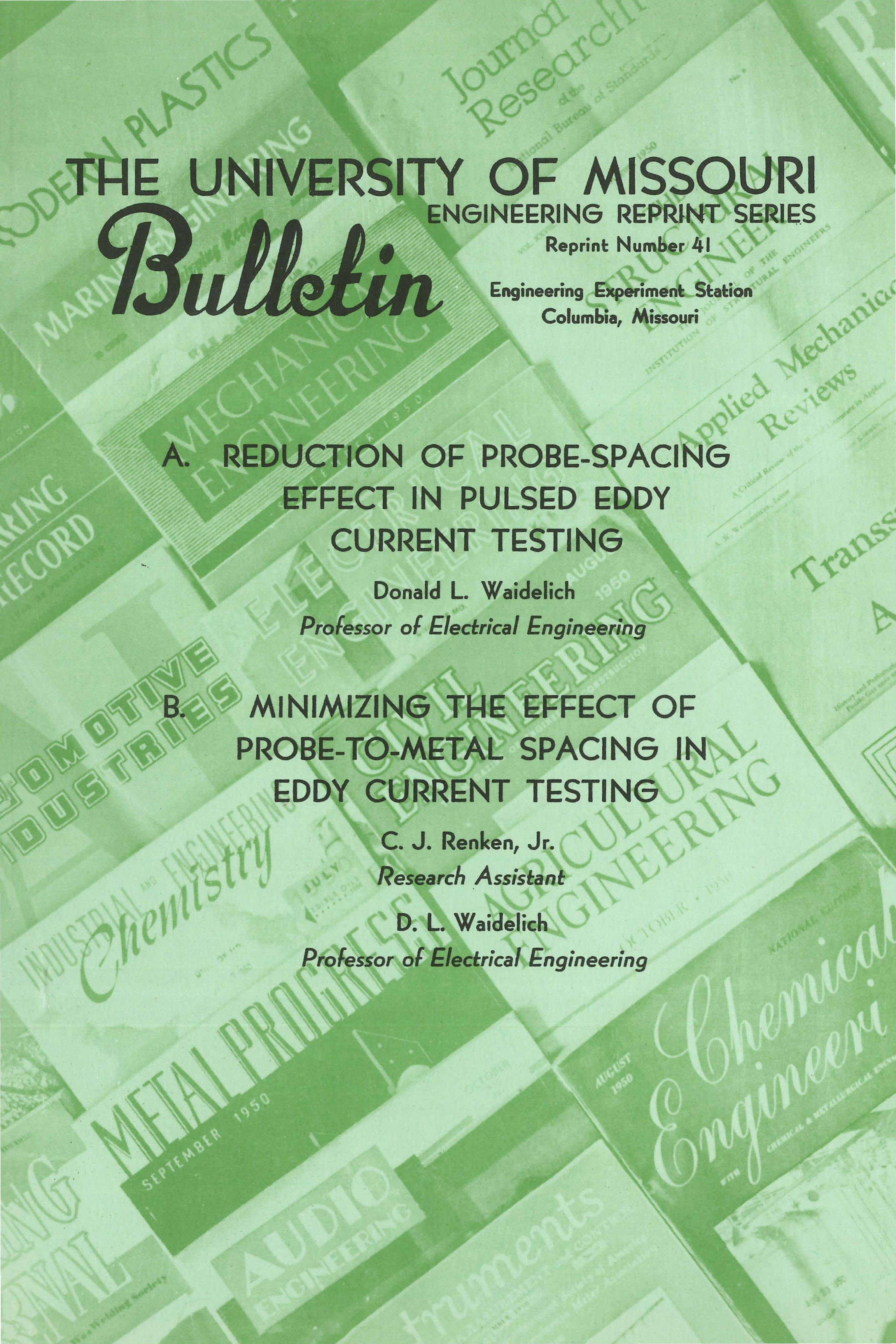

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ENGINEERING REPRINT SERIES
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Engineering Experiment Station
Columbia, Missouri

A. REDUCTION OF PROBE-SPACING EFFECT IN PULSED EDDY CURRENT TESTING

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B. MINIMIZING THE EFFECT OF PROBE-TO-METAL SPACING IN EDDY CURRENT TESTING

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Professor of Electrical Engineering

COLLEGE OF ENGINEERING
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MINIMIZING THE EFFECT OF PROBE-TO-METAL SPACING IN EDDY CURRENT TESTING

By C. J. Renken, Jr., and D. L. Waidelich[1]

In the nondestructive testing of metals by eddy current methods, a continuing problem has been the reduction of the effect of varying probe-to-sample spacing on the test results. In the testing of samples of circular cross-section by means of circular test coils, changes in coil-to-sample distance may be caused by diameter variations of the samples, while in the testing of plane samples such as a plate with a point type of probe, the variation in probe-to-sample spacing may be caused by irregularities of the surface of the sample or by vibrations of the probe or sample. This paper is concerned exclusively with the testing of plane samples. Production test situations require constant movement of the probe parallel to the surface of the sample, and it is preferred that no contact occur between the probe or probe holder and the metal sample.

Some earlier work on the reduction of the effect of varying probe-to-sample spacing has been done in Germany (**1**)[2] and in this country (**2**,**3**). This paper presents still another method of reducing this effect, a method using a phase angle meter which is corrected automatically for changes caused by spacing variations.

Bridge Circuit

Theoretical and experimental work (**2**,**4**) has shown how the impedance of a probe may vary in proximity with a plane piece of non-ferromagnetic metal. Figure 1, curve *A*, is the type of curve obtained as the probe-to-sample spacing is varied. The ordinate is the fraction of the free space inductance obtained when the metal is in proximity; the abscissa is the incremental change in resistance from the free space value divided by a constant, the free space reactance. The axis of the probe was maintained perpendicular to the plane of the metal. Curve *B*, Fig. 1, is the type of curve obtained when the probe-to-sample spacing is maintained constant and the conductivity is varied. Any information to be gained from a test must be carried by changes in the probe resistance and inductance. Measurements of small changes in probe resistance and inductance are slow and tedious, so the information to be derived from a test should be presented in another, more convenient form. One way to do this is to connect the probe as an element of an alternating current bridge. This bridge can then be balanced with the probe in a particular test situation. Any change in the probe's situation in relation to the metal, such as a change in probe-to-sample spacing, or a change in sample conductivity will

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[1] Argonne National Laboratory, Lemont, Ill.

[2] The boldface numbers in parentheses refer to the list of references appended to this paper, see p. 188.

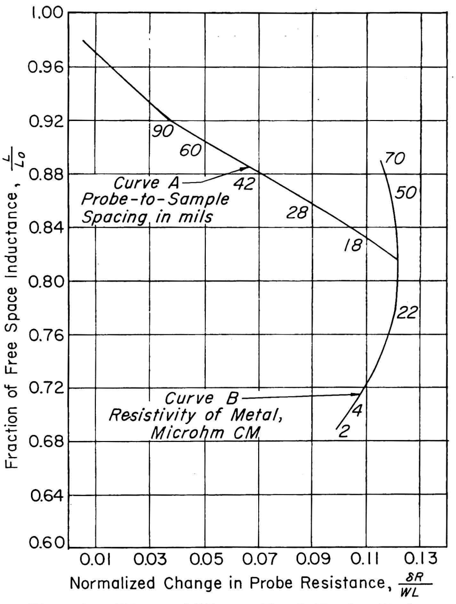

FIG. 1.—Plots of Normalized Probe Inductance *versus* Normalized Change in Probe Resistance. In curve A, distance is varied, while in curve B, resistivity is varied.

