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MISCELLANEOUS EDDY CURRENT TECHNIQUES

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By

H. L. Libby

January 1969

PACIFIC NORTHWEST LABORATORY
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MISCELLANEOUS EDDY CURRENT TECHNIQUES

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H. L. Libby

INTRODUCTION

This report describes several eddy current test techniques. These are presently in different stages of development and may be of interest to those developing or using eddy current nondestructive test methods.

The following techniques are described:

1. Controlling the curvature of test coil impedance lift-off loci.
2. Stabilizing the temperature of eddy current test coils.
3. Notes on the eddy current ultrasonic transducer.
4. Notes on the impedance relationship of a solenoid encircling a bar.
5. Measuring the flow of eddy currents in liquid Wood's metal.
6. An operational test for phase detectors.

CONTROLLING THE CURVATURE OF TEST COIL IMPEDANCE LOCI

An eddy current nondestructive testing device has been previously described⁽¹⁾ which provides compensation for variation in probe-to-specimen spacing and surface irregularities. One of the main features of the technique is the use of more than one eddy current test coil, with essentially independent control of the relative amplitude and phase angle output of each coil. The outputs of the two or more test coils are adjusted so that the combined output approximates the desired result. For example, control over the curvature of the lift-off locus is obtained by manipulating the relative phase and amplitude of the signal contribution from the large and small coils of a two coil probe. The curvature may actually be reversed by proper adjustment of the signal contributions.

An intermediate set of adjustments may be found to give a very nearly straight probe motion locus. It is believed that although the locus thus obtained appears straight, it actually has some S type curvature due to the difficulty in getting the

electromagnetic field effects to all be so proportioned to give a perfectly straight line. However, if required, further straightening effect can be obtained by adding coils of other diameters to the probe and properly adjusting their contributions to the total probe output.

The use of a probe having straight probe motion locus has several advantages. When the output of a conventional flat or probe type coil having a curved probe motion locus is used with a phase amplitude detector whose axes are so aligned to minimize the effect of probe motion signal, the required alignment is ideal for only one probe position. This is due to the fact that as the probe to test specimen spacing changes, the angle of the signal changes due to the curvature, requiring continual adjustment of the detection axes; a very impractical requirement. With a straight probe motion locus this undesirable effect may be considerably reduced or even eliminated.

The straightening of the probe motion locus makes it possible to apply a phase detector which is made purposely amplitude insensitive to indicate relative conductivity of the test specimen. The signal fed to the phase detector is nulled at a point of intersection of the straight line portions of the probe motion signals for metals of various conductivities. The phase angle for a particular conductivity then does not vary with probe position because of the straight probe motion locus, and the phase detector output should change only with sample conductivity.

Figure 1, made using a phasorscope (vectorscope) operating at 5000 Hz, shows the straightening of lift-off loci using this technique. The coil assembly used, to be described in more detail later, consisted of a small excitation winding and two sensing coils having different diameters. Figure 1(a) illustrates the curved lift-off loci obtained using only the small excitation coil and the small sensing coil. The loci, in the order of increasing signal amplitude, are for stainless steel, lead, brass, aluminum and copper test specimens respectively. The curvature depends on the exact relations existing between the effective fields or field of influence of driver and pick-up coils and the distribution of the flow of

a. Small pick-up coil only for stainless steel, lead, brass, aluminum and copper. Note curvature.

b. Combined effect of small and large pick-up coils.

c. Relative phase and amplitude of contribution from small coil (nearly vertical line) and large coil (nearly horizontal line) for Fig. 1(b).

FIGURE 1
Straightening of Probe Motion Locus by use of Multiphase
Differential Probe

eddy currents in the test specimens. As the distribution of currents may change as probe spacing changes, the curvature differs some for test specimens having different electrical characteristics. It will also differ depending upon the configuration of the probe coils, especially upon the placement of the different coils and changes in type and shape of core material if any. The phasor diagrams shown are mirror images of the conventional representation. The vertical axis represents reactance, and the horizontal axis represents resistance, with positive resistance to the left.

