TRANSIENT EDDY-CURRENT NDE FOR HIDDEN CORROSION IN MULTILAYER STRUCTURES

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INTRODUCTION

The development of reliable nondestructive evaluation (NDE) techniques to detect and characterise hidden corrosion in aircraft structures is one of the key problems in maintaining aging military aircraft. Previous work [1–3] has demonstrated that transient eddy-current techniques have significant advantages for the detection of hidden corrosion in multilayer structures compared with conventional eddy-current NDE. The use of a pulsed rather than single-frequency excitation, combined with time-domain measurements, allows the response over a wide range of frequencies to be captured in a single measurement, giving a very significant performance advantage over multi- or swept-frequency methods. Furthermore, by detecting the transient magnetic field using a Hall-effect device rather than detecting the voltage developed in a pickup coil, transient eddy-current NDE can probe more deeply into a multilayer structure than conventional eddy-current NDE, providing greater sensitivity to deeply hidden corrosion.

The quantitative interpretation of the results of transient eddy-current NDE is still in the early stages of development. Research is required to: (i) discriminate genuine material loss due to corrosion from other possible changes such as variations in the interlayer separation or in probe liftoff, (ii) quantify the amount of structural material which is lost due to corrosion, and (iii) locate the layer(s) in the structure where corrosion has occurred. The present paper presents the results of an experimental and theoretical study of transient eddy-current NDE for a simple multilayer structure. The long-time behaviour of the transient magnetic field, and the effect of material loss, changes in coil liftoff and variations in the interlayer separation, are examined in detail and promising new approaches for the analysis of transient eddy-current NDE of multilayer structures are presented.

THEORY

The experimental configuration, Fig. 1, comprises a cylindrical air-cored coil (with inner radius \( r_1 \), outer radius \( r_2 \) and width \( w \)) located at a liftoff \( l_1 \) above two parallel conducting layers occupying the region \( z \leq 0 \). The two layers \( (j = 1, 2) \) are assumed to have a uniform thickness \( h_j \), conductivity \( \sigma_j \) and are separated by an insulating gap \( g \). The coil is excited by a transient current of the form \( I_0(t) \) and the normal component of the transient induced magnetic field is detected by a Hall-effect device located on the coil axis.
The measured field $H_z$ can be expressed as the sum of the transient source magnetic field $H_z^s$ (ie the known field produced by an isolated coil) and the reflected magnetic field $H_z^R$ due to eddy-current induction in the conductor system. Using the polar coordinate system in Fig. 1, the normal ($z$) component of the reflected magnetic field is given by \[4-5\]

\[H_z^R(r,z,t) = \frac{n}{k^3} \int dk k C(k) J_0(k r) \exp(-k z) \Psi(k,t), \tag{1}\]

where $n$ is the coil turn density, and $C(k)$ depends on the coil geometry and liftoff,

\[C(k) = \frac{1}{2k^3} \left[ e^{-k \theta} - e^{-k (\theta + \omega)} \right] \int_{kr}^{kr} dx J_1(x). \tag{2}\]

The time dependence of $H_z^R$ is determined by the function

\[\Psi(k,t) = L^{-1} \left[ L[I_0(t);s] R(k,s/i);t \right], \tag{3}\]

which is constructed using the known solution to the corresponding problem for a single frequency excitation by making the formal replacement $\omega = s/i$ in the frequency-domain reflection coefficient $R(k, \omega)$. Here, the Laplace transform and inverse Laplace transform are denoted by $L$ and $L^{-1}$, respectively. We have chosen to use Laplace (rather than Fourier) transforms as, for the limiting cases presented here, the appropriate Laplace transforms are known exactly.

The behaviour of the transient reflected field will be considered for a two layer system using a "thin plate" approximation in which the current density in the conductors is replaced by an equivalent current sheet located at the midplane of each layer \[6-7\]. This approximation is valid in the frequency domain when (i) the skin depth is large compared with the layer thickness and (ii) the variation of the source magnetic field through the thickness of the layer is small. Hence, the thin plate approximation is expected to be valid in the time domain for large $t$. The theoretical results presented here assume a step function current excitation, $I_0(t) = 0,t < 0$; $I_0(t) = I_o,t \geq 0$. Identical results are expected for an exponentially-damped step-function current excitation in the limit $t \gg$ rise time $\tau$.

