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ARGONNE NATIONAL LABORATORY
P.O. Box 299
Lemont, Illinois

A DOUBLE PULSE EDDY CURRENT TESTING SYSTEM

by

C. J. Renken and R. G. Myers

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A DOUBLE PULSE EDDY CURRENT TESTING SYSTEM

C. J. Renken and R. G. Myers

I. INTRODUCTION

The system described in this report is an outgrowth of a number of eddy current systems developed at Argonne National Laboratory and described in an earlier publication.¹ The Double Pulse System possesses enough significant advantages over the systems previously described to justify the issuance of the information in a separate report. Two voltage pulses of different time duration replace the two sinusoidal voltages used in earlier systems. The longer duration pulse replaces the low frequency channel of the two frequency systems. The shorter pulse replaces the high frequency channel of the older systems. The short duration pulse produces information about probe-to-specimen spacing which is independent of metal conductivity. This makes it possible to use the system for a much wider variety of test situations than the two frequency system described in ANL-5861. It is no longer limited to the measurement of cladding or plating, or the detection of only those irregularities in a metal which lie below the depth of appreciable penetration of the higher frequency eddy currents. As long as the total metal thickness is over a few mils and the size of the specimen is large enough so that end effects are not important, the short pulse channel produces the same signal at a given spacing for all metals with resistivity in the range of 1.63 to 150 μ ohm-cm.

II. THE COAXIAL PROBE

The bridges which have been a feature of the other pulse and sinusoidal systems described in ANL-5861 have been eliminated. An entirely different probe design is used. These so called coaxial probes are constructed with two separate loosely coupled windings which are concentric. A cross section of a typical probe is shown in Figure 1. Two voltage pulses of different duration are applied to the outer core, one several hundred microseconds after the other. The length of the longer pulse can be varied to achieve the depth of penetration desired in the test problem. The short pulse has a duration in the neighborhood of 1 to 2 microseconds. The current passing through the outer coil induces a voltage in the inner coil. When the probe is brought near a metal, the apparent inductance and resistance of both coils change.

¹"Status Report in Eddy Current Theory and Application," ANL-5861, Chapter VI, p. 37, November 1958.

However, it is easier to understand the operation of the coaxial probe by considering the mutual inductance between the outer and inner coil. Each pulse can be shown by analysis to be the vector sum of a large number of separate frequencies. Each type of pulse has its unique spectrum. The reason why the short pulse channel measures only probe-to-specimen spacing and the long pulse channel measures both conductivity and probe-to-specimen spacing is associated with the changing value of the mutual inductance with frequency. These effects are discussed in more detail in the Appendix.

III BLOCK DIAGRAM AND CIRCUITRY

A block diagram of the system is shown in Figure 2 and detailed circuit diagrams are shown in Figures 3 to 9. A master oscillator of frequency 35 kc is used to stabilize a multivibrator-differentiator combination which supplies pulses at 8.37 kc. These pulses in turn are used to stabilize another multivibrator-differentiator combination which provides pulses at 837 cps. These timing circuits were originally designed to provide the greatest possible freedom from frequency drift and time jitter. If the utmost in stability were not necessary, this whole section could be replaced by a single free running blocking oscillator.

The 837 cps pulses are used to trigger thyratrons. These thyratrons generate the long and short duration pulse. There is a delay of several hundred microseconds between generation of the long and short pulse.

The two voltage pulses developed across the inner coil of the probe are separated by filter circuits. After separation the voltage pulses are each transformed into a sawtooth voltage for ease of handling in later stages. A portion of the output from each pulse generator is also changed into a sawtooth voltage. This latter voltage is used to stabilize the corresponding sawtooth produced by the "separating circuits" for variations in thyatron anode voltage and other causes of instability. The short pulse sawtooth voltage is rectified and used to control the gain of a distance compensating stage just as in the dual frequency system.¹ The compensated long pulse voltage is rectified and is available for recording or metering.

The short pulse current waveform in the outer coil is shown in Figure 10. This is an actual photograph from an oscilloscope face. The short pulse voltage across the inner coil is shown in Figure 11. The first negative going portion of this waveform plays an important role in the system. The negative part of the current is rectified and produces the compensating voltage. The negative loop has exactly the same

magnitude when the probe is placed on brass or 304 stainless steel. However, the negative loop has a much greater amplitude when no metal is near the probe.