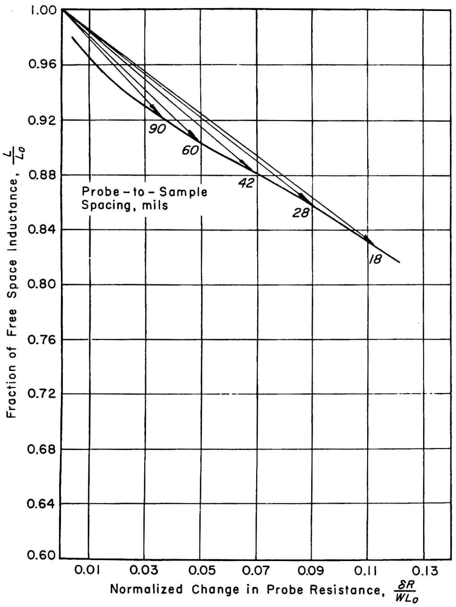

FIG. 2.—Diagram Showing How the Phasor $\left(1-\frac{L}{L_o}\right)+j\frac{\delta R}{\omega L_o}$ Varies with Probe-to-Metal Spacing.

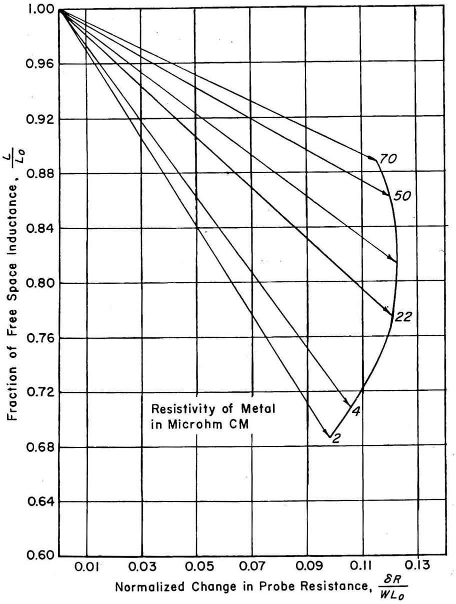

FIG. 3.—Diagram Showing How the Phasor $\left(1-\frac{L}{L_o}\right)+j\frac{\delta R}{\omega L_o}$ Varies with Sample Resistivity.

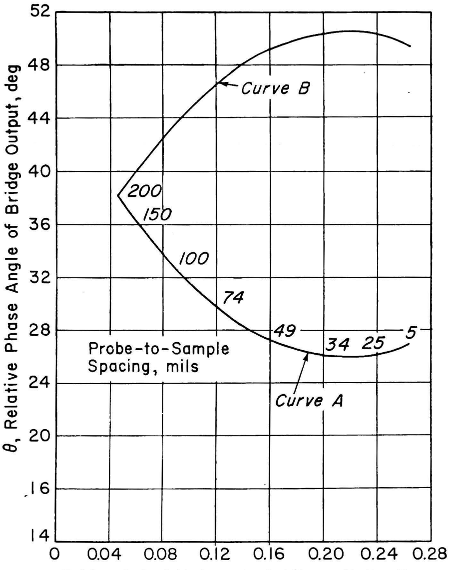

FIG. 4.—θ, The Phase Angle of the Bridge Output Voltage, Compared to the Input Voltage Plotted *versus* the Bridge Output Voltage, E_1. The sample used to obtain curves was composed of a 10-mil thick piece of brass shim on zirconium. Curve B represents the way the phase angle of the amplification characteristics of the compensator should change with varying bridge output voltage for perfect compensation.

disturb the balance of the bridge and cause a sinusoidal voltage to appear at the detector terminals. In the system presented here, an Owen bridge was used and balanced with the probe far away from any sample (the reason for which will be shown presently). As is seen in the Appendix, the impedance looking into the bridge output terminals can be given by:

$$Z = \frac{K}{\left(1 - \frac{L}{L_o}\right) + j\,\frac{\delta R}{\omega L_o}}$$

assuming that the bridge is balanced with the probe at a great distance from a metal and then brought close to it. The quantity K is nearly constant for small changes in the inductance and resistance of the probe. The phase angle of the quantity in the denominator of the expression for Z may be represented by the set of phasors shown in Fig. 2, where probe-to-sample spacing is varied. This phase angle also varies when changes in the other test variables, such as sample conductivity, are made. This is shown in Fig. 3. In Fig. 2, note how the phase angle change is relatively small over a considerable range of probe-to-sample spacings. This is the reason for balancing the bridge with the probe far away from any sample, and is an advantage inherent in this system.

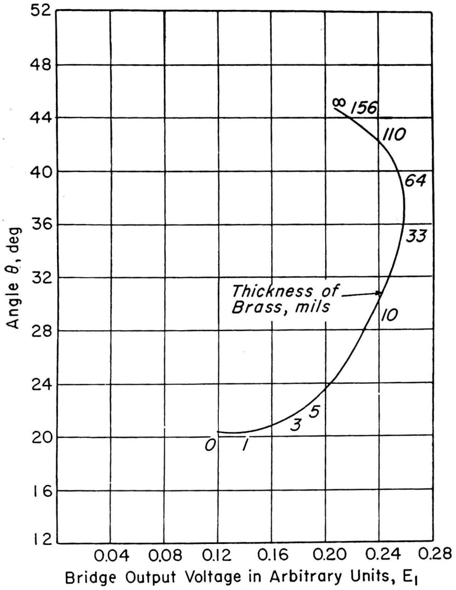

FIG. 5.—Curve Showing the Variation of θ with E_1 for Samples Using Different Thicknesses of Brass Shims on Zirconium. The probe-to-metal spacing was maintained constant.

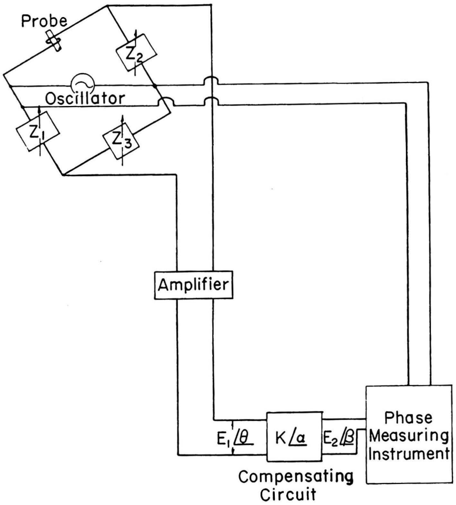

FIG. 6.—Block Diagram of the System.

In Fig. 4, curve A, is plotted the phase angle, θ, of the bridge output voltage relative to the driving oscillator voltage *versus* the relative magnitude of the voltage developed across the bridge output terminals, E_1. In Fig. 4, curve A, a composite sample was formed by laying a 10-mil thick piece of brass shim stock on a thick piece of zirconium and clamping the two together. This type of sample is impractical but illustrative. To obtain curve A, the probe-to-sample spacing was varied. In Fig. 5, the probe-to-composite sample spacing is maintained constant, while the thickness of the brass shim on the zirconium is varied.

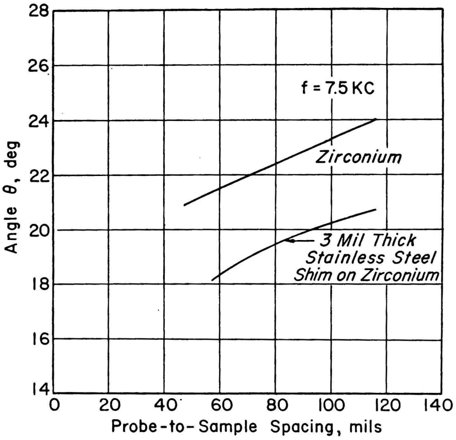

FIG. 7.—θ Plotted *versus* Varying Probe-to-Sample Spacings. Thick zirconium alone was used in the upper curve, while a 3-mil thick piece of stainless steel shim was used on the zirconium to obtain the lower curve.