The function $\Psi(k,t)$ which determines the time dependence of the transient reflected field can be obtained by substituting the known frequency domain reflection coefficient for a system of two thin layers \[7\] into Eq.3. The evaluation of the inverse Laplace transform which arises in Eq.3 can be performed exactly to give

\[\Psi(k,t) = -\frac{1}{2} I_0 \left[ f^+ \exp[-\bar{\eta} t/(1+\rho)] + f^- \exp[-\bar{\eta} t/(1-\rho)] \right] \exp[-kh_{\bar{\eta}}], \tag{4}\]

where $\bar{\eta} = 2k/\kappa_i$, $\kappa_i = \mu_0 \lambda_j / 2$, $\lambda_j = \sigma_j h_1 + \sigma_j h_2$ is the total integrated conductivity,

\[p^2 = 1 - 4\kappa_i \kappa_2 (1 - e^{-2k d})/\kappa_i^2,\]

\[f^\pm = \pm(1 \pm \rho)(1 - \kappa_j (1 \mp \rho)/(2\kappa_j))/p, \tag{5}\]

$\kappa_j = \mu_0 \lambda_j / 2$, $\lambda_j = \sigma_j h_j$ is the integrated conductivity (or conductivity-thickness product).
of layer $j$ and $d = g + (h_1 + h_2)/2$.

The asymptotic behaviour of the reflected magnetic field for large times can be found by substituting Eq. 4 into Eq. 1 and integrating by parts to give, for $z = 0, r = 0$,

$$H^R_z = -2m_0 \left( \frac{\kappa_z}{t} \right)^3, \quad t \to \infty,$$

(6)

where $m$ is the dipole moment of the coil. The constant $\kappa_z$ depends on the layer parameters only though the total integrated conductivity of the system $\lambda_z = \sigma_1 h_1 + \sigma_2 h_2$. Consequently, the long-time behaviour is independent of the gap between the two layers. The $1/t^3$ decay predicted for a thin layer system is more rapid than the corresponding behaviour for the half-space geometry where the field decays as $1/t^{3/2}, t \to \infty$.

The relationship between the long-time decay of the reflected field and the total integrated conductivity can be made more explicit by rearranging Eq. 6, and noting that the next two terms in the asymptotic expansion are of order $1/t^4$ and $1/t^5$ respectively, so that,

$$t(H^R_z)_{1/3} = \alpha + \beta/t + \gamma/t^2, \quad t \to \infty,$$

(7)

where $\alpha = -\mu_0 \lambda_z (2m_0)^{3/2}$ is proportional to the total integrated conductivity.

Effect of changes in two layer system

The two layer system provides a simple but useful framework for investigating the effect on the transient reflected field of changes in layer thickness (hidden corrosion), changes in coil liftoff and changes in the interlayer gap. The effect of a change in layer thickness enters the long time behaviour only via the change in the total integrated conductivity of the system $\Delta \lambda_z = \Delta \sigma_1 h_1 + \Delta \sigma_2 h_2$. From Eq. 6, the change in the reflected magnetic field $\Delta H^R_z$ due a change in the integrated conductivity can be written in the form

$$\Delta H^R_z = -2m_0 \left( \frac{\Delta \kappa_z}{\lambda_z} \right)^3 \left( 1 + \frac{\Delta \lambda_z}{\lambda_z} \right)^{-1} \left( \frac{\kappa_z}{t} \right)^3, \quad t \to \infty.$$

(8)

Hence, the normalised change in the reflected magnetic field at long times,

$$\xi = \lim_{t \to \infty} \frac{\Delta H^R_z}{H^R_z} = \left( 1 + \frac{\Delta \lambda_z}{\lambda_z} \right)^{-1},$$

(9)

is independent of time and depends only on the fractional change in integrated conductivity. In the special case where the two layers have the same conductivity, $\Delta \lambda_z / \lambda_z = \Delta h_1 / h_1$ and the long time behaviour of the normalised reflected field gives a direct measure of the fractional thickness loss of the system, irrespective of whether the thickness loss occurs in the upper or lower layer.