A photograph of the long pulse current waveform is shown in Figure 12. The thyatron ceases conduction about 15 microseconds after the current begins to flow. This causes the sudden damping of this waveform. The long pulse voltage waveforms produced across the inner coil of the probe are shown in Figure 13. The long pulse duration can be changed by varying the charging capacitor in the thyatron plate circuit.

IV. CONCLUSION

The eddy current system described here, using two pulses of different duration and a new probe design, appears to be more versatile than previous eddy current systems developed at Argonne National Laboratory. It is especially useful for the nondestructive measurements of metal electrical conductivity of oddly shaped specimens. These measurements can be made to within one per cent on an absolute basis.

The gain stability of this instrument after a thirty minute warm up is better than 0.01 per cent. The main source of drift is the variation of ambient temperature of the air surrounding the probe. Self heating of the probe is negligible.

APPENDIX

The object of this analysis was to determine the factors which gave the voltage and current pulse waveforms their characteristic shapes. It was especially desired to determine why the first negative loop of the short pulse inner coil voltage waveform was independent of metal conductivity. To do this, it was only necessary to examine the relative magnitudes of the waveforms, and no attempt was made to compute the actual voltage magnitudes.

The short pulse generator will be analyzed first. The simplified circuit used in this analysis is shown in Figure 14a. For time $t > 0$, the approximate circuit of Figure 14a was taken as shown in Figure 14b. The current through the outer coil is designated (i_p). Investigation showed that the resistance of the probe was small compared to (R_2), and could be neglected whether the probe was near a metal or not. In addition, changes in outer coil inductance caused the current waveform to change very little because of the choice of circuit parameters. What changes in the current waveform do occur can be shown to have no important effect on the final results of the analysis. They are neglected here for sake of simplicity.

Assuming that the switch is closed at $t = 0$, the LaPlace transform of the outer coil current for $t > 0$ is given by equation 1.

$$L(i_p) = \frac{-pR_1R_3E}{ap^4 + bp^3 + cp^2 + dp + e} \quad (1)$$

where

$$a = L_1L (R_1 + R_2 + R_3)$$

$$b = R_3L_1 (R_1 + R_2) + \frac{L_1L}{C_2} + R_1L (R_2 + R_3)$$

$$c = \frac{L}{C_1} (R_1 + R_2 + R_3) + \frac{L_1}{C_2} (R_1 + R_3) + R_1R_2R_3$$

$$d = \frac{R_3}{C_1} (R_1 + R_2) + \frac{L}{C_1C_2} + \frac{R_1R_3}{C_2}$$

$$e = \frac{R_3}{C_1C_2}$$

$$E = E_s - E_t$$

For Probe C-7, a typical probe, $L = 100$ uhy. Using this value and the other values given in Figure 14b,

$$L(i_p) = \frac{-7.18 \times 10^{10} E_p}{p^4 + 15.9 \times 10^6 p^3 + 69.4 \times 10^{12} p^2 + 354 \times 10^{18} p + 282 \times 10^{24}} \quad (2)$$

$$L(i_p) = \frac{K_p}{[(p + 1.25 \times 10^6)^2 + (4.76 \times 10^6)^2] (p + .933 \times 10^6)(p + 12.47 \times 10^6)} \quad (3)$$

For the purpose of this analysis, one is only interested in pulse shapes and relative magnitudes so $-7.18 \times 10^{10} E$ can be replaced by the arbitrary but fixed constant K .

The original of equation (3) is given by

$$\begin{aligned} \frac{i_p}{K_1} = & 1.78e^{-1.25 \times 10^6 t} \sin(4.76 \times 10^6 t - 12.1^\circ) - .354e^{-.933 \times 10^6 t} \\ & + .727e^{-12.47 \times 10^6 t} \end{aligned} \quad (4)$$

where (K_1) is another arbitrary but fixed constant. This function is graphed in Figure 15. The function graphed by the dashed waveform is the actual waveform photographed from an oscilloscope face. The peak positive values of the two curves were set equal.