COMPENSATING NETWORK

Consider a network such as the one shown in Fig. 6 with an amplification characteristic:

$$K/\alpha = \frac{E_2/\beta}{E_1/\theta}$$

Note $\beta = \alpha + \theta$. The system of minimizing the effect of varying probe-to-sample spacing presented in this paper requires a network in which α varies in such a way with changes in probe-to-sample spacing that the effect is to maintain β constant. Figure 4, curve *A*, gives a typical relationship that may exist between θ and E_1 as the probe-to-sample spacing is varied. What is done is to use E_1 to control the α of the

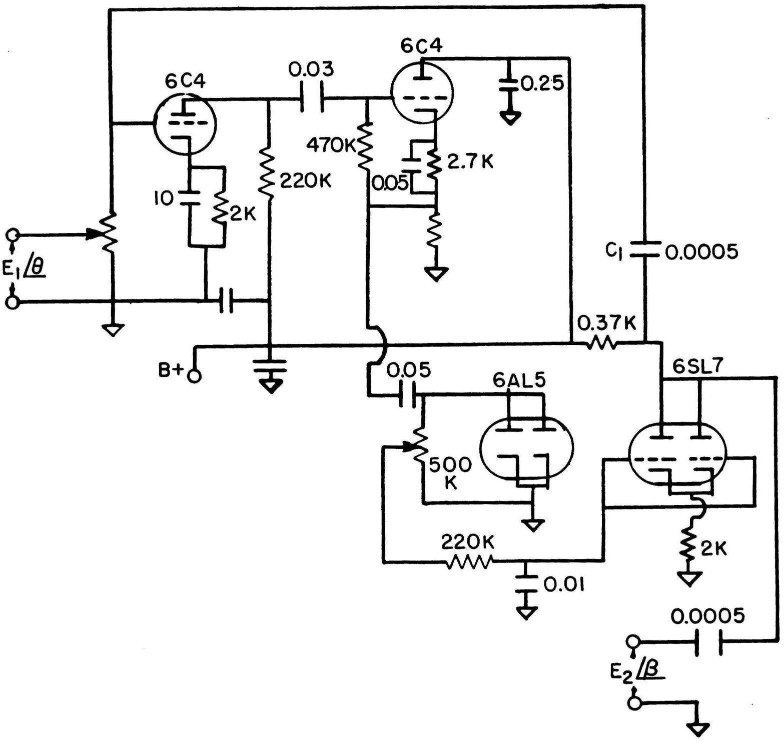

FIG. 8.—Simple Compensating Circuit.

network so as to maintain the sum of α and θ constant. The angle β then carries the test results, but they are not dependent on probe-to-sample spacing changes. If α for this compensating network is plotted *versus* E_1, it will appear as curve B in Fig. 4. Note that the sum of curves A and B produces a straight line.

A compensating network such as the one mentioned will eliminate one of the effects of varying probe-to-sample spacing. Another effect to be considered involves the question of whether an irregularity that should be detected in a sample produces the same output from the test instrument at one probe-to-sample spacing as at another. In other words, will the sensitivity of the instrument change at different probe-to-sample spacings? An illustration will make this problem clearer. Suppose, in the case presented in Fig. 4, the normal probe-to-sample spacing is 50 mils and the normal thickness of brass on zirconium is 10 mils. If the thickness of brass changes to 13 mils, a change in β of perhaps 1 electrical deg might result. But if for some reason the probe-to-sample spacing is not 50 mils but rather 40 mils, will β still change 1 deg? It has been found that it will over a useful range of probe-to-sample spacings in this and many other situations. An example is given in Fig. 7. Note how the change in β stays nearly constant when a 3-mil thick shim of stainless steel is placed upon a thick piece of zirconium while probe-to-sample spacing is varied from 60 to 100 mils.

Still another effect which should be considered is in a sense opposite to the one just discussed. Taking the same example, suppose the 3-mil change in the thickness of the brass has just occurred, giving a total of 13 mils of brass. The compensating circuit has been set to compensate for the effect of probe-to-sample spacing using the zirconium and 10-mil thick brass shim as a sample. Will the compensating circuit still compensate properly with the sample now composed of zirconium and the 13-mil brass shim? It will as long as the change in the characteristics of the metal sample is not too great.

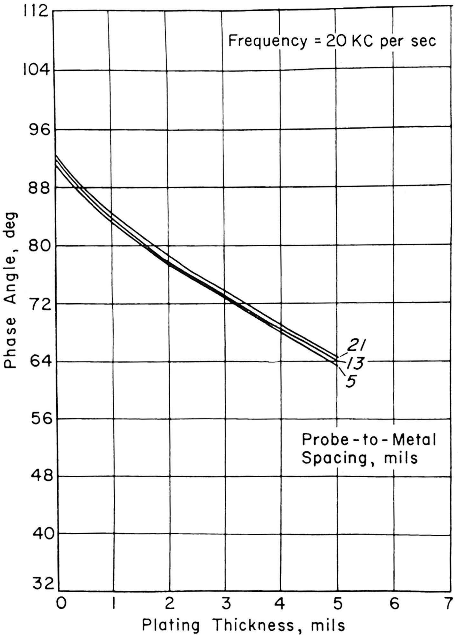

FIG. 9.—Phase Angle of the Output Compensator Plotted *versus* Plating Thickness for Copper Plate on Stainless Steel.

In the example just cited, compensation would still be satisfactory for 13 mils of brass on zirconium, but probably not for 23 mils of brass. A curve similar to curve A in Fig. 4 could be drawn for 13 mils of brass on zirconium, and it would run nearly parallel to curve A.

A block diagram of the system is shown in Fig. 6. A simple compensating circuit is shown in Fig. 8. The plate resistance of the 6SL7 in connection with C_1 provides the actual phase shift.

The input voltage (E_1) is rectified and applied to the grids of the 6SL7. The plate resistance of the 6SL7 changes as the input voltage changes, thus changing the phase of the input voltage relative to the output voltage, α. More elaborate circuits may be needed, depending on the test situation. Two other possible schemes involve the controlling of the amount of feedback current flowing in an amplifier feedback loop, thus changing the over-all amplification characteristic of the amplifier, or varying the saturation in the case of a saturable reactor and thus change its inductance to provide a phase shift which varies with the saturating current.

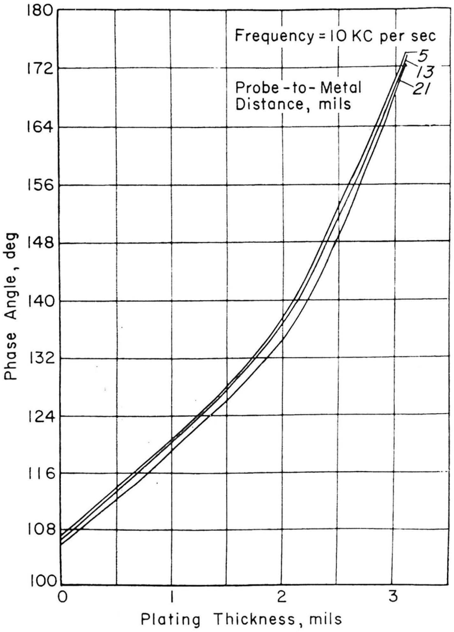

FIG. 10.—Phase Angle of the Output Compensator Plotted *versus* Plating Thickness for Nickel Plate on Uranium.