The straightening of the lift-off loci is shown in Figure 1(b). Here the outputs of both small and large diameter sensing coils were used. The output of each sensing coil was fed to a separate circuit consisting of a simple R-C phase shifter and an amplitude control. The outputs of these two circuits were connected in series and applied to the input of the phasorscope. Thus, the contribution of each of the two coils; the small diameter coil, or the large diameter coil, could be adjusted in both amplitude and phase. The straightening of the lift-off loci was obtained by adding a contribution from the large coil leading that of the small coil by about 100 electrical degrees. The amplitude of this contribution was adjusted until it appeared to the eye that the A1 locus was straight. The loci for stainless steel and lead are not straight, but as pointed out above, it is not expected that the straightening effect will be uniform over wide ranges of conductivities. It is of interest to see that the sensitivity to conductivity is not adversely affected.

The relative amplitudes and phases of the contributions of the two coils for Figure 1(b) are shown in Figure 1(c). It is noted that a scale change factor exists between Figures 1(b) and 1(c).

Figure 2 shows that a large amount of control over the loci curvature is obtained. Reverse curvature is displayed in Figure 2(a). This was obtained by increasing the contribution from the large coil as shown in Figure 2(b).

An increase in curvature can be obtained by adjusting the relative contribution from the coils as shown in Figure 2(c). Here the large coil contribution lags that of the small coil by about 150 degrees.

- a. Reverse curvature of Probe Motion Locus obtained by increasing contribution of large coil.

- b. Relative amplitude and phase of contributions from small coil (nearly vertical locus) and large coil (nearly horizontal locus for Fig. 2(a)).

- c. Increased curvature obtained by changing relative phase of contributions from small coil (locus extending to left) and large coil (locus extending to right)

- d. Relative sensitivity of small coil (nearly vertical locus) and large coil (nearly horizontal locus) for 0.020 inch intervals of probe motion.

FIGURE 2
Additional Effects Obtained with Multiphase Differential Probe

The dot loci of Figure 2(d) shows the relative change in amplitude of the small and large coil signals as a function of probe to specimen spacing. The spacing intervals are 20 mils. As expected the small coil signal drops more rapidly with increased spacing than the large coil signal. From these loci different combinations of small and large coil signals can be added graphically or analytically to determine various loci.

An interesting curve is obtained when the large and small coil loci differ in phase by about 180 degrees. The sensitivity is greatly reduced and the probe motion loci can be made to have a very sharp angle, or V, which in turn can be closed to give almost a single straight line.

The probe used consisted of a driver coil (20 turns, No. 34 copper wire) wound on a magnetic core 0.050 inch in diameter. The small pick-up or sensing coil was wound directly over the driver and consisted of 90 turns of 2.5 mil copper wire. The outer diameter of this small pick-up coil was about 1/8 inch. The large coil was wound on a core made by winding a piece of magnetic tape, .004 x 1/16 x 2 inches on a 1/4 inch form, making 2-1/4 layers of tape. The large coil consisted of 46 turns of #34 copper wire. The outer diameter of the large coil was 3/8 inch. The central .050 inch diameter magnetic core was wound tightly using a piece of .004 inch magnetic tape 1/4 inch wide and 5/16 inch in length. This core was inserted in a small hole in a piece of phenolic so that 5/32 inch remained. The driver coil was wound on this part of the core, thus, none of the coil was of greater depth (measured along the core) than about 5/32 inch.

TEMPERATURE STABILIZING TECHNIQUE FOR EDDY CURRENT TEST COILS

Temperature variations of eddy current test coils used in nondestructive testing applications cause changes in test coil impedance and test coil output voltages. These changes are reflected in the output readings of the eddy current devices and are most objectionable in the case of instruments which provide a direct current output reading such as those measuring electrical conductivity, thickness, and other dimensional quantities. The temperature changes are usually the result of two main dimensional

factors. One of these is the heating of one or more test coils due to the flow of the test coil excitation current. The other is due to the fluctuation of the temperature of the probe environment, such as that caused by placing the test coil adjacent to or upon test specimens having temperatures which differ from that of the test coil assembly. The undesired effects arise from several sources such as change in resistance of the coil, change in coil inductance due to thermal expansion, and changes in coupling between adjacent coils and between test specimens due to thermal expansion. A method for stabilizing the temperature of an eddy current test coil is shown in the block diagram in Figure 3.

The purpose of the system is to stabilize the temperature of the test coil L_1 which in use is subjected to changing environmental temperatures. The system includes a direct current bridge with the eddy current test coil L_1 and isolating choke coil L_2 in one arm, a direct current amplifier, a bridge current controller, and the eddy current test instrument being used for the specific nondestructive testing application.

