to present the possibility of pot core shaped probe utilization and analytical approach for lift off distance effect.**

Keyword - Impedance characteristics, liftoff distance effect, multi-frequency technique, polynomial approach, eddycurrent testing.

I. INTRODUCTION

In nondestructive testing, electromagnetic methods use electromagnetic sources in order to extract properties of under test samples. In order to extract its properties of under test samples in nondestructive testing, electromagnetic methods use electromagnetic source into the inspected material.One of the conventional electromagnetic methods utilized for the inspection of conductive materials such as copper, aluminum or steel is eddy current nondestructive testing [1]. Eddy current nondestructive testing is specialized on employment for certain applications such as flux leakage, remote field eddy current, and impedance analysis with multi-frequency. Multi-frequency Eddy current technique, in particular, can be applied for the optimization of several performance variables such as sensitivity and penetration used in eddy current testing [2].The principle of the eddy current technique is based on the interaction between a magnetic field source and the test material. This interaction induces eddy currents in the test piece and it can detect the presence of very small cracks by monitoring changes in the eddy current flow [3].

Development of eddy current testing makes possible for the inspection of the conductivity variations, inspection of surface and beneath the surface of conductivity materials and liftoff property to characterize nonconductive materials. ECT systems typically have three parts – excitation coil, sensing probe device and signal processing for further analysis of material characteristics [4]. The liftoff between the ECT probe and the surface of specimenshas a strong influence on the acquired signals which is related with electromagnetic characteristics. In general, a very small, uniform lift-off is preferred for achieving better detection sensitivity to defects and for fast, reliable scanning.

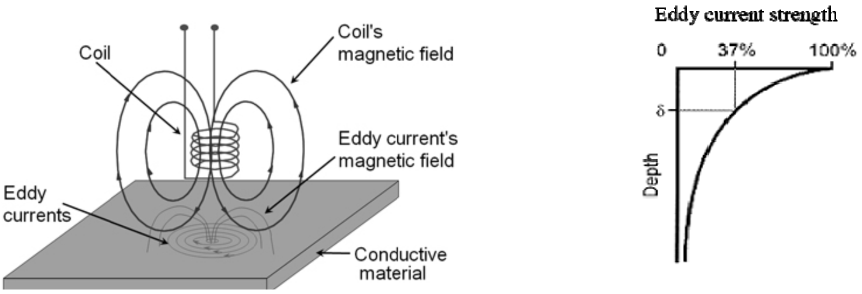
In this paper, we investigated impedance analysis with multi-frequency eddy current techniques and include developing techniques to account for analysis of liftoff variations on sample surface among several liftoff distance effect works [5-7]. The fundamentals of eddy current inspection and analysis used in the main variables of this technique are presented in Sections 2. Section 3describes experimental system design and data analysis. Section 4 discusses results on acquired data from provided system and Section 5 presents conclusion of this research.

II. EDDY CURRENT TESTING AND POLYNOMIAL APPROXIMATION

A. *Review of Eddy current testing*

Eddy currents are loops of electrical current induced by changing the magnetic field within a conductor.Eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux. Interruptions in the flow of eddy currents, caused by imperfections, dimensional changes, or changes in the material's conductive and permeability properties, can be detected with the proper equipment. Eddy current testing can be used on all electrically conducting materials with a reasonably smooth surface [8]. The testingsystemusually consists of a generator, a test coil and acquisition equipment for further analysis. It can be used for crack detection, material thickness measurement and metal detection, etc.

Figure 1(a) describes the principle of eddy currents. When analternating current passes through a test coil, a primary magnetic field is set up around the coil. The AC primary field induces eddy current in the test object held below the test coil. A secondary magnetic field arises due to the eddy current that opposes the primary magnetic field created by the test coil. Eddy currents normally travel parallel to the coil's winding and the flow is limited to thearea of the inducing magnetic field.Since eddy currents are concentrated near to the surface adjacent to an excitation coil, theirstrength decreases exponentially with depth i.e. distance from the coil. This phenomenon is known as the skin effect and is shown in Figure 1(b). The skin effect is the tendency of an alternating current to become distributed within a conductor such that the current density is largest near the surface of the conductor, and decreases with greater depths in the conductor. In this experiment,this is due to the opposing eddy currents induced by the changing magnetic field resulting from the alternating current.



