MEASUREMENT AND CALCULATION OF TRANSIENT EDDY-CURRENTS IN LAYERED STRUCTURES

J.R. Bowler
University of Surrey
Guildford
Surrey, GU2 5XH
UK

and

D.J. Harrison
Materials and Structures Department
Defence Research Agency (Aerospace Division)
RAE Farnborough, Hants., GU14 6TD
UK

INTRODUCTION

In transient eddy-current inspection, an electromagnetic field pulse is excited in a conductor by causing a step change in the current through a coil. As this pulse propagates into the material, it is broadened by dispersion and scattered by discontinuities in the conductivity and permeability of the conductor. Subsurface defects cause part of the pulse to be scattered back to the surface of the conductor where it can be observed as a transient signal in the time domain, either as an EMF across the coil, or by direct measurement of the magnetic field using, for example, a Hall sensor. The observed transient is essentially the response function of the specimen with the transducer at a particular position. It contains information over a broad spectrum in contrast to time-harmonic excitation which yields information only at a single frequency.

Eddy-current inspection has for a long time been one of the most effective methods of detecting cracks and other defects at, or close to the surface of conducting materials. Since induced currents in planar structures flow parallel to the interfaces, only cracks that are predominantly perpendicular to the surface are readily detectable and measurements are related to the area of the crack. Corrosion in aircraft structures, on the other hand, tends to occur in planes that
are parallel to the surface. Particular inspection problems are, for example, exfoliation corrosion and corrosion in lap joints. In such cases, eddy-current measurements are related to the thickness of the corrosion layer by virtue of the change in conductivity caused by the decomposition of the metal. Consequently, eddy current detection of corrosion between plates is not easy in the early stages when the nonconducting region is thin.

In order to get a better understanding of the capabilities of eddy currents for detecting and characterising corrosion, a layered structure is used as an idealised model of corrosion attack between two plates. A series of electromagnetic field pulses is induced in the specimen by passing a square wave current through a coil.Transient fields are scattered to the surface by the various interfaces in the specimen. These fields are measured by means of a Hall sensor and the observations compared with theoretical predictions.

DETECTION OF SUBSURFACE DEFECTS

Conventional eddy-current inspection is based on the measurement and interpretation of changes in the complex electrical impedance of a coil as it is moved over the surface of a specimen. Whilst this is very effective for surface defects, traditional techniques have drawbacks if used for defects that are significantly below the surface. In order to clarify the nature of these limitations, eddy-current inspection for flaws can be viewed as two separate processes, excitation and detection. Firstly, the defect must be illuminated with an incident electromagnetic field. In order to propagate such a field into the conductor effectively, the coil should be driven by a current containing predominantly low temporal frequencies. Also the field distribution in space must be characterised by predominantly low spatial frequencies since high spatial frequencies are rapidly attenuated with increasing depth; this means that a large coil is needed. Secondly, the electromagnetic field scattered by the defect is measured at the surface of the conductor. Signal detection using a coil depends on the rate of change of flux linkage rather than magnetic field intensity. Thus at low temporal frequencies a coil becomes ineffective as a means of measuring magnetic field. It can be seen that if the same coil is used for both excitation and detection of subsurface defects then the requirements for achieving a substantial flaw signal are in conflict.

In order to overcome this conflict a relatively large coil is used to illuminate the subsurface region and an independent sensor measures the scattered normal magnetic field at the surface. A Hall device is used for detection as it has two significant advantages. Firstly, by virtue of its small size it provides excellent spatial resolution and, secondly, it is sensitive from DC to an upper frequency limit which depends on the chosen device, 100 kHz in the present case. Here an air-cored coil was used to induce eddy currents in order to permit accurate modelling and the Hall sensor was mounted on the coil axis 0.75 mm from bottom face, Fig. 1.

EXPERIMENTAL PROCEDURE

Measurements were made using a recently-developed transient eddy-current scanning system (TRECSCAN). This consists of several
signal generating and processing units controlled by a 386 PC via an IEEE-488 bus. A schematic diagram of the system is shown in Fig. 2. The source coil, driven by a square-wave voltage, is in a series inductance-resistance circuit where the coil current rises with a time constant, \( \tau_0 = L/R = 88 \mu \text{sec} \), to an asymptotic limit.

