NDT&E International 80 (2016) 65–70

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Transient eddy current method for the characterization of magnetic permeability and conductivity

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ARTICLE INFO

Article history:
Received 6 August 2015
Received in revised form
22 November 2015
Accepted 16 February 2016
Available online 23 February 2016

Keywords:
Transient eddy current
Characterization
Permeability
Conductivity
Tube

ABSTRACT

Recent analytical solutions, that correctly describe transient eddy current signals in voltage-controlled driver-pickup circuits, are applied for the case of a coaxial probe encircling a long ferromagnetic conducting tube. Experimental results, obtained for the case of a square wave excitation, are in excellent agreement with the predicted driver and pickup responses. Using the forward solutions, a novel inverse method, that enables simultaneous and accurate characterization of magnetic permeability and electrical conductivity, has been developed. Specifically, the method considers computed areas under scaled transient eddy current signal curves. In the generalized case, multiple parameters of interest can be extracted from a single transient signal by taking advantage of the frequency domain differentiation property of the Laplace transform. Preliminary experiments show that permeability and conductivity values, calculated for a variety of ferromagnetic and non-ferromagnetic tubes, agree well with published values (permeability) and with values obtained by four point measurement (conductivity). The inverse method introduced in this work may be straightforwardly extended to consider other parameters, such as lift-off and material thickness, and to consider other geometries, such as conducting plates.

1. Introduction

Conventional eddy current inspection of equipment and infrastructure is a critical element in all industrial maintenance operations. Analytical models, built upon the original 1968 Dodd and Deeds formalism [1], have been used to enhance analysis and information, extracted from signals obtained using electromagnetic non-destructive evaluation technologies. The common approach is to formulate time-harmonic solutions, which describe the electromagnetic fields in a system, in order to calculate the change in a coil's impedance as it interacts with a conducting structure [2–6]. In a less developed approach, transient eddy current models consider the voltage induced in a pickup circuit [7–12] given a prescribed current that has been applied to a driver coil. Under voltage control, changing material characteristics and inspection geometries will distort the resultant current signal through feedback effects. In order to circumvent the feedback challenge, the common approach has been to employ current control systems. In such systems, however, the level of signal distortion from feedback effects is largely dependent on the quality of the current generator.

Consequently, a persistent challenge for the development of transient driver-pickup models, particularly under voltage control, has been a lack of experimental agreement. Ferromagnetic materials, which are commonly encountered in industry, exhibit stronger and, therefore, more complicated feedback effects between driver, pickup and sample circuit elements. Since driver-pickup transient eddy current non-destructive testing is an increasingly popular technique for the inspection and characterization of metallic objects, solutions that correctly incorporate all electromagnetic interactions arising in inductively coupled circuits, are of significant interest. Exact mathematical models would facilitate the quantitative analysis and interpretation of experimental signals obtained from particular inspection geometries, thereby enhancing the potential applicability of transient eddy current non-destructive evaluation.

The seminal formalism developed by Dodd and Deeds [1] assumes an invariant driver current and an open pickup circuit, effectively ignoring feedback effects on the driver signal and effects of the pickup coil on the system. Under time-harmonic conditions, feedback effects exhibit themselves as a phase change. Since phase is relatively arbitrary, adjusted relative to lift-off in practical applications, feedback generally has little impact on actual comparisons between experiment and theory in the time harmonic case. The time harmonic analysis also permits a direct solution, as demonstrated by Dodd and Deeds [1]. This is not true

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http://dx.doi.org/10.1016/j.ndteint.2016.02.010
0963-8695/

in the transient case, however. Here feedback effects cannot be neglected as they result in a significant change in the original driving pulse [13]. One approach is to counter feedback effects on the driving signal by using sophisticated, and often expensive, current control systems. Current control presents an ‘engineering limit’, since under large back-emf conditions, such as coils in the presence of ferromagnetic materials or transformers, the technology becomes more challenging to implement [14–16]. Feedback may also modify the pickup response in the driver-pickup configuration if the open circuit pickup is not a sufficient approximation [16]. In systems designed to emulate an open circuit pickup, signal-to-noise may be compromised by the high impedance requirement, since maximum power transfer occurs when impedances are matched.

Recently, a complete analytical description of a voltage-controlled driver-pickup circuit has been developed [14] and applied for the case of a ferromagnetic conducting rod structure. Experimental results, obtained for the case of square wave excitation, are in excellent agreement with the analytical predictions, and validate the correction applied to the Dodd and Deeds formalism for the case where open pickup circuits are not assumed. In this work, the formalism from [14] is applied for the case of a driver-pickup probe encircling a conducting tube. An encircling tandem driver-pickup probe was constructed and experimental results obtained for square waveforms. The complete agreement between theory and experiment further supports the solutions developed in [14]. Such solutions are useful for developing inverse models for material characterization.

In the case of material characterization, a broadband eddy current method [16], developed in 2006, compares impedance analyser data with theoretical calculations in order to estimate the conductivities and permeabilities of coaxial rod structures. The authors use the imaginary component of the impedance change at low frequencies (≈ 63 Hz) in order to estimate a sample's magnetic permeability, and subsequently use that value in conjunction with a range of measured impedance measurements in order to obtain its conductivity. The selected operation frequency range is critical to achieving reliable results. Furthermore, each low frequency measurement has to be integrated for a long period of time (10 s), in order to achieve an acceptable signal-to-noise ratio.