Figures 9 and 10 give examples of the use of this system in measuring plating thickness. These examples are illustrative, but probably not too practical. Figure 9 shows a plot of the phase angle of the output from the compensator plotted *versus* plating thickness. Using curves like these, the output from the phase meter could be continuously recorded, thus furnishing a permanent record of the plating thickness of the material. The separate curves of Fig. 9 were obtained at three different probe-to-metal spacings of 5, 13, and 21 mils, respectively. This illustrates the use of the compensator in keeping the measurements nearly independent of probe-to-metal spacing. Many commercial phase-measuring instruments have relative accuracies of 1 deg at 20 kc per sec, and some are much better than that. Assuming the 1-deg figure, the accuracy of measurement in Fig. 9 is about 0.25 mil. Generally, the amount of care necessary in the design of the compensating circuit depends on the accuracy of the phase-measuring instrument available. Figure 10 shows the measurement of nickel plating on uranium. Nickel is slightly ferromagnetic; this makes measurement of the plating thickness much easier. Again three separate curves are given for the 5, 13, and 21 probe-to-metal spacings. Probe-to-metal spacing of up to 200 mils is possible, but with some loss in sensitivity. In the case of the nickel-plated uranium, a phase-measuring instrument with a relative accuracy of 1 deg should give a sensitivity of at least 0.1 mil.

Because of the lack of a sufficiently accurate theoretical analysis of the problem, the optimum frequency to be used in measurements in a particular situation must be found by experiment. This involves very little trouble in the system described here because of the ease with which the frequency is varied. Choice of frequency is usually not too critical; usually there is a relatively wide band of frequencies which give about the same sensitivity.

CONCLUSION

The main advantage of this system is that it is adaptable to continuous or assembly line processes since the probe is maintained a significant distance away from the sample and the effects of distance variations are largely canceled out. Its operation could easily be made almost completely automatic. It is also relatively simple and very stable. A disadvantage lies in the fact that phase angle measuring instruments are expensive. They operate by measuring precisely very small time intervals. As yet, there are few commercial instruments capable of measuring time intervals of less than 1 microsecond accurately, so this imposes a limitation on the sensitivity of the system.

APPENDIX

BRIDGE ANALYSIS

The current i flowing through Z_5 in a bridge such as the one in Fig. 11 is given (5) by:

$$i = \frac{Z_1Z_3 - Z_2Z_4}{\Delta}\cdot e \tag{1}$$

where:

$$\Delta = \begin{vmatrix} -Z_3 & -(Z_3 + Z_4) & Z_3 + Z_4 + Z_6 \\ Z_2 + Z_3 + Z_5 & Z_2 + Z_3 & -Z_3 \\ -Z_5 & Z_1 + Z_4 & -Z_4 \end{vmatrix}$$

$$\frac{e}{i} = \frac{\Delta}{Z_1Z_3 - Z_2Z_4} \tag{2}$$

For the Owen bridge,

$$Z_1 = R + R_2 + j\omega L_0$$

where:

$R + j\omega L_o$ = probe impedance

$$Z_2 = R_3 - \frac{j}{\omega C_1}$$

$$Z_3 = \frac{-j}{\omega C_2}$$

$$Z_4 = R_1$$

ω = angular frequency of source

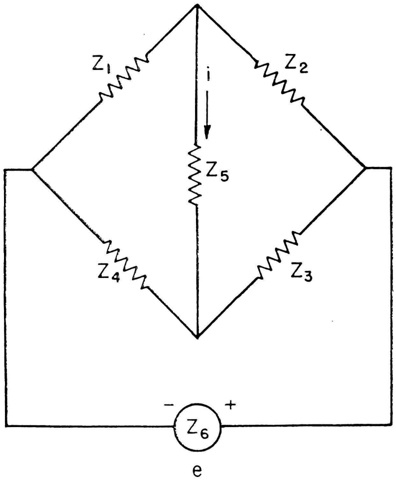

FIG. 11.—Bridge Circuit.

When the above substitutions are made in Eq 2, the result is:

$$\frac{e}{i} = \frac{\Delta}{(R + j\omega L_o + R_2)\left(\frac{-j}{\omega C_2}\right) - \left(R_3 - \frac{j}{\omega C_1}\right)R_1} \qquad \text{(3)}$$

For balance,

$$R = \frac{R_1 C_2}{C_1} - R_2$$

$$L_o = C_2 R_3 R_1$$

or:

$$R_3 = \frac{L_o}{R_1 C_2}$$

Suppose balance has been attained and a metal sample is brought near the probe. R_2 was zero:

$$\frac{e}{i} = \frac{\Delta}{[R + \delta R + j\omega(L_o - \delta L)] - \left[\left(\frac{-j}{\omega C_2}\right)\right] - \left(\frac{L_o}{C_2 R_1} - \frac{j}{\omega C_1}\right) R_1} \qquad \text{(4)}$$

δR and δL are always positive. Since Δ stays nearly constant for small changes in R and L, then:

$$\frac{e}{i} = \frac{\Delta}{-\left(\frac{\delta L}{C_2} + \frac{j\delta R}{\omega C_2}\right)} \qquad \text{(5)}$$

$$= \frac{\omega C_2}{\omega \delta L + \delta R}$$

Since $L = L_o - L$, where L_o is the inductance of the probe in air and L is the inductance of the probe with the sample in proximity, then:

$$\frac{e}{i} = \frac{\frac{-C_2}{L_o}\Delta}{\left(1 - \frac{L}{L_0}\right) + \frac{j\delta R}{\omega L_0}} = \frac{-C_2\Delta}{(L_0 - L) + j\delta R}$$

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(2) H. L. Libby, "Basic Principles and Techniques of Eddy Current Testing," *Non-Destructive Testing*, Vol. XIV, No. 6, p. 12, Nov.–Dec., 1956.

(3) W. A. Yates and J. L. Queen, "Sheet and Plated-Metal Measurements with a Phase-Angle-Type Probe," *Transactions*, Am. Inst. Electrical Engrs., Vol. 73, Part I, p. 138 (1954).

(4) D. L. Waidelich and C. J. Renken, "The Impedance of a Coil Near a Conductor," to be published in *Proceedings*, National Electronics Conference, p. 188 (1956).

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DISCUSSION

Mr. E. J. Hander.[1]—It was mentioned that in order to obtain accurate reaction on eddy current apparatus that it must be calibrated on a test specimen which has a chemical analysis, heat treatment, and cold-rolled properties, plus conductivity, similar to that of the material to be examined. The question is:

1. What about the effect of permeability of material to be tested; does it affect reaction of instrument? If so, what compensating arrangement in the instrument is necessary?
2. What factors, in order of their importance, influence depth penetration in materials?

Mr. Roy A. Nance.[2]—When I stated that the material used as reference standards for instrument calibration must have the same chemical composition, conductivity, and mechanical and thermal histories, I did not mention permeability since all the materials examined in this study had a permeability of about 1. The permeability characteristics of the reference standard and the inspected item should also be identical. However, in some cases involving the inspection of permeable materials special techniques can be used to compensate for permeability differences.

In reply to the question as to what factors influence the depth of penetration in materials:

The effective depth of penetration is a complex function involving the product of frequency, conductivity, and permeability. A unit variation in any one of these will produce approximately the same change in depth of penetration.

An increase in the permeability of an item will decrease the depth of penetration of the eddy currents.

Mr. C. J. Renken, Jr. (*author*).—I do not have a lot to add to what Mr. Nance said.

This question—what about the effect of permeability of the material to be tested? Does it affect the reaction of the instrument? Naturally it does, to a very great extent. If so, what compensating arrangements in an instrument are necessary?

I do not exactly understand this. What is the object in the test? Why do you want to compensate out the fact of permeability? Is it not the same in all the test specimens? Does it vary?

Mr. Hander.—Yes, it could. That was what prompted my question—to find out what relationship there was between permeability, conductivity, and frequency.