The change in the reflected magnetic field effect $\Delta H^R_z$ due to a small change in coil liftoff $\Delta l_1$ can be established by taking the derivative of Eq. 1 with respect to $l_1$. After performing the asymptotic expansion for large $t$, it can be shown that, to first order in $\Delta l_1$,

$$\Delta H^R_z = 12m_0 \Delta l_1 \left( \frac{\kappa_z}{t} \right)^4, \quad t \to \infty,$$

(10)

and the normalised change in reflected field due to a change in liftoff tends to zero at large times,

$$\frac{\Delta H^R_z}{H^R_z} = -6\Delta l_1 \frac{\kappa_z}{t}, \quad t \to \infty.$$

(11)

The change in the reflected magnetic field $\Delta H^R_z$ due to a small change in the interlayer separation $\Delta g$ can be found in a similar manner so that to first order in $\Delta g$, 309
and the normalized change in reflected field due to a change in interlayer gap also tends to zero at large times.

The general features of the asymptotic behaviour described above for a two-layer system are also expected to apply for a general multilayer system provided the thin-plate approximation is satisfied. In particular, the long-time behaviour of the reflected magnetic field should still follow a $1/t^2$ decay, Eq.(6), with the constant $\kappa$, being proportional to the total integrated conductivity $\lambda_i = \sum \sigma_i h_i$, independent of the presence of multiple gaps $g_j$ between the layers in the structure.

EXPERIMENTAL

Measurements were made using the transient eddy-current system (TRECSCAN) developed at the Defence Evaluation and Research Agency, Farnborough [1]. The air-cored coil, described in Table I, was excited in a current-controlled mode by a bipolar exponentially-damped square-wave current source. A relatively large diameter coil was used in order to satisfy the thin-plate assumption that the variation of the source magnetic field through the thickness of the layer is small. The normal component of the magnetic field on the axis of the coil was measured using a commercial Hall-effect device. After suitable amplification and filtering to reduce high-frequency noise, the signal was digitized using a 100kHz 16-bit data acquisition card (Data Translation model DTI004). Thermal drift in the sensitivity of the Hall-effect device was eliminated by normalizing the measured bipolar transient to a constant peak-to-peak amplitude [1]. The measured bipolar transients were then converted to a unipolar transient by subtracting the positive and negative half-cycles. The experimental measurements reported here represent the average of up to 16 bipolar transients.

For convenience, the two layer system was constructed by stacking together a set of $n$ identical Al alloy sheets, each with thickness 0.9 mm and electrical conductivity 34% IACS. In this way, the layer thickness and location of the interlayer separation could be easily varied by adding or removing sheets, or by inserting an insulating spacer in the appropriate position. The sheets in each layer were kept in close mechanical contact so that any gap between individual sheets in the layer was negligible.

RESULTS AND DISCUSSION

The transient magnetic field $H_z(t)$ measured with the probe positioned on a layer of $n$ Al alloy sheets is shown in Fig. 2(a). As expected, $H_z(t)$ increases most rapidly for an isolated coil ($n = 0$) as in this case $H_z(t)$ is directly proportional to the coil current $I_0(t)$. Increasing the thickness of metal under the probe ($n = 1, 2, 4$) resulted in a successively slower increase in the field, with the slowest rise observed for the case $n = \infty$, when the probe was positioned above a large thickness of Al alloy approximating a half-space. The reflected magnetic field $H_z^R = H_z - H_z^S$, where the source field $H_z^S$ is the isolated coil field.