Here, a novel method for the simultaneous characterization of a tube's magnetic permeability and electrical conductivity-based on pulsed eddy current (PEC) signals-is developed, and applied to a variety of magnetic and non-magnetic conducting tubes. The frequency-domain differentiation property of the Laplace transform is applied to the Laplace-space transient pickup coil solution, providing a simple method for the generation of multiple linearly independent correspondences between theory and experiment. In this work, an experimental PEC signal with good signal-to-noise ratio required less than 25 ms to obtain, a 2 to 3 order magnitude improvement over the method presented in [16]. Conductivity values, obtained using the proposed PEC method, are validated by standard four point measurements.

2. Forward problem

A description of the model geometry is as follows. A coaxial tandem driver-pickup probe is centered about the axis of a long, ferromagnetic and conducting tube as shown in Fig. 1.

Time-varying currents flowing in the driver and pickup coils will induce eddy currents within the volume of the tube. These eddy currents give rise to transient magnetic fields which, in turn, induce currents within the coils. The exact series solutions to the circuit equations describing time-dependent currents $i_1(t)$ and $i_2(t)$ flowing in the driver and pickup, respectively, have been developed in [14] and are written here as

$$i_1(t) = \frac{v_0}{2R_1} + \frac{2v_0}{P}\sum_{n=1}^{\infty}\frac{1}{\varpi_n}\sqrt{\frac{(\varpi_n(L_2+\mathfrak{R}(\mathcal{L}_2)))^2+(R_2-\varpi_n\mathfrak{I}(\mathcal{L}_2))^2}{\alpha_n^2+\beta_n^2}} \times \sin\left(\varpi_n t - \arctan\left(\frac{(R_2-\varpi_n\mathfrak{I}(\mathcal{L}_2))\beta_n-\varpi_n(L_2+\mathfrak{R}(\mathcal{L}_2))\alpha_n}{(R_2-\varpi_n\mathfrak{I}(\mathcal{L}_2))\alpha_n+\varpi_n(L_2+\mathfrak{R}(\mathcal{L}_2))\beta_n}\right)\right), \tag{1}$$

$$i_2(t) = \frac{2v_0}{P}\sum_{n=1}^{\infty}\sqrt{\frac{(M+\mathfrak{R}(\mathcal{M}))^2+\mathfrak{I}(\mathcal{M})^2}{\alpha_n^2+\beta_n^2}} \times \sin\left(\varpi_n t - \arctan\left(\frac{\mathfrak{I}(\mathcal{M})\beta_n+(M+\mathfrak{R}(\mathcal{M}))\alpha_n}{\mathfrak{I}(\mathcal{M})\alpha_n-(M+\mathfrak{R}(\mathcal{M}))\beta_n}\right)\right) \tag{2}$$

where the coefficients α_n and β_n are defined as

$$\alpha_n \equiv (R_1-\varpi_n\mathfrak{I}(\mathcal{L}_1))(R_2-\varpi_n\mathfrak{I}(\mathcal{L}_2)) - \varpi_n^2(L_1+\mathfrak{R}(\mathcal{L}_1))(L_2+\mathfrak{R}(\mathcal{L}_2)) + \varpi_n^2\left((M+\mathfrak{R}(\mathcal{M}))^2-\mathfrak{I}(\mathcal{M})^2\right), \tag{3}$$

$$\beta_n \equiv \varpi_n(R_1-\varpi_n\mathfrak{I}(\mathcal{L}_1))(L_2+\mathfrak{R}(\mathcal{L}_2)) + \varpi_n(R_2-\varpi_n\mathfrak{I}(\mathcal{L}_2))(L_1+\mathfrak{R}(\mathcal{L}_1)) + 2\varpi_n^2(M+\mathfrak{R}(\mathcal{M}))\mathfrak{I}(\mathcal{M}), \tag{4}$$

where v_0 is the amplitude of an applied voltage square waveform with period P, L_1 and L_2 are the coils' self-inductances, R_1 and R_2 are the total driver and pickup circuits' resistances, and M is a

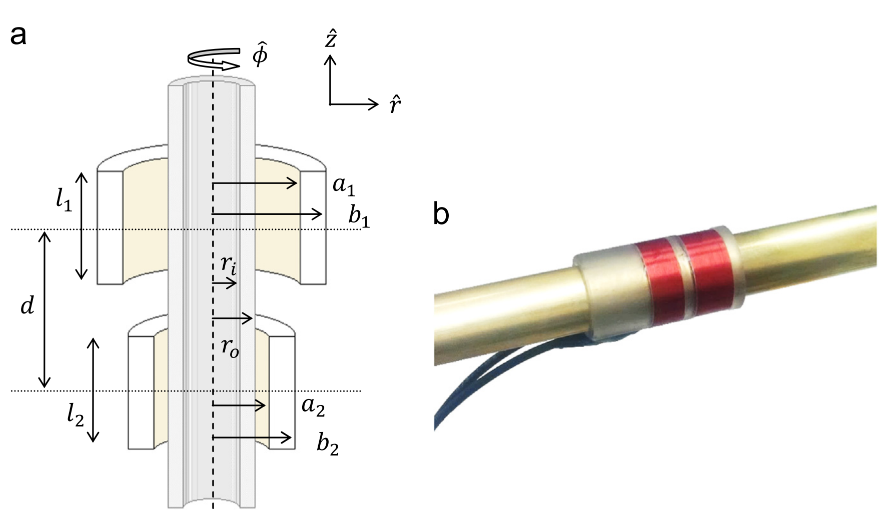

Fig. 1. Coaxial driver coil, pickup coil and tube configuration; (a) diagram and (b) experimental set-up.