The sensor signal, containing contributions from both the direct source field and the transient field scattered by a specimen, is digitised using an analogue-to-digital converter (ADC). The presence of defects in the specimen modifies this transient but the magnitude of defect signals is small compared with that of the source field and must be amplified. To avoid saturating the amplifier, the large signal due to the source field and unflawed specimen is balanced out. This is achieved by generating a balancing signal in real time using an arbitrary waveform generator in conjunction with the PC, Fig. 2. Thus the output of the ADC can be brought to zero in the time domain at any desired reference point where the material is unflawed. The small transient signals due to flaws are thereby referred to a zero baseline and can be amplified to any desired level. As a consequence of the square-wave current excitation, transients form a bipolar series. The differences between corresponding points in a positive-going transient and the subsequent negative-going one are stored for subsequent processing and display. The transducer can be either handheld or mounted in a 3-axis scanning frame. Area scans of a specimen can be made with a transient being measured at each point of the scan.

The Hall sensor is contained in an IC with an operational amplifier and is mounted in a dual-in-line package. Since it separates the coil from the workpiece, the encapsulated chip is carefully ground down until the overall thickness is 1.0 mm in order to minimise the coil lift-off. To calibrate the measurement system, the field on the axis of the coil at the site of the Hall plate has been calculated for unit
change in the steady state coil current. This enables a calibration constant to be determine for converting the observed transient voltages into magnetic field measurements.

THEORY

If the magnetic field at the site of the Hall probe is calculated as a function of frequency, the corresponding time domain result $H(t)$ can be found by taking the Fourier transform,

$$H(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} h(\omega) \exp(i\omega t) \, d\omega,$$  \hspace{1cm} (1)

where $h(\omega)$ is the frequency domain solution.

Adopting a cylindrical polar coordinate system with its $z$–axis normal to the conductor, the $z$–component of the magnetic field due to a cylindrical coil above a planar structure can be expressed in closed
form by the Hankel transform

\[ h_z(\rho, z, \omega) = \frac{nI(\omega)}{2} \int_0^\infty \Gamma_s(\kappa, \omega) \exp(-\kappa z) J(\kappa) J_0(\kappa \rho) \, d\kappa, \]  

(2)

where \( n \) is the turns density of the excitation coil, \( I(\omega) \) is the current, \( \Gamma_s(\kappa, \omega) \) is the appropriate transverse electric reflection coefficient for the structure and \( J(\kappa) \) is a function determined by the current distribution in the coil. \( \Gamma(\kappa) \) is found by integrating over the coil cross-section1. For a coil of uniform turns density, axial length \( 2b \), inner radius \( a_1 \), outer radius \( a_2 \) and whose center is at a height \( h \) above the conductor,

\[ J(\kappa) = \int_{a_1}^{a_2} \int_{h-b}^{h+b} \exp(-\kappa z') J_1(\kappa, \rho') \rho' d\rho' dz'. \]

(3)

The above integrals can be evaluated in terms of standard function1.

What is actually observed, is the difference between two field values since a reference signal, in the present case found from measurements made over a homogeneous conducting plate, has been subtracted in the balancing operation referred to above. The required field difference is given by

\[ \Delta h_z(\rho, z, \omega) = \frac{nI(\omega)}{2} \int_0^\infty [\Gamma_s(\kappa, \omega) - \Gamma_{ref}(\kappa, \omega)] \exp(-\kappa z) J(\kappa) J_0(\kappa \rho) \, d\kappa, \]  

(4)

where \( \Gamma_s(\kappa, \omega) \) and \( \Gamma_{ref}(\kappa, \omega) \) are transverse electric reflection coefficients for the multi-layered structure and the reference structure respectively.

Here the reference structure is an infinite plate, thickness \( d \), conductivity \( \sigma \), whose reflection coefficient is given in terms of the half-space reflection coefficient, \( \Gamma(\kappa, \omega) \) as

\[ \Gamma_{ref}(\kappa, \omega) = \Gamma(\kappa, \omega) \frac{e^{2\gamma d} - 1}{e^{2\gamma d} - \Gamma^2(\kappa, \omega)} \]  

(5)

where \( \gamma = (\kappa^2 - i\omega \mu_0 \sigma)^{1/2} \) and \( \Gamma(\kappa, \omega) = (\kappa - \gamma)/(\kappa + \gamma) \).

For a \( N \)-layered piecewise homogeneous stratified half-space, one defines the reflection coefficients

\[ \Gamma_j(\kappa, \omega) = \frac{\gamma_j - \gamma_{j-1}}{\gamma_j + \gamma_{j-1}} \]  

(6)

for the interface between layer \( j \) and \( j-1 \). \( j = 1, 2, 3, \ldots N \) and \( \gamma_j = (\kappa^2 - i\omega \mu_0 \sigma_j)^{1/2} \), taking the root with a positive real part. Then the overall reflection coefficient of the structure is given by

\[ \Gamma_s(\kappa, \omega) = \frac{\Gamma_1(\kappa, \omega) e^{2\gamma_1 d_1} + r_1(\kappa, \omega)}{e^{2\gamma_1 d_1} + \Gamma_1(\kappa, \omega) r_1(\kappa, \omega)} \]  

