Abstract
Transient eddy current (TEC) testing, driven by square waves, is also known as pulsed eddy current (PEC) testing and offers practical advantages over conventional, sinusoidally-driven eddy current testing in certain applications. By effectively sampling a continuous and very broad range of frequencies, the TEC technique generates data useful for materials of low electrical resistivity or high magnetic permeability, both of which may require testing at very low frequency. TEC also has an advantage for complicated configurations, which may have characteristic responses at a variety of frequencies and are therefore best analyzed by multi-frequency techniques. While quantitative analysis techniques have evolved over half a century for discrete-frequency eddy current testing, these techniques do not apply directly to TEC testing. A method for quantitative analysis of signals obtained in TEC testing is presented here. The method transforms time-domain signal response to the frequency domain; established response functions from traditional eddy current testing can then be used with a trial set of initial geometrical and material properties to calculate signals for comparison. A multi-frequency optimization of the geometrical and material properties is performed to minimize the difference between the calculated and the observed signal, and the optimized values are proposed as solutions. Applications to high-permeability materials like carbon steel, to low-resistivity materials like aluminum, and to complicated geometries, are discussed, as is integration of the technique with commercial instruments and software.

Keywords: transient eddy current (TEC), pulsed eddy current (PEC), multi-frequency analysis

1. Introduction

Traditional eddy current testing may be challenged by materials that are thick, highly conductive, ferromagnetic, or at variable distances from the test coil, which can limit electromagnetic skin depth or cause large signals from lift-off. In these cases, transient eddy current or pulsed eddy current (TEC or PEC) testing may confer practical advantages. Since the decay of a sharp pulse can be decomposed into contributions from a broad range of frequencies, the very low frequencies needed to increase skin depth are accessible. The relationship between time-dependent and time-harmonic responses is recognized in the scientific literature dealing with TEC or PEC testing; see, for example, Safizadeh et al. [1]. Comparisons have been made of modeled and observed signals transformed from the time domain to the frequency domain, and discrete-frequency analysis of the Fourier-transformed signals at specific frequencies, optimized for response to effects of interest, has been proposed (Pavo [2]). These methods have been used, for example, as a rationale for application of Principal Component Analysis (Pan [3]).

Such calibrated techniques for geometrical reconstruction do not perform a simultaneous calculation of signals from the full set of frequencies available from transformed TEC measurements at every inspection point. Within large-scale (e.g. finite element or analytical) models, this is computationally cumbersome and would not be practicable in common NDE applications. As a consequence, quantitative methods for analysis of TEC are of great interest. Several analysis methods are surveyed in a contribution to this conference from J.A. Buck et al. on carbon steel inspection [4].
Simple, but physically realistic, approximations of phase and amplitude response at discrete frequencies, such as those provided by skin depth considerations, have evolved over half a century of practice in conventional eddy current testing. See for example, Cecco et al. [5]. These approximations are computationally tractable when applied to many frequencies at once and have been incorporated into a suite of techniques referred to as Multi-Frequency Analysis, or MFA [6,7]. The sum, over a large number of frequencies, of the residuals of measured signals relative to calculated signals, can be obtained and minimized for varying parameters for which the frequency-dependent behaviour is understood. Parameters of interest include defect extent, remaining conductor thickness, and lift-off of the sensor from the surface. The combination of transformation to the frequency domain, analytical approximations to frequency dependence, and residual minimization to obtain material and geometrical properties is presented here as self-consistent means of TEC signal analysis.

2. TEC signals and their transformation

TEC pulses are typically driven as square-wave voltage inputs. The voltage is held at a constant value for only a few milliseconds and then cut to zero; to minimize coil heating, the duty cycle is often less than 50%. The decay of the field is measured at either the rise or the fall of the pulse, with the region of interest digitized and the rest ignored. Figure 1 shows schematically the time relationship between the driving pulse and the acquired data.

Figure 1. Time structure of TEC pulses and acquired data. The solid black line is the driving pulse, and the solid blue line is the digitized data from a sensing coil.
For high conductivity, high magnetic permeability, or thick samples, there is particular interest in the later times of the pulse decay, as these correspond to the lower frequencies and the larger skin depths; this can influence choice of cycle times. Since later times have lower amplitude, signal-to-noise ratio in this region is also important.

The transformation from time domain to frequency domain is accomplished by a fast Fourier transform (FFT). During early development, this was done in Microsoft EXCEL; subsequently, a feature of InspectionWare\(^1\) was used for direct extraction of frequency-based data.

Analysis requires a minimum of two signals: a reference point of the defect-free full-thickness material and a test point where one or more unknown parameters are to be evaluated. In addition, use of phase angle conventions from classical eddy current testing require knowing the phase angle corresponding to lift-off at each frequency, obtained by lifting the probe off the sample at the reference point. The rotational offset in the complex plane at each frequency is deduced by performing trigonometry on the real and imaginary components of the complex division result. In Figure 2a, below, the phase angle offset increases (in the clockwise direction) with increasing frequency, ranging from approximately 90 to 180 degrees over many different frequencies. A quantitative lift-off distance calibration, from data taken at different values of lift-off, may also be performed if the probe-to-test-piece distance is to be extracted from the subsequent analysis. Lift-off phase angles can be obtained by the complex division of lift-off signal by reference-point signal. Test-point data are shown in Figure 2b, normalized by the complex division of the test point signal by the reference-point signal, and with phase angles referenced to the lift-off phase at each frequency. See the upper left-hand side of Figure 3 for a generalized view of the data acquisition and transformation process.