The circuit associated with the inner coil of the probe is shown in the circuit diagram, Figure 7. The rectifiers make this circuit prohibitively complex to analyze as it stands, but simple experiments with the inner coil connected and disconnected from the rest of the circuit show that the simple circuit given by Figure 16 provides a very good approximation to the more complex actual circuit where

$$e_2 = -M_{12} \frac{di_p}{dt} \quad (5)$$

Since the inner coil current is very minute, and the coupling is loose, the effect of the inner coil current on the outer coil circuit was negligible. Then $[L(e_0)]$, the transform of the voltage appearing at the inner coil output terminals with the coil connected to its associated circuitry is given by

$$L(e_0) = \frac{\frac{M_{12}}{L_2 C} p L(i_p)}{p^2 + \left(\frac{R}{L_2} + \frac{1}{CR_4} \right) p + \frac{R + R_4}{L_2 CR_4}} \quad (6)$$

At this point the variation of (M_{12}) with frequency and metal conductivity should be examined since it is the key to the reason why the short pulse channel measures probe-to-metal spacing, but not metal conductivity. Measurements of the angle associated with (M_{12}) show that it is approximately 270° or 90° depending on how polarities are chosen, and it is independent of probe-to-metal spacing or of metal conductivity. Figure 17 shows that the magnitude of (M_{12}) is dependent on both metal conductivity and frequency. As the frequency increases, the value of (M_{12}) when the

probe is placed on brass and when the probe is on stainless steel approaches each other more closely. The fundamental frequency of the short pulse current flowing through the outer coil is in the neighborhood of 700 kc; so in this part of the analysis the value of (M_{12}) used in the computations for brass and the computations for 304 stainless steel is nearly the same, but different than in the case of the coil alone.

The resistance of the inner coil varies with frequency. An expression for the variation of coil resistance could have been used in the analysis, but since the resistance plays only a minor part in the final results, a compromise value was chosen for each particular case. Figure 18 gives a summary of the results of measurements of inner coil resistance of probe C-7 under various conditions.

Considering first the coil with no metal present, with $R = 20$, $L = 295$ uhy, $M_{12} = 53$ uhy.

$$\frac{L(e_0)}{K_2} = \frac{4.25 \times 10^9 p^2}{(p^2 + 2.5 \times 10^6 p + 24.3 \times 10^{12})(p^2 + 1.63 \times 10^6 p + 83.4 \times 10^{12})(p + .933 \times 10^6)(p + 12.47 \times 10^6)} \quad (7)$$

The original of which this is the image is given by:

$$\frac{e_0}{K_3} = 6.0e^{-1.25 \times 10^6 t} \sin(4.76 \times 10^6 t + 96.3^\circ) - 4.59e^{-.815 \times 10^6 t} \sin(9.14 \times 10^6 t + 69.3^\circ) + .167e^{-.933 \times 10^6 t} - 1.745e^{-12.47 \times 10^6 t} \quad (8)$$

This expression is plotted as the solid line in Figure 19. Next consider the probe placed on a piece of thick brass. In this case, $M_{12} = 25$ uhy, $L_2 = 250$ uhy, $R = 50$.

$$\frac{L(e_0)}{K_2} = \frac{2.49 \times 10^9 p^2}{(p^2 + 2.5 \times 10^6 p + 24.3 \times 10^{12})(p^2 + 1.76 p + 100.3 \times 10^{12})(p + .933 \times 10^6)(p + 12.47 \times 10^6)} \quad (9)$$

The original is:

$$\frac{e_0}{K_3} = 2.85e^{-1.25 \times 10^6 t} \sin(4.76 \times 10^6 t + 95.6^\circ) - 2.135e^{-.88 \times 10^6 t} \sin(10 \times 10^6 t + 67.6^\circ) + .082e^{-.933 \times 10^6 t} - .961e^{-12.47 \times 10^6 t} \quad (10)$$

This expression is plotted as the dashed line in Figure 19.

When the probe is placed on 304 stainless steel, $M_{12} = 26$ uhy, $L_2 = 260$ uhy, $R = 76$.

The image is:

$$\frac{L(e_0)}{K_2} = \frac{2.50 \times 10^9 p^2}{(p^2 + 2.5 \times 10^6 p + 24.3 \times 10^{12})(p^2 + 1.86 \times 10^6 p + 96.4 \times 10^{12})(p + .933 \times 10^6)(p + 12.47 \times 10^6)} \quad (11)$$

The original is:

$$\begin{aligned} \frac{e_0}{K_3} = & 3.02e^{-1.25 \times 10^6 t} \sin(4.76 \times 10^6 t + 94.9^\circ) - 2.3e^{-.93 \times 10^6 t} \sin(9.76 \times 10^6 t + 67.1^\circ) \\ & + .0865e^{-.933 \times 10^6 t} - e^{-12.47 \times 10^6 t} \end{aligned} \quad (12)$$

This expression is plotted as the dotted line in Figure 19. It can be seen that the waveforms for these cases behave like the actual waveforms shown in Figure 11. The first large negative loop is independent of metal conductivity, but dependent on probe-to-metal spacing. The results of this analysis show that it is the action of (M_{12}) which is largely responsible for this effect.