<table>
<thead>
<tr>
<th>Table I. Coil Parameters</th>
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<tbody>
<tr>
<td>Inner radius $r_1$</td>
</tr>
<tr>
<td>Outer radius $r_2$</td>
</tr>
<tr>
<td>Width $w$</td>
</tr>
<tr>
<td>Number of turns</td>
</tr>
</tbody>
</table>
Figure 2. (a) Total magnetic field and (b) reflected magnetic field as a function of time. Measurements performed with the probe positioned on a stack of \( n \) Al alloy sheets.

\( (n = 0) \), is plotted in Fig. 2(b) for \( n = 1, 2, 3, \ldots, \infty \). The reflected field \( H^R_z \) quickly reaches a peak, whose magnitude is approximately independent of the number of sheets for \( n > 2 \), and then decays at long times, the decay time increasing with the number of sheets.

The \( 1/t^3 \) decay for the reflected field at long times predicted by Eq.6 was tested by plotting the reflected field against time using log-log axes. As shown in Fig. 3, the gradient of the curves approaches \(-3\) at long times for \( n = 1, 2, 3 \), confirming the \( 1/t^3 \) behaviour. The gradient of the curves at long times also tends to \(-3\) even for a relatively large numbers of sheets (up to \( n = 10 \)), despite the fact that the assumptions of the thin-plate approximation are not well satisfied for large \( n \). The curve for the half-space case (\( n = \infty \)) approaches a slope of \(-3/2\) at long times, consistent with the \( 1/t^{3/2} \) decay noted previously.

The relationship between the total metal thickness and the coefficient of the \( 1/t^3 \) decay term was investigated by plotting the quantity \( t (H^R_z)^{1/3} \) as a function of \( 1/t \) in Fig. 4(a). As predicted from Eq.7, the plots are linear for small \( 1/t \) with a negative intercept \( \alpha < 0 \). The magnitude of the intercept \( |\alpha| \) is plotted as a function of \( n \) in Fig.4(b), where \( \alpha \) was determined by least-squares quadratic regression over a suitable domain of \( 1/t \). The plotted values of \( \alpha \) represent an average of typically 20 to 100 independent determinations performed in real-time using the data acquisition software. \( \alpha \) is observed to be initially proportional to \( n \) for \( n \leq 5 \), as required by Eq.7 which predicts \( \alpha \) to be proportional to the total integrated conductivity and hence \( n \). The relationship then falls away from a strict linear proportionality at larger \( n \), consistent with the expected breakdown in the thin-plate approximation for large layer thickness. The observed curve, Fig. 4(b), is fitted very

Figure 3. Log-Log plot of the reflected magnetic field vs time, \( n \) Al alloy sheets.
Figure 4. (a) Variation of \( t(H_z^m)^{1/3} \) vs \( 1/t \) for \( n = 1 \) to 10 Al alloy sheets. (b) magnitude of the intercept \( |\alpha| \), obtained from least squares fits to the data in Fig.4(a), as a function of \( n \).

accurately by a 3rd order polynomial forced through the origin, even for \( n = 18 \), which corresponds to a total thickness of Al alloy of 16 mm.

Fig. 4(b) can be used as a calibration curve which relates the total metal thickness to experimental measurements of \( \alpha \) for a given conductivity. Table II shows the predicted values of \( n \) obtained using this curve for an independent set of measurements with \( n = 1, 2, 5, 10 \) sheets. The fitted values of \( n \) obtained in this way agree with the actual values to better than 2%. Since the numerator in Eq.6 is independent of both coil liftoff and interlayer gap, the total thickness measured using this method should also be independent of coil liftoff and interlayer gaps. To test this prediction, further measurements were made for a stack of 5 sheets with either a 2.5 mm increase in probe liftoff or a 2.5 mm gap between the 2nd and 3rd sheets. Here, 2.5 mm is a significant fraction (55%) of the total metal thickness. The results (Table II) show that fitted values of \( n \) in these cases agree with the actual values to better than 4%, indicating that the method has the potential to determine corrosion-related thickness loss independently of changes in coil liftoff or interlayer gaps.