(a) (b)

Fig. 1. The principle of eddy current testing and eddy current field depth of penetration [9,10]

The standard depth of penetration is described as the following function:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (1)$$

where, δ=standard depth of penetration [mm], f=test frequency [Hz], μ=magnetic permeability [H/mm] and σ=material electrical conductivity [Ω/mm^2]. Eddy currents are strongest at the surface of the material and decrease in strength below the surface. The depth that the eddy currents are only 37% as strong as they are on the surface is known as the standard depth of penetrations of skin depth. This depth changes with probe frequency, material conductivity and permeability [11].

B. Polynomial approximation

Suppose that a fit function *f* must be defined which generally contains adjustable fit parameters, a_i, *i=0,…, n*. In this paper, we consider the general case of a set of collected data $y_k, k = 1, \dots,$ M which are collected as a function of one independent variable *x* at the points x_k. We define the fit function *f* to describe collected data in an approximation approach as presented followingapproximation equation:

$$y_k \approx f(a_{0,} \dots a_{n,} x_k). \qquad (2)$$

In order tofind the parameters a_i for the best approximation, we have to minimize the appropriately defined deviation. In this approach, we can minimize the sum over the squared residuals rather than root mean squared error

$$r = \sum_k (y_k - f(a_0, \dots a_{n,} x_k))^2 \qquad (3)$$

which will yield the same results. A function f can be generally written as a sum of linear combinations

$$f(a_0, \dots a_n, x_k) = a_0 + a_1 f_1(x_k) + a_2 f_2(x_k) + \cdots + a_n f_n(x_k). \qquad (4)$$

The minimum is found by forcing the derivatives of r with respect to all $a_i$to be zero

$$\frac{\partial r}{\partial a_0} = 0, \quad \frac{\partial r}{\partial a_1} = 0, \dots, \quad \frac{\partial r}{\partial a_n} = 0. \qquad (5)$$

Whether and how these partial derivatives can be calculated depends on the detailed form of the function f. It is obvious that a fit approximates the data the better when more parameters are used. In our paper, we introduce two terminologies - residuals and norm of residuals. The residualsare the differences between data values and corresponding calculated fit data. The normof a mathematical object is a quantity that – taken in the right sense – describes the length, size or extent of this object. Mathematically more precisely, usually the L_2-normis meant. Given a vector z

$$z = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix} \tag{6}$$

the L_2-norm is defined as

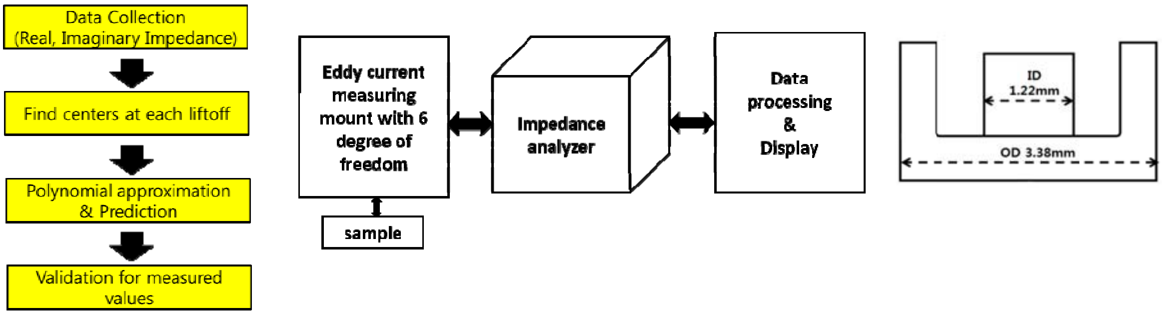
$$\|z\|_2 = (|z_1|^2 + |z_2|^2 + \cdots + |z_n|^2)^{1/2} \tag{7}$$

The norm of residualsis thus the square root of the $r$defined in Eq. 3. It is often used as a measure for the goodness of fitwhen comparing different fits [12].

III. EXPERIMENTAL SYSTEM DESIGN

A. *Experimental setup for impedance analysis*

The overall procedure and our measuring system are shown in Figure 2. The implemented system usedan eddy current probewound on a pot core with 3.38mm OD and of 1.22mm ID as shown in Figure 2(c). Taking impedance analysis and the need for larger penetration depth into consideration, an appropriate frequency was selected based on sensitivity and skin depth. The variation in the imaginary (inductive) component of impedance with changes in sample conductivity is relatively small. On the other hand, the real (resistive) component is directly related to conductivity variations. In addition, the measuring system will utilize multi-frequency to characterize proper frequency range.