Mr. Renken.—These are all independent variables, and they all appear as a product of three, in the so-called standard depth of penetration—a formula which is, incidentally, based on the plain wave case. It was originally derived by assuming a plain wave impinging on the metal.

It is only, as I think was brought out earlier, an approximation.

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[1] Division Supervisor, Asiatic Petroleum Corp., New York, N. Y.

[2] Engineer, Oak Ridge National Laboratory, Oak Ridge, Tenn.

If varying permeability affects your test, it could perhaps be compensated for in some way. Are you thinking of stainless steel?

MR. HANDER.—Yes, or something magnetic.

MR. RENKEN.—I think that normally you would find that there is, as far as the eddy current results are concerned, greater effect due to the spread in the permeability of the stainless steel than there would be due to the spread in the conductivity.

Certainly in the case of a rolled nickel sheet, the conductivity may be practically the same throughout. One can make eddy current measurements on the sheet and easily determine the roll pattern on the nickel sheet due to changes in the permeability from point to point.

MR. HANDER.—I take it, then, that you have not actually examined any specimens which have emitted the characteristic?

MR. RENKEN.—Yes, we have.

MR. HANDER.—What were the reactions in those cases regarding the permeability with respect to conductivity, and so on, and the reaction of your eddy current apparatus?

MR. RENKEN.—I should say that in the problem of testing nickel plate, the fact that it is nickel and that it does have appreciably greater than unit permeability makes it much easier to measure nickel plate on some other material than if it had a relative permeability of 1, and one had to use the conductivity differences. It can certainly help in some cases.

On the other hand, in the case of nickel plate on some other metal as the base material, the nickel would provide very good shielding for whatever occurred below it.

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REDUCTION OF PROBE-SPACING EFFECT IN PULSED EDDY CURRENT TESTING

By Donald L. Waidelich[1]

Synopsis

In using pulsed eddy currents to determine the thickness of cladding, it was found that the output wave as observed on the screen of a cathode-ray oscilloscope had several unusual points. These points were stationary as the probe-to-metal spacing varied, but moved vertically as the cladding thickness changed. Tests on a clad plate seemed to indicate that the points could be used to determine cladding thickness with little interference from changes in the probe-to-metal spacing. One such method involves the use of small photocells placed in front of the oscilloscope screen with the output of the photocells connected to a recorder. The initial tests with such a system are presented in this paper.

Measurement of the cladding thickness of one non-ferrous metal on another non-ferrous metal has been done using pulsed eddy currents (**1–3**).[2] The method described in the papers cited involved manually varying the distance between the test probe and the metal sample to be measured until the slope of the oscilloscope trace was a fixed value whereupon the thickness of the cladding could be read from the point at which the oscilloscope trace crossed the zero axis. This is a rather tedious and time-consuming operation, and investigations were made to determine how to reduce the time necessary for a measurement. Results of the investigation of a possible improved method are given and in addition, since it is helpful to record the cladding thickness, some of the development in this phase of the program is also presented.

Crossing Points

The block diagram of the system used is shown in Fig. 1. The pulse circuit produces a pulse which drives both the standard and the test probes through a transformer and bridge circuit. The difference voltage of both probes is passed through an amplifier to the oscilloscope where the voltage may be observed.

It was found experimentally that there were one or more points on the difference voltage curve which were not affected by the probe-to-metal spacing. Such curves are shown in Fig. 2, in which the points called "crossing points" are plainly visible. These curves were made for a series of probe-to-metal

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[1] Argonne National Laboratory, Lemont, Ill.

[2] The boldface numbers in parentheses refer to the list of references appended to this paper, see p. 198.

spacings, and at least three of the crossing points are shown. The curves indicate that at the crossing points the effect of changing the probe-to-metal spacing is to change the slope of the curves but the height of the crossing points above the axis remain unchanged.

An approximate analysis of the probe has been made to determine where the crossing points should occur and this analysis is presented in the Appendix. The probe is assumed to have the approximate equivalent circuit shown in Fig. 3. Use is made of the fact that in sinusoidal steady state tests on the probes (4), as the probe-to-metal spacing is decreased, the inductance of the probe decreases while the resistance of the probe increases in a proportional manner. The result of the analysis is shown as the intersections *A*, *B*, *C*, . . . of the curve of Fig. 4 which indicate the times from the start of the pulse at which the crossing points should occur. These calculated values appear to agree quite well with the observed values as shown in Fig. 2. Damping of the output pulse is visible in Fig. 2 and this permits only the first three points *A*, *B*, and *C* to be observed. The analysis also shows that the slope of the waves of Fig. 2 at the crossing points varies with the probe-to-metal spacing while the vertical height of the crossing points above a zero line should vary with the composition or type of metal used. Hence the thickness of one metal clad on another should be measurable by determining the variation of the height of a crossing point above

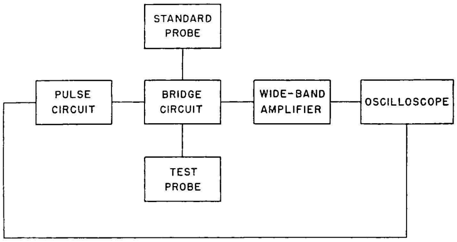

FIG. 1.—Block Diagram of Pulsed Eddy Current System.

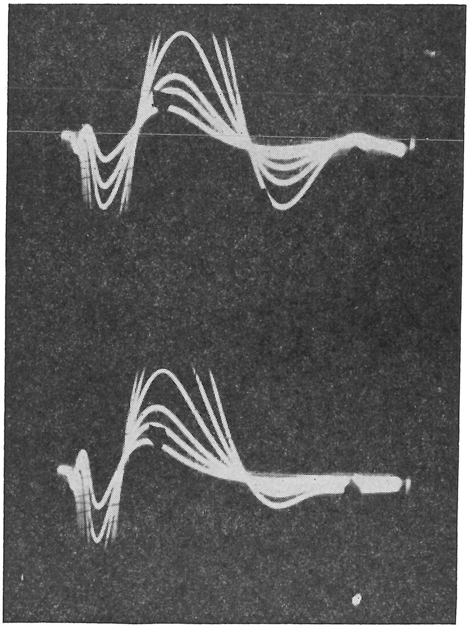

FIG. 2.—Pulse Response Showing the Crossing Points.

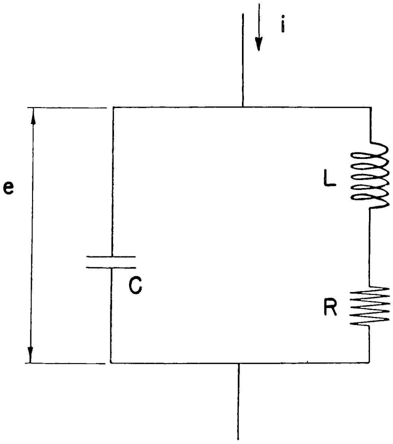

FIG. 3.—Equivalent Circuit of the Probe.

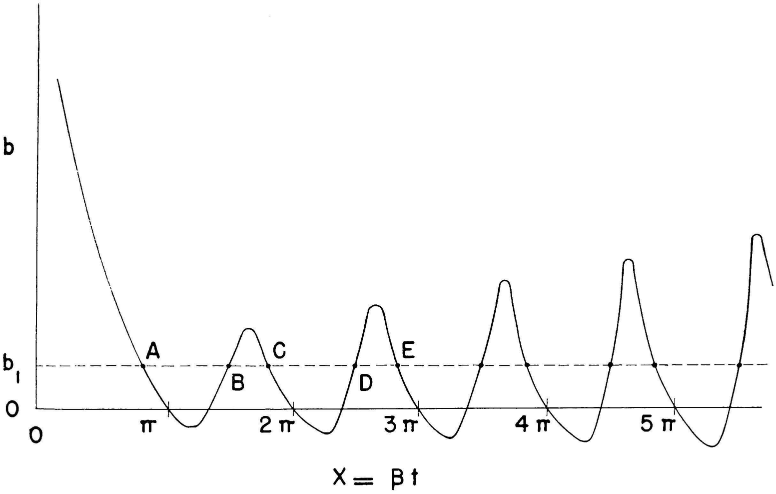

FIG. 4.—Results of the Analysis Showing the Crossing Points A, B, C, ... $x = \beta t$.

a zero line. The analysis also indicates that if too large a variation in probe-to-metal spacing is permitted, the result will be a slight horizontal shift of the crossing points along the time axis. This horizontal shift has been observed experimentally.