The temperature control of the test coil L_1 is accomplished by sensing its resistance changes by means of the direct current bridge, and using these changes to control the direct current bridge current. The direct current bridge unbalance signals are fed to the direct current amplifier and bridge current controller which provide a variable direct current bridge current. The circuit is connected so that when the combined test coil L_1 resistance plus choke L_2 resistance increases (due to temperature increase) over a nominal value set by R_3 , the resulting bridge unbalance will cause the bridge circuit controller to reduce the bridge current, thus permitting the test coil L_2 to cool, maintaining its temperature nearly constant. If the test coil L_1 environmental temperature drops below the nominal value, the bridge unbalance is of the opposite polarity and the controller increases the bridge current, causing the test coil temperature to increase. Thus, the system tends to hold the test coil temperature constant within a small error dependent upon the system design even though the test coil experiences environmental temperature changes.

An important feature of this system is that the test coil L_1 is used both as a temperature sensor and heater element, making

FIGURE 3
Block Diagram of Temperature Control System for Eddy Current Test Coils

possible rapid detection and correction of temperature changes at the point where they are most effective in causing drift and errors in the eddy current instrument output.

The bridge current is prevented from flowing into the eddy current instrument by the use of the blocking capacitor C_1 . The same bridge arrangement can be used with eddy current testers using two or more test coils in the test probe as indicated by coil L_3 shown in Figure 1. In this case coil L_3 could represent an excitation coil and coil L_1 a sensing coil.

Other arrangements are possible with the heater current (which is also the temperature sensing current) being caused to flow through all or any number of the test coils. Test coil temperature excursions were reduced 90% using a control system employing four transistors and an operational amplifier.

EDDY CURRENT ULTRASONIC TRANSDUCER

An eddy current-ultrasonic transducer was previously described⁽²⁾ which generated and detected ultrasonic waves in nonferrous metals without use of any coupling medium except free space. Improved output signal-to-noise ratios have been obtained by making a fivefold increase in the peak excitation current of the send coil. The arrangement of equipment and typical signals at the receiver coil are shown in Figure 4. A 50 turn transmitter coil about 3/4 inch in diameter was driven with 150 ampere peak current pulses from a No. 6587 hydrogen thyatron.

The permanent magnet at the receiver coil supplies a magnetic field required for the generation of currents by the ultrasonic wave. Portions of both received signal wave trains in Figure 4 marked L and S are the first longitudinal and first shear wave signals respectively.

The generation of ultrasonic waves by electromagnetic field effects has also been investigated by others.^(3, 4, 5)

IMPEDANCE RELATIONSHIPS OF A SOLENOID ENCIRCLING A BAR

A review of the literature of eddy current nondestructive testing techniques shows the use of several systems of units and different ways of presenting the same data. For example, the normalized impedance or voltage plane diagrams for a solenoid containing an electrically conducting bar are treated differently

FIGURE 4
Generation and Detection of Ultrasonic Waves Using Eddy-
Current-Ultrasonic Transducers - Through Transmission

by different authors as shown in Figure 5. Each of these has its special advantage and usage. Although they are related in a straight-forward manner, the nature of the relationships is not obvious.

In Figure 5(a) is shown an often used diagram, one using mixed units, introduced by Foerster.^(6,7) A second representation using MKS units presented by Hochschild⁽⁸⁾ is shown in Figure 5(b). A third little known representation⁽⁹⁾ shown in Figure 5(c) is included here because it helps to show the physical relationship between skin depth, δ , and the coil impedance.

In Figure 5(a), Foerster used as the argument in the related Bessel functions the quantity:

$$A = \frac{f \mu_{rel} \sigma d^2}{5066} \quad (1)$$

where f = frequency of the exciting field

σ = electrical conductivity of test material in meter/ohm-mm²

d = diameter of test object, cm

μ_{rel} = relative permeability of bar

He then defined the frequency f_g as the frequency at which $A = 1$ for specific values of σ , d , and μ_{rel} . This is called the limit frequency. Then, from Equation (1)

$$f_g = \frac{5066}{\mu_{rel} \sigma d^2} \quad (2)$$

and

$$\frac{f}{f_g} = \frac{f \mu_{rel} \sigma d^2}{5066} \quad (3)$$

He then labeled computed impedance positions along the conductivity locus with their corresponding $\frac{f}{f_g}$ reference values.