Eqs.8–13 indicate that the change in the reflected magnetic field \( \Delta H_z^m \) due to changes in coil liftoff or interlayer gap should decay more rapidly at long times than the change in reflected field due to actual loss of metal. This behaviour is shown in Fig. 5, where experimental results are presented for the cases: (i) where metal loss at different depths is simulated by removing one sheet from a stack of four sheets and replacing it by an insulating spacer with approximately the same thickness (four curves), (ii) where the insulating spacer is introduced between the sheets to produce an interlayer gap without metal loss (three curves), and (iii) where the spacer is introduced immediately under the probe to produce additional coil liftoff (one curve). The long-time behaviour of the curves clearly fall into two groups. The curves for which there was no loss of metal (ie. cases (ii) and (iii) for changing

<table>
<thead>
<tr>
<th>Actual number of Al sheets, ( n ),</th>
<th>Calculated ( n )</th>
<th>% Deviation</th>
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<tbody>
<tr>
<td>1</td>
<td>0.989</td>
<td>-1.1%</td>
</tr>
<tr>
<td>2</td>
<td>2.016</td>
<td>+0.8%</td>
</tr>
<tr>
<td>5</td>
<td>5.04</td>
<td>+0.8%</td>
</tr>
<tr>
<td>10</td>
<td>9.84</td>
<td>-1.6%</td>
</tr>
<tr>
<td>5 (+2.5mm coil liftoff)</td>
<td>4.87</td>
<td>-2.6%</td>
</tr>
<tr>
<td>5 (+2.5mm gap)</td>
<td>4.82</td>
<td>-3.6%</td>
</tr>
</tbody>
</table>
Figure 5. Change in the reflected magnetic field due to metal loss (1–4), changes in coil liftoff (5) and changes in interlayer gap (6–8) for a system of four Al alloy sheets.

Figure 6. Normalised change in the reflected magnetic field for the cases in Fig.5. For large \( t \), the curves for metal loss tend to a constant value while the curves for interlayer gap or liftoff tend to zero.

Figure 7. \( \Delta H_z^R/H_z^R \) for the data in Fig.6 replotted as a function of \( 1/t \). The curves for metal loss extrapolate to a value \( \xi \), related to the fractional metal loss via Eq.9.
gap or liftoff), all decay to zero more rapidly than the curves due to loss of metal. The four curves due to loss of metal tend to a common curve at long times, independent of the depth from which the metal was removed.

The discrimination between metal loss and changes in gap or coil liftoff becomes strikingly evident when the normalised change in reflected field $\Delta H_r / H_r$ is plotted either as a function of $t$, Fig. 6, or $1/t$, Fig. 7. At short times, the magnitude of the normalised change in reflected field initially increases in all cases. At later times, the response due to changes in gap or coil liftoff reaches a broad peak and then tends toward zero as $t \to \infty$. In contrast, the normalised response due to metal loss varies monotonically with time and tends to a constant value as $t \to \infty$. These results are consistent with the theoretical predictions, Eq. 11 and Eq. 13, that the normalised change in reflected field due to variations in liftoff or gap should decrease as $1/t$ as $t \to \infty$ whereas, from Eq. 9, the normalised change due to metal loss should tend to a constant value $\xi$ as $t \to \infty$. This behaviour is further confirmed in Fig. 7, where the curves corresponding to metal loss all extrapolate to a common intercept $\xi = -0.53$ at $1/t = 0$. From Eq. 9, the fractional change in the total metal thickness can be obtained directly from this value of $\xi$ to give $\Delta h / h = -22\%$. This estimate agrees well with the actual thickness change of $-25\%$.

CONCLUSION

An experimental and theoretical study of the long-time behaviour of the transient magnetic field induced in a model multilayer structure has been presented. The results lead to a simple method for measuring either the absolute metal thickness or the percentage loss of metal in a multilayer structure using transient eddy-current NDE, with only a weak dependence on any simultaneous changes in coil liftoff or interlayer gap. Furthermore, it has also been shown that measurements of the transient reflected magnetic field at long times allow the response from genuine metal loss arising from hidden corrosion to be discriminated from unwanted signals due to changes in probe liftoff or interlayer gap.

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REFERENCES