To test the above conclusions experimentally, metal plates having the same clad metal and the same base metal but with different depths of cladding were obtained and tested. The results are shown in Fig. 5 in which the thinnest cladding is shown in the middle wave while the top wave has cladding approximately twice as thick and the bottom wave four times as thick. The variation of the vertical height of the crossing points with the cladding thickness is easily discernible in Fig. 5. The variation of probe spacing used in Fig. 5 was about five to one with the largest spacings producing the steepest slopes at the crossing point. Variation of the gain and phase shift with frequency or limiting occurring in the wide-band amplifier produced crossing points which shifted both horizontally and vertically with

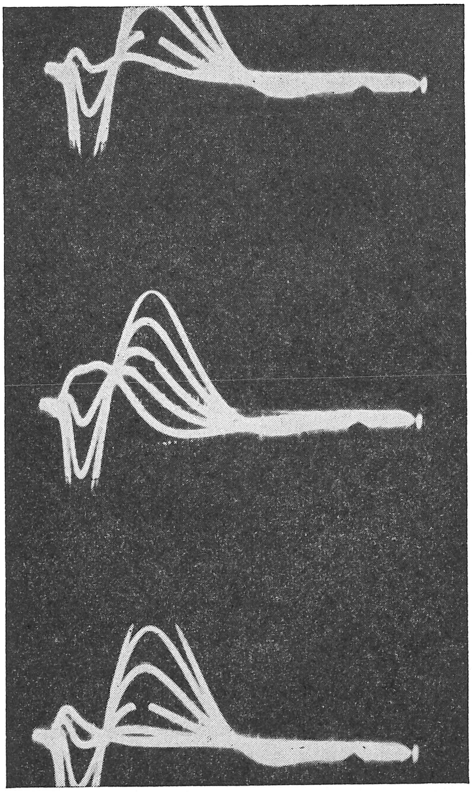

FIG. 5.—Variation of the Crossing Points with Cladding Thickness.

variation of the probe constants. Hence these effects should be kept to a minimum. Changing the clad or base metals would usually move the crossing points vertically. If the change were severe, the balance of the bridge circuit might have to be readjusted.

It was found that the crossing points could be moved vertically by varying the amount of unbalance in the bridge circuit. This has the advantage in that the middle of the range of cladding thicknesses to be measured could be located approximately on the zero line of the oscilloscope trace. It was also found that the slope of the trace could be varied most easily by varying the air gap in the probes. This adjustment had the advantage that the oscilloscope trace could be made horizontal for the middle of the range of probe-to-metal spacing to be used. With these two adjustments limiting in the wide-band amplifiers could be held to a minimum. The two adjustments are not entirely independent of one another, but it was found, for example, that the variation of slope caused by changing the probe air gap was much more than the vertical movement caused by the same adjustment. Since the crossing points can be moved vertically by varying the amount of unbalance in the bridge circuit, it might appear that a null-balance recording system might be used. Unfortunately the required information occurs during a part of the output pulse of about 10 to 20 millimicroseconds in length, and no commercially available null-balance recording system known to the author is able to operate under these conditions.

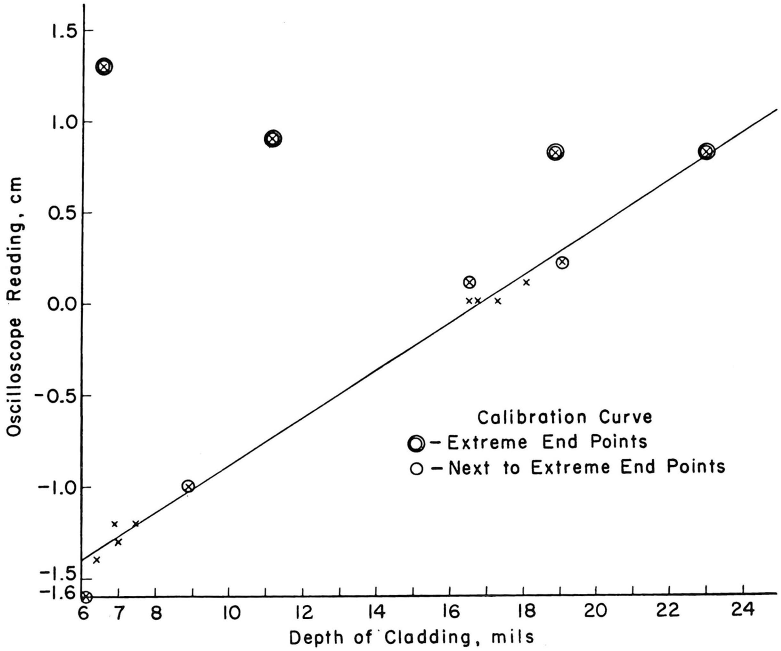

FIG. 6.—Calibration Curve for the System. The extreme end points indicated cannot be used.

EXPERIMENTAL MEASUREMENTS

The instrument was calibrated using plates with varying thicknesses of cladding. The resulting calibration curve relating the depth of cladding with the oscilloscope reading is shown in Fig. 6. The extreme end points of Fig. 6 are those for which the probe was very close to the edge of the plate. Another plate was measured on the oscilloscope and then sectioned and measured optically. Figure 7 shows the optical measurements as crosses and the oscilloscope measurements as circles. Agreement appears to be good. The line mentioned in Fig. 7 was a line drawn in the length direction of the clad plate. The line was located 100 mils from the edge of the metal, and the 100 mils was measured in the width direction.

Substantially thicker clads could be measured by this technique but longer pulse lengths might be necessary (1).

The information used in obtaining the above results is contained in a small part of the pulse, which part is about 10 to 20 millimicroseconds long. This information can be extracted by an operator observing the trace on the oscilloscope screen; this system was used in obtaining Figs. 6 and 7. The use of an observer limits severely the amount of information that can be recorded; therefore it was decided to try to make the system directly recording so that the speed of recording could be increased considerably. Two possible methods are: (1) the use of photocells placed on the oscilloscope screen to measure the height of the trace and transfer the information to a recorder, and (2) the construction of an electronic sampling circuit to isolate this part of the pulse and measure its height by an electronic voltmeter designed for pulse measurements. The second method would have the advantage of eliminating the oscilloscope.