Hochschild has used

$$Ka = a \sqrt{\omega \mu \sigma} \quad (4)$$

as the argument of the related Bessel functions where

a = radius of bar, meter

ω = 2π x frequency

μ = permeability of free space = 4×10^{-7} henry/meter

σ = electrical conductivity, mho per meter

(a) $\frac{f}{f_g} = \frac{f_{\mu_{rel}} \sigma d^2}{5006}$
 f = Hertz
 σ = Meters/ohm-mm²
 d = Diameter of Bar, cm.

For the Same Bar and Frequency

(b) $Ka = a \sqrt{\omega \mu \sigma}$
 $\omega = 2 \pi f$
 f = Hertz
 $\mu = 4 \times 10^{-7}$ Henry/Meter
 σ = mhos/Meter
 a = Radius of Bar, Meters
 $Ka = \sqrt{\frac{f}{f_g}} = \sqrt{2} \frac{a}{\delta}$

(c) $\frac{a}{\delta} = a \sqrt{f \mu \sigma} = \frac{a \sqrt{\omega \mu \sigma}}{\sqrt{2}} = \frac{Ka}{\sqrt{2}}$
 δ = Skin Depth, Plane Wave Case
 Units Same as in (b)

FIGURE 5
 A Comparison of Impedance Diagrams Using Different Systems of Units

In Figure 5(c) the impedance positions have been labeled with reference numbers corresponding to the related ratios of radius to skin depth for the plane wave semi-infinite plane conductor.

When the conversion of the mixed units used in Equation 1 is made it can be shown that the numbers on the diagram in Figure 5(b) are simply equal to the square root of the reference numbers associated with corresponding points on the diagram in Figure 5(a). The number 5066 is the factor relating the two systems of units used and appears as follows:

$$\frac{4}{(2\pi) (4\pi \times 10^{-7}) (10^6) (10^{-4})} \omega \mu \sigma a^2 = f_{\mu \text{rel}} \sigma d^2 \quad (5)$$

or

$$\frac{5 \times 10^4}{\pi^2} = 5066 \omega \mu \sigma a^2 = f_{\mu \text{rel}} \sigma d^2 \quad (6)$$

$$(Ka)^2 = \omega \mu \sigma a^2 = \frac{f_{\mu \text{rel}} \sigma d^2}{5066} \quad (7)$$

The relationship between the numbers at corresponding impedance points of Figure 5(b) and Figure 5(c) is that the latter are equal to the former divided by $\sqrt{2}$. This follows from the relation:

$$\frac{a}{\delta} = a \sqrt{\pi f \mu \sigma} = \frac{a \sqrt{\omega \mu \sigma}}{\sqrt{2}} \quad (8)$$

The representation in Figure 5(c) shows how the solenoid impedance varies with the ratio of the radius of the bar to the eddy current depth of penetration (or skin depth). Here, following the usual custom, the depth of the penetration is that depth in the plane wave, semi-infinite conductor case at which the eddy current density has decreased to $\frac{1}{e}$ times its value at the surface.

FLOW OF EDDY CURRENTS

Measurements using refined techniques show that eddy current flow direction in the neighborhood of a nonconducting barrier in liquid Wood's metal is complex and that the direction of flow is a function of frequency. These results are in agreement with the conclusion of Burroughs⁽¹⁰⁾ who shows by mathematical treatment that eddy current flow direction in other than circularly symmetrical cases varies with frequency and that the flow direction is complex.

The tests were performed using Wood's metal in a cylindrical stainless steel container 6-1/2 in. diameter with 0.034 in. wall thickness. Fumes of cadmium, a constituent of Wood's metal, are very toxic. The container was heated in a double boiler as a safety precaution to prevent overheating of the cadmium. Water was used in the outer boiler. A thermostat control held the temperature at about 85°C. Eddy currents were induced in the metal by a solenoid on the outside of the Wood's metal container. Excitation frequency was either 1kHz or 5 kHz. A test probe for measuring resistive voltage drops within the liquid metal consisted of two 0.005 in. diameter wires shielded by two type 304 stainless steel tubes except for about 3/16 in. at the end of the wire. These unshielded ends were bent to form a miniature dipole with a tip-to-tip distance of 0.117 in. Each wire was insulated except the end of the wires which formed the dipole element. The test probe was mounted vertically and was movable in three mutually orthogonal directions by means of micromanipulators. The probe mounting also allowed rotation of the probe around its axis. A pointer and scale mounted at the top of the probe provided a readout of probe alignment direction.