The analysis of the long pulse generator is somewhat simpler. The simplified circuit is given in Figure 20a, while the equivalent circuit is shown in Figure 20b. From this circuit

$$L(i_p) = \frac{-ER_1}{L_1 L_p^3 + [L_1(R_1 + R_2) + R_1 L]p^2 + \left(\frac{L}{C_1} + R_1 R_2\right)p + \frac{R_1 + R_2}{C_1}} \quad (13)$$

Substituting values:

$$L(i_p) = \frac{-E \times 10^{10}}{p^3 + 12 \times 10^6 p^2 + 1.05 \times 10^{12} p + 0.55 \times 10^{18}} \quad (14)$$

$$\frac{L(i_p)}{K_4} = \frac{1}{[(p + .04212)^2 + (.211 \times 10^6)^2] (p + 11.92 \times 10^6)} \quad (15)$$

The inverse transform of equation 15 is given by:

$$\frac{i_p}{K_5} = 0.399e^{-.0421 \times 10^6 t} \sin(.211 \times 10^6 t - 1.04^\circ) + .0071e^{-11.92 \times 10^6 t} \quad (16)$$

The dotted line curve of Figure 21 is a graph of this function. The solid curve is the actual current waveform taken from a scope face. The actual current becomes almost zero after 15 microseconds since the thyatron ceases conducting about that time. A photograph of the current waveform is shown in Figure 12. This current is for all practical purposes independent of the conductivity of the metal near the probe, or whether metal is present at all. A few simple calculations shows that this is the case in the analysis also.

The loading of the inner coil by the rest of the circuit in the case of the long pulse is so slight that the output voltage (e_0) developed across the inner coil output terminals is given accurately by $e_0 = M_{12} di_p/dt$. A proper value of (M_{12}) must be picked from Figure 17. Since the fundamental

frequency of the long pulse current is so much lower than in the case of the short pulse, (M_{12}) is no longer independent of metal conductivity in this part of the analysis. The most accurate analysis would substitute a frequency dependent function of (M_{12}) in equation 16. However, it is just as instructive and less troublesome to pick a compromise value of (M_{12}) at about the fundamental frequency of the current pulse. For the coil alone

$$\frac{L(e_0)}{K_5} = \frac{55p}{[(p + .04212 \times 10^6)^2 + (.211 \times 10^6)^2] (p + 11.92 \times 10^6)} \quad (17)$$

where $M_{12} = 55$ uhy.

The original is:

$$\frac{e_0}{K_6} = 4.73e^{-.0421 \times 10^6 t} \sin (.211 \times 10^6 t + 102.3^\circ) - 4.65e^{-11.92 \times 10^6 t}$$

for $0 < t \leq 15 \mu\text{sec.}$

This is plotted as the solid line in Figure 22. For the coil on brass

$$\frac{L(e_0)}{K_5} = \frac{27}{[(p + .0421 \times 10^6)^2 + (.211 \times 10^6)^2] (p + 11.92 \times 10^6)} \quad (19)$$

where M_{12} is taken as 27 uhy

For the coil on 304 stainless steel:

$$\frac{L(e_0)}{K_5} = \frac{40}{[(p + .0421 \times 10^6)^2 + (.211 \times 10^6)^2] (p + 11.92 \times 10^6)} \quad (20)$$

where M_{12} is taken as 40 uhy.

The originals of equations 19 and 20 are also plotted in Figure 22. These waveforms can be compared to the actual waveforms shown in Figure 13.

Figure 1

SCALE= 10:1

Cross Section of Coaxial Probe C-7

Figure 2

Block Diagram

Figure 3

Master Oscillator, Multivibrator, Differentiator

Figure 4

Multivibrator, Differentiator, 837cps Trigger Pulse Generator

Figure 5

Univibrator, Differentiator and Delayed Trigger Pulse Generator

Figure 6

Long and Short Pulse Generator

Figure 7

Pulse Rectifying and Shaping Circuits, Sawtooth Bucking
Circuits, Compensating Voltage Rectifier

Figure 8

Long Pulse Channel Cathode Follower, Compensating Stage and Rectifier

Figure 9
Meter Circuits

Figure 10

The short pulse voltage available at the inner coil output terminals of probe C-7 when the probe is connected to the rest of the circuit. The lowest waveform is