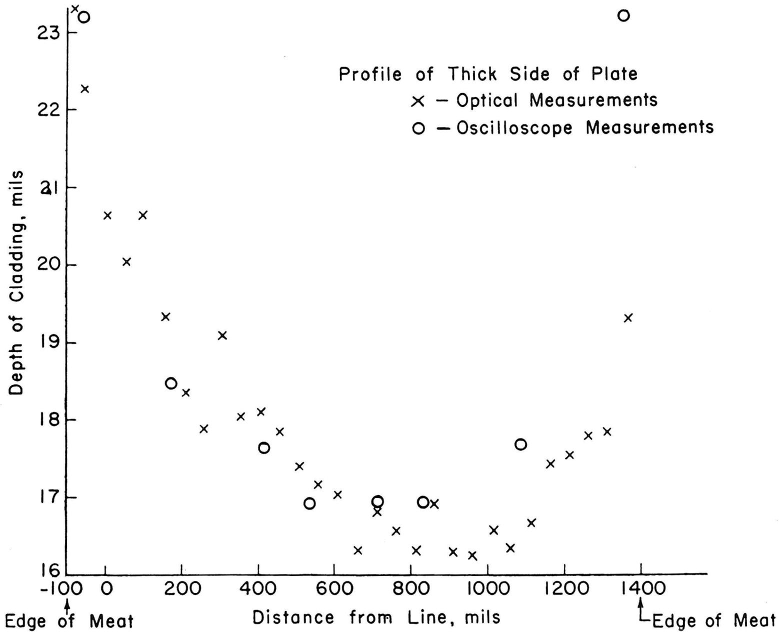

FIG. 7.—Optical and Oscillographic Measurements of an Actual Clad Plate. Profile is of the thick side of plate.

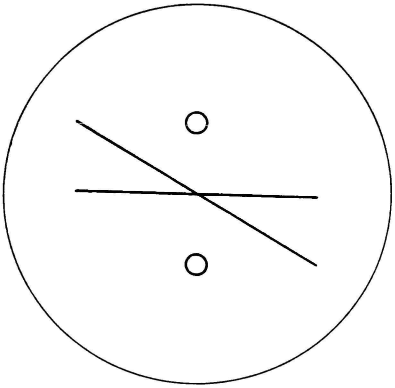

FIG. 8.—Arrangement of Photocells on the Oscilloscope Screen.

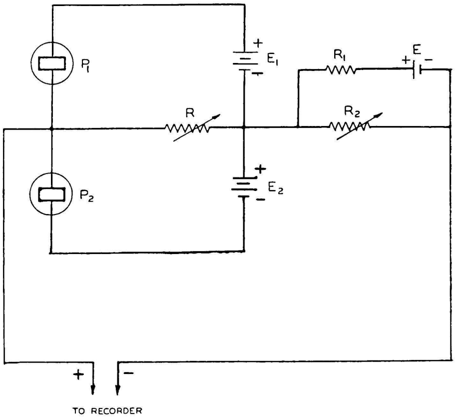

FIG. 9.—Photocell Circuit for Connection to Recorder.

PHOTOCELL ARRANGEMENT

A number of possibilities for the photocell method of recording the height of the crossing point were explored and the one that seemed most promising is described here. Two cadmium sulfide photocells were placed upon the plastic bezel of the oscilloscope with the positions indicated as small circles in Fig. 8. The sensitive surfaces of the cells were facing the screen of the oscilloscope tube and the crossing point of the oscilloscope trace was centered on the vertical straight line connecting the two cells. As the probe-to-metal spacing varied the slope of the oscilloscope trace changed as shown in Fig. 8, but the height of the crossing point did not change. Under these conditions the output of the photocells should not change; this appeared

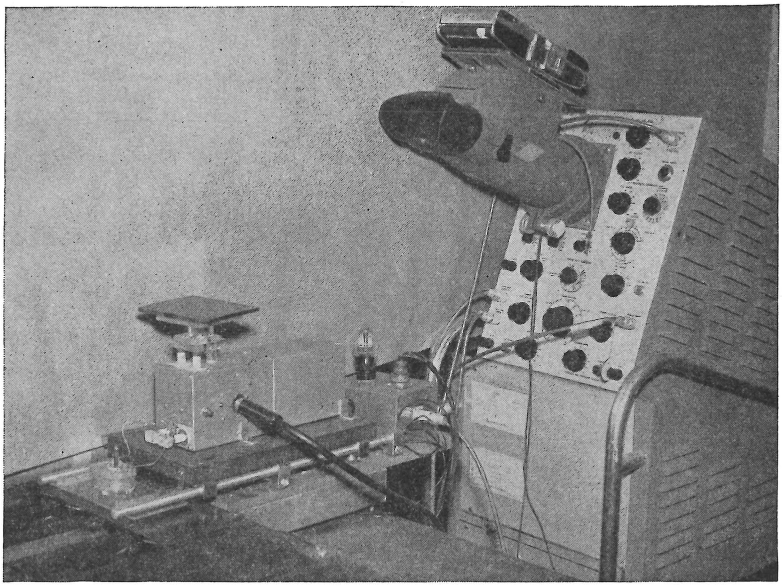

FIG. 10.—Photograph of the Probe Head.

to be true experimentally. When the thickness of the cladding is changed, the height of the crossing point changes and the output of the photocells should change with it. This was found to be true, and practically a linear relationship between the height of the crossing point and the photocell output held as long as the crossing point did not approach too closely to either of the photocells.

The differential circuit used for connecting the photocells to the recording microammeter is shown in Fig. 9. E_1 and E_2 are batteries energizing the respective photocells, P_1 and P_2. The difference current of the photocells flows through the recorder, while R is a variable resistor used to control the sensitivity of the recorder. The part of the circuit composed of the battery E, resistor R_1 and variable resistor R_2 was used to control the zero position of the recorder. While the vertical movement of the crossing point may be small, the amplification of the recording microammeter is sufficient so that full scale deflection of the recorder is obtained. Since the photocells used varied considerably in sensitivity, it was found that this effect could be overcome by making the battery voltages, E_1 and E_2, inversely proportional to the sensitivity of the respective photocells, P_1 and P_2.

An arrangement was made so that the clad plates to be tested could be moved at constant speed underneath the stationary probe, as shown in Fig. 10. To keep the probe-to-metal spacing variation down to a minimum and thus minimize also the slope variation on the oscilloscope screen, a plastic shoe was placed around the probe; this shoe rode on the plate at all times. One plate tested in this way had a recorder reading *versus* inches measured along the plate as shown in Fig. 11(*a*). An average straight line drawn through the points as shown had a negative slope of 2.78 recorder divisions per in. length of the plate. The plate was then sectioned and the thickness of cladding in mils was measured optically, with results as shown in Fig. 11(*b*). Again the average straight line had a positive slope of 0.863 mils of cladding thickness per in. length of plate. The combination of both slopes gave a negative value of 0.31 mils of cladding thickness per recorder division.

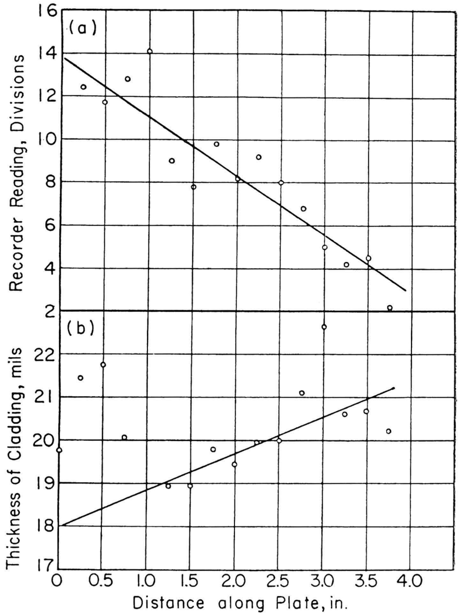

FIG. 11.—(*a*) Recorder Readings *versus* Distance Along Clad Plate; (*b*) Optical Cladding Thickness Readings *versus* Distance Along Plate.

In Fig. 11 there are two points where marked discrepancies occur, one at about 0.5 in. and the other about 3 in. along the surface of the plate. Several reasons may be advanced for these discrepancies. In the cutting process the plate was accidentally mutilated around 0.5 in., and this meant that the errors in the optical measurements at that end were greatly increased. A second consideration is that the resolving power of the probe coil is probably of the order of the diameter of the coil which was $\frac{1}{2}$ in. The resolution of the optical system, on the other hand, was more on the order of 1 mil or better. This would indicate that a large variation of cladding thickness occurring in a small distance of about $\frac{1}{16}$ in. along the surface of the plate would be detected as a much smaller variation of cladding thickness by the probe coil. This may explain the divergence of points at the 3-in. position.