(a) (b) (c)

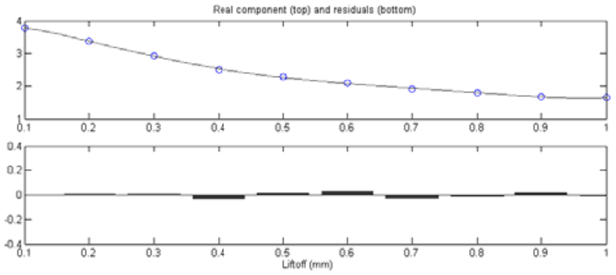
Fig. 2.The overall diagram and experimental setup. (a) flowprocedurefor impedance analysis and liftoff effect, (b) experimental setup block diagram for measuring impedance values and (c) pot coregeometry.

B. *Liftoff distance effect*

Most of applications in eddy current testing, in general, liftoff distance effect is one of main considerations. The liftoff is the impedance change and can be measured in the distance between the inspection coil probe and the test piece. However, unlike fine grinded test sample surfaces, liftoff effect for irregular and coarse sample surfaces can be also applied to ECT. In order to minimize liftoff distance effect, polynomial approach has been adopted to predict zero of liftoff distance after finding centers at each liftoff of increment 0.1mm up to 1mm. To find the polynomial function, a fit function f must be defined which generally contains adjustable fit parametersa_i, $i = 0 . . . n$. We can minimize the sum over the squared residuals.

IV. RESULT AND DISCUSSION

Results of the experimented measuring system are shown in Figure 3 and 4. We collected impedance values with impedance analyzer at each liftoff distance by increment 0.1mm up to 1mm. These measured values at each liftoff distance are calculated to centers to optimize and minimize impedance variations. Figure 3 shows polynomial curve fit for real and imaginary components and residuals at each liftoff distance, respectively. Once find out polynomial curve, new collected data was applied to polynomial equation and zero of liftoff distance values can be predicted and compared. Comparison of the error rate between measured and modelling (polynomial approach) values are shown in Figure 4. The measured norm of residuals for real and imaginary part is 0.053556 and 0.06834, respectively.



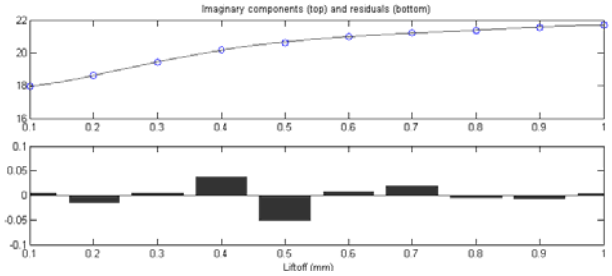


Fig. 3. Polynomial coefficients and residuals

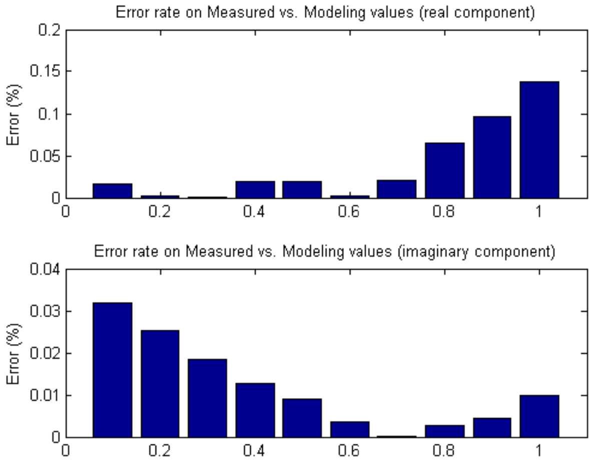


Fig. 4. Comparison of error rate for any measured real and imaginary component

V. CONCLUSION

In this paper, we have introduced an impedance analysis and prediction for the zero of liftoff distance from test sample for measured values with any liftoff impedance. The experimental test with pot core shaped probe has best performance in the frequency range 1 MHz-3MHz and the trend is reasonably consistent in this range. In our experiment, we used the proper frequency range 700KHz – 1.5MHz. As we can see in Fig. 4, we have shown the zero of liftoff distance can be measured using polynomial approach with low error rate. The further work from preliminary works will be applied to eddy current array measuring system with different type of material characteristics including defect classification in multilayer structures.

ACKNOWLEDGMENT

This research was supported by Daegu University Research Grant, 2015.

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