(7)
where \( r_1 \) is determined by repeated application of the recursion formula

\[
  r_{j-1}(\kappa, \omega) = \frac{\Gamma_j(\kappa, \omega)e^{2\gamma_d j} + r_j(\kappa, \omega)}{e^{2\gamma_d j} + \Gamma_j(\kappa, \omega)r_j(\kappa, \omega)} \quad j = 2, 3, 4 \ldots N - 1, \quad r_N = 0 \tag{8}
\]

A conducting slab is a simple example of the general scheme. In the case of a slab \( N = 2 \), \( \Gamma_1(\kappa, \omega) = \Gamma(\kappa, \omega) \) and \( r_1 = -\Gamma(\kappa, \omega) \). Substituting these identifications into (7) recovers (5).

The time variation of the magnetic field is found by numerical evaluation of (4) for a current varying in the time domain as \( 2(1 - e^{-t/\tau}) \). Evaluation of (4) at say 512 frequencies, is followed by a fast Fourier transform of the results to get the variation of magnetic field with time.

RESULTS AND DISCUSSION

The specimen consists of a pair of aluminium alloy plates 300 mm x 150 mm x 2.00 mm thick. Each plate has an 50 mm x 50 mm milled depression 0.43 mm deep, as shown in Fig. 3. The transducer is balanced over the central part of the specimen pair which represents two sound plates in contact and is equivalent to a single plate of thickness 4.00 mm, Fig. 3A. Transients are then measured with the transducer above the depression in the bottom of the top plate and above the depression in the top of the bottom plate. Finally a dielectric spacer of thickness equal to that of the depressions is inserted between the plates and a third transient is measured with the transducer in the central position.

Measurements have been made in this way for 0.43mm depression and gap thicknesses. The coil dimensions are, O/D 20.65mm, I/D 5.0mm, axial length 2.80mm and liftoff 1.00mm. The material has a conductivity in the range 34 – 42% IACS, however a value at the upper limit was found to give the best agreement with experiment. Theoretical predictions have been calculated for this geometry. The results, shown in Fig. 4, demonstrate that good agreement is achieved between theory and experiment. The main features of the data are discussed below.

The transients from the two depressions exhibit the features that might be expected. The depression nearest to the surface reflects a transient that is larger and arrives earlier than that from the deeper depression. At longer time delays both transients tend to the same function. In contrast the transient that arises from a plate gap that is equal to the depression thickness gives rise to a signal that is significantly different from the other two. It rises with the signal due to the lower plate depression but reaches a maximum value earlier than the other responses. Its magnitude is much smaller than might be expected and it decays more rapidly. The difference between the gap transient and that due to the lower plate depression is entirely due to the difference in the position of the bottom surface of the bottom plate. This difference can be eliminated by having the bottom plate sufficiently thick that the transient reflected from the bottom surface has no noticeable effect on the detected signal. Under these circumstances, the response from a gap and an indentation in the lower plate are the same. Under these circumstance it would be impossible, using the eddy current signal alone, to distinguish between plate separation and the loss of metal due to corrosion.
Fig. 3. Test specimens. A Plates in contact. B Plates separated. C Material loss from lower plate. D Material loss from upper plate.

Fig. 4. Variation of magnetic field with time.

Plate thickness 2.00mm, gap 0.45mm.

Expt. Theory

- depression in top plate
- depression in btm plate
+ plate separation
CONCLUSION

With regard to the inspection of layered structures for corrosion there are several pieces of information that can possibly be inferred from eddy-current measurements apart from the physical extent of any damaged area. Whether the signals are caused by loss of material due to corrosion in the top or bottom plate and whether corrosion products have forced a gap between the plates.

The results presented here provide some initial information on what might be inferred from transient eddy current data. It is clear that there is no problem in detecting the effect of quite small layers of material loss. Furthermore, careful processing of the data can lead to a measurement that is sensitive to the depth below the surface at which the material loss occurred. It is certainly possible to distinguish between signals from immediately adjacent layers although associating absolute depths with these signals would not be very accurate. The potential to identify a gap between the plates depends on the overall thickness of the plates. In the case of thin plates, the dominant reflection from the bottom surface causes the transient associated with a change of gap to appear to return much earlier than expected. This feature fortuitously permits unambiguous identification of a gap change. However, as the overall thickness of the structure is increased, this effect is progressively diminished and the signals arising from air gaps become indistinguishable from the signals arising from change of plate thickness.

ACKNOWLEDGEMENTS

This work is supported by the Procurement Executive, Ministry of Defence, UK.

REFERENCE