Probe voltage measurements were first made in the liquid metal for the case of circular symmetry (without barrier). Figure 6 shows the relative amplitude and phase of the test probe signals as displayed on a complex voltage plotter. Measurements were made with the dipole 3/16 in. below the surface of the liquid metal. Starting near the outside wall of the container, the probe was positioned successively at each of 20 points at 0.10 in. intervals along the container radius. At each point the probe was rotated, giving the voltage loci shown. The longest locus represents the voltage obtained at a probe position point about 0.08 in. from the edge of the container. Maximum signal was obtained as expected, with the dipole direction normal to a radius of the container.

Next an insulating barrier was placed in the liquid metal as shown in Figure 7, and voltage plots were made at several points in the neighborhood of the barrier. The directions of maximum voltage drop across the probe at 1 and 5 kHz at point A are shown. At each point the probe was rotated from the zero position in steps

FIGURE 6
Probe Voltage LOCI-No Barrier-Circular Symmetry

FIGURE 7
Liquid Wood's Metal Bath with Phenolic Current Barrier

of 20 mechanical degrees and complex voltage plots of the probe voltage at 1 and 5 kHz were made. The test results obtained with the probe at point A in Figure 7 for 1 kHz exciting frequency are shown in Figure 8(a). The large spot on the dotted elliptical locus represents the complex voltage output of the probe when oriented parallel with the barrier (voltage zero is at the center of each ellipse). The probe was rotated counterclockwise in steps of 20 mechanical degrees and successive voltage locus points were recorded as shown in the figure. The probe was rotated through 360° and no zero was found. If the current direction were real, a zero would be observed when the dipole direction was normal to the current flow direction as in Figure 6. The elliptical locus shows that the current direction is complex, consisting of two simple harmonic motions whose phase difference is at some angle other than 0 or 180 . Maximum voltage drop was obtained at an angle of approximately 120° rotation.

Results obtained at the same point A at a frequency of 5 kHz are shown in Figure 8(b). Again the probe output voltage traced an elliptical locus when the probe was rotated through 360° . At this higher frequency a maximum signal was obtained at an angle of about 110° , slightly less than for the 1 kHz excitation. This shows that the main direction of flow for the higher frequency case is more nearly normal to the container radius than for the lower frequency case. There is no significance in the relative orientation of the two ellipses shown as no attempt was made to maintain phase reference between the 1 and 5 kHz patterns.

OPERATIONAL TEST FOR PHASE DETECTORS

Synchronous phase-amplitude detectors are used in many eddy current nondestructive test devices to demodulate the test signal. A block diagram of a two detector system is shown in Figure 9. Its function is to provide two output signals E_3 and E_4 which are proportional to the components of the input signal E_1 which are in phase with the 0° and 90° reference (switching) signals E_5 and E_6 , respectively.

Following is described a convenient method to test the operation of the phase detectors and to aid in their adjustment. Output signals E_3 and E_4 are applied to an oscilloscope's vertical and horizontal deflection circuits respectively, so that a Lissajou figure is formed as the phase of the input signal E_1 is varied

(a) 1 kHz

(b) 5 kHz

FIGURE 8
Probe Voltage LOCI with Barrier

FIGURE 9
Phase Detector System

continuously with respect to the reference signal E_2 . The phase of the input signal E_1 is caused to vary by temporarily replacing the normal input signal with one having fixed amplitude from a separate oscillator circuit where frequency differs from that of the reference signal by a few hertz. Under these conditions the oscilloscope beam spot moves, forming a Lissajou figure at a rate dependent on the difference frequency. The desired figure is a circle, and the phase detector, phase shift and amplitude adjustments can readily be trimmed to give the proper pattern. Some error in switching period occurs using this method. However, the error is small, the effective switching period being changed by only

$$100\left(\frac{\Delta f}{f_2}\right) \text{ per cent} \quad (9)$$

where $\Delta f = f_2 - f_1 =$ frequency difference

$f_2 =$ reference frequency

$f_1 =$ temporary signal frequency for adjustment purposes

This method eliminates amplitude errors occurring when a phase shift circuit or resolver is used to provide the needed phase shift.

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