A third reason for the divergences is that the crossing point might have shifted horizontally. Analysis indicates that this might occur when the variation of the probe parameters becomes large, as would result if the cladding thickness or the probe-to-metal spacing changed considerably. It is believed also that if the surface of the metal is not parallel to the surface of the probe, a particularly large change of this nature will result.

To overcome to some extent the effects of the lesser resolution of the probe coils, smaller coils might be tried although this would probably decrease the sensitivity and increase the horizontal shift of the crossing point. Several methods have been suggested to overcome the effect of the shifting crossing point:

1. In an analysis made of the probe it is indicated that it might be possible to decrease the horizontal shift by making the second and higher derivatives zero or small.
2. The probe might be driven toward or away from the metal to counteract the change of slope as seen on the oscilloscope screen. This might be done by the use of additional photocells on the screen or perhaps by the use of the pulse wave which is reflected from the surface of the metal and which is balanced out by the bridge circuit.
3. The development of a photocell system that is not nearly so sensitive to the horizontal shift of the crossing point. This would have more of the effect of integrating over the region around the crossing point.
4. An electronic pulse sampling circuit which was mentioned previously would also have the effect of integrating over the region around the crossing point and thus should minimize the effect of the shift of the crossing point.

CONCLUSIONS

Some research work done on the spacing problem of the pulsed eddy current method of measuring cladding thicknesses has been presented, and some of the paths for future developmental work have been suggested. It is to be hoped that further work will lead to a probe that will eliminate the necessity of touching the material to be tested.

Acknowledgments:

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APPENDIX

POSITION OF CROSSING POINTS

The probe is assumed to have the approximate equivalent circuit of Fig. 3 where e is the voltage across the probe and i the current through the circuit. The circuit constants are assumed to be C for the shunting capacitance, R for the series resistance, and L for the inductance. Assume also that the input current pulse i is an impulse of area Q coulombs. The Laplace transform of the current is

$$\mathcal{L}(i) = Q \tag{1}$$

The voltage transform is:

$$\mathcal{L}(e) = \mathcal{L}(i) \frac{(R + pL)\left(\frac{1}{pC}\right)}{R + pL + \left(\frac{1}{pC}\right)}$$

$$= \frac{Q}{C} \frac{p + 2\alpha}{(p + \alpha)^2 + \beta^2} \tag{2}$$

where:

$$\alpha = \frac{R}{2L}$$

$$\beta = \sqrt{\left(\frac{1}{LC}\right) - \alpha^2}$$

Then:

$$e = \frac{Q}{C} \epsilon^{-\alpha t} \left(\frac{\alpha}{\beta} \sin \beta t + \cos \beta t\right) \tag{3}$$

The effect of decreasing the probe-to-metal spacing is to decrease the inductance L of the probe and increase the resistance R of the probe (4). Let it be assumed that the decrease in L for a given small change in spacing is λ and that the corresponding increase in R is $K\lambda$ where K is a constant. The problem is to show that there are points whose amplitude remains essentially constant as λ changes. Thus the values of the time t at which $\frac{de}{d\lambda} = 0$ should be found.

$$\frac{de}{d\lambda} = \frac{\partial e}{\partial \alpha}\frac{\partial \alpha}{\partial \lambda} + \frac{\partial e}{\partial \beta}\frac{\partial \beta}{\partial \lambda} = 0 \tag{4}$$

From Eq 3:

$$\frac{\partial e}{\partial \alpha} = \frac{Q\epsilon^{-\alpha t}}{C\beta}\left[\sin \beta t - \beta t\left(\frac{\alpha}{\beta}\sin \beta t + \cos \beta t\right)\right] \tag{5}$$

$$\frac{\partial e}{\partial \beta} = \frac{Q}{C\beta}\epsilon^{-\alpha t}\left[-\beta t \sin \beta t + \frac{\alpha}{\beta}(\beta t \cos \beta t - \sin \beta t)\right]$$

Now:

$$\alpha = \frac{R}{2L} = \frac{R_0 + k\lambda}{2(L_0 - \lambda)}$$

$$\beta = \sqrt{\frac{1}{LC} - \alpha^2} = \sqrt{\frac{1}{(L_0 - \lambda)C} - \alpha^2} \tag{6}$$

where R_0 and L_0 are the resistance and inductance of the probe before the probe-to-metal spacing is changed slightly.

From Eq 6:

$$\frac{\partial \alpha}{\partial \lambda} = \frac{R_0 + KL_0}{2(L_0 - \lambda)^2}$$

$$\frac{\partial \beta}{\partial \lambda} = \frac{1}{2\beta(L_0 - \lambda)^2}\left[\frac{1}{C} - \alpha(R_0 + KL_0)\right] \tag{7}$$

From Eqs 4, 5, and 7:

$$(\sin \beta t - \beta t \cos \beta t) \left[\frac{R_0 + KL_0}{\beta(L_0 - \lambda)} - \frac{\alpha}{\beta}\right] - \beta t \sin \beta t = 0 \,..(8)$$

Let $x = \beta t$

and

$$b = \left[\frac{R_0 + K\,L_0}{\beta(L_0 - \lambda)} - \frac{\alpha}{\beta}\right]$$

Then Eq 8 becomes:

$$b = \frac{1}{\left(\frac{1}{x}\right) - \cot x} \,..........(9)$$

A sketch of b as a function of $x = \beta t$ is shown in Fig. 4. For a given value of b, say b_1, the intersection of the b_1 ordinate (dotted line) with the solid curve would be the solution of Eq 9. Such solutions are shown as points A, B, C, D, E, $\cdots$ of Fig. 4. The solutions corresponding to A, B, and C may be observed in Fig. 2. According to the solution A should be near $\beta t = (\pi/2)$ while B should be near $\beta t = (3\pi/2)$. This appears to be true in Fig. 2. In almost all cases b will be a positive number. Evidently there is too much damping to make points D, E, $\cdots$ appear in Fig. 2, although by suitable circuit changes it is possible to observe further crossing points.

From Eq 3 the time derivative e' of the voltage e is

$$e' = \frac{de}{dt} = \frac{Q}{\beta C^2(L_0 - \lambda)} \epsilon^{-\alpha t} \sin \beta t. \ldots (10)$$

For a given value of $x = \beta t$ as determined from Eq 9, the value of e' from Eq 10 will be found to be a function of λ which indicates that the slope of the oscillograph traces will vary with the change in spacing between the probe and the metal. The change in slope as indicated by Eq 10 is small but after the balancing operation in the bridge and the subsequent amplification the change in slope becomes substantial. The variation in slope with the probe-to-metal spacing is shown in Fig. 2.

If now the constants of the probe are changed in some other manner than that dictated by the variation in probe-to-metal spacing, the amplitude of the crossing points will change and this change can be observed. This type of change might be caused by a variation in the constants of the metal or by a change in the thickness layer of one metal clad on another metal. Hence a vertical change in the crossing point could be used as a measure of cladding thickness.

It should be noted, however, that in Eq 4 only the first derivative of the voltage e with respect to λ was made zero. The higher derivatives and in particular, the second derivative, are not zero. Thus if too large a change in the probe constants is attempted, the first derivative will deviate from zero and the crossing point will shift along the time axis. This shift has been observed experimentally and indicates that the probe-to-metal spacing variation must be kept below a certain maximum value or the horizontal shift of the crossing point will be too large for the recording system used. One possible method to reduce this horizontal shift would be to make the second derivative and some of the other higher derivatives zero. This last method of reduction has not, to the author's knowledge, been tried.

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