Figure 2. Transformed signals for discrete frequencies plotted in a complex impedance plane representation: (a) Signal for 1 mm lift-off, relative to reference, plotted in the complex plane. (b) Signal at test point, relative to lift-off, after rotation by lift-off phase.

\(^1\) InspectionWare is a software platform from UTEX Scientific.
3. Frequency domain analysis

Frequency-dependent estimates of signal response to wall loss, the areal extent of a flaw, or variations in material-to-sensor separation (lift-off) can often be approximated by expressions containing the skin depth, $\delta$, which is defined as
where the skin depth in mm is obtained from resistivity in $\mu\Omega$-cm, frequency in inverse seconds and relative permeability (dimensionless). The signal amplitude of an infinitesimal void at depth $x$ is proportional to $e^{-2x/\delta}$, and the phase, $\phi$, attributable to the signal is $\phi = 2x/\delta$. Weighted integration of these quantities, over the range of the feature’s depth, can provide a convenient analytical expression for frequency dependence [7]. Alternatively, an empirical expression or more elaborate calculations may be used.

The method uses initial estimates of the parameters of interest in analytical expressions to obtain the resulting signal phase and amplitude at multiple frequencies (upper right-hand side of Figure 3). These are compared to the measured TEC signals transformed into the frequency domain in Figure 4a. Iterative optimization of the estimated parameters minimizes the summed (squared) residuals of the differences between data and calculation until the required convergence is reached (Figure 4b). Wall loss, areal extent of the flaw, lift-off, or other parameters are then saved as output. If data from a sequence of positions have been collected, the process can continue to analyse a one-dimensional strip or a two-dimensional surface; see the lower part of Figure 3.

4. High-conductivity examples

The National Research Universal (NRU) Reactor at Canadian Nuclear Laboratories has a calandria vessel surrounded by an aluminium-walled light-water shield, with regions where wall thickness inspection is impeded by corrosion product on the near surface. This presents the problem of inspecting a high-conductivity material through an unknown lift-off. Samples relevant to this geometry, both of large-area wall loss (scalloped regions) and small-area features (flat-bottom holes) were inspected by TEC and the results analyzed.

Figure 4. (a) Initial and (b) final calculated frequency trajectories relative to measured signal at a flat-bottom hole of 0.5 mm remaining wall (same data as Figure 2b). The initial arbitrary values of depth and diameter were adjusted to minimize the sum of the squared residuals between the calculation and data.
Localized defects: In this example, the surface of an aluminum sample, 8 mm thick (Figure 5a), containing three holes of 4 mm diameter (0.0, 0.5, and 1.0 mm remaining wall) and one of 1.7 mm diameter (0.0 mm remaining wall), was scanned. The depths obtained by the technique of Figure 4 were within 0.1 mm of the nominal sample values, but due to the spatial response of the probe (field spread, coil diameter, and coil separation) the scan image gave surface extents much larger than the hole diameters (see Figure 5b). In this technique the analysis also extracts an amplitude related to the areal extent of the flaw. A calibrated scaling factor was applied to obtain a reasonable diameter for a realistic 3D reconstruction of the sample, as in Figure 5c.

![Figure 5. (a) 8-mm Al sample with three 4-mm flat bottom holes (0.0, 0.5, and 1.0 mm remaining wall) and one 1.7-mm diameter hole (0.0 mm remaining wall). (b) correct depth sizing but misleading surface extent due to field spread. (c) 3D reconstruction of sample by TEC/MFA including calibrated extent.](image)

Generalized wall loss: In contrast to the test piece above, the scalloped sample contains gradually changing wall thickness. Since the sensing area is then much smaller than the feature, localization is less important, and the amplitude parameter related to areal extent, used in the previous example, need not be extracted; see Figure 6. The ability to ignore a parameter can be useful, in that it frees the analyst to make different use of the information collected at different frequencies. For example, in the NRU reactor application mentioned above, an additional parameter representing the thickness of the corrosion layer could be extracted from the measurements.
Carbon steel is a common material in waste management, pipeline, and other large-scale applications. Unlike aluminium, zirconium, stainless steel, Inconel and other materials commonly encountered in the nuclear and aerospace industries, carbon steel has relative permeability greater than one. This reduces skin depth, making electromagnetic inspection of unsaturated material difficult. As with highly conductive samples, TEC testing with sensitivity to late times in the signal decay tail can overcome this difficulty.

Inspection of carbon steel pipes in waste management “tile hole” applications is reported in this conference [4]. Wall thickness scans from that work along eight parallel strips of pipe wall are analyzed by the TEC/MFA method with resolution sufficient to show the spiral structure of the piping (typically 0.5 mm oscillatory thickness variation). Figure 7 shows an “unrolled” image of the wall thickness map for one of the pipes inspected. In this particular case it was possible to confirm the TEC results with ultrasonic testing measurements. In other applications, e.g. for pipelines under insulation, confirmation with ultrasonic testing may not be practical.
6. Future exploitation

Confounding effects from lift-off, feature geometry, and thickness of remaining material can be disentangled and quantified when TEC measurements are transformed to be processed by multi-frequency techniques. This extends electromagnetic inspection capability to otherwise challenging materials, such as those with high magnetic permeability or high conductivity. In addition to nuclear power and waste management applications, both carbon steel inspection in pipelines and infrastructure, and aluminium alloy inspection in the aerospace industry are possible uses of the TEC/MFA technique.

The method is the subject of a recent patent disclosure [8]. Potential future exploitation ranges from in-house use developing dedicated inspection techniques to the licensing of technology for commercial systems. Intermediate between these extremes is collaboration with developers of inspection instruments and software in joint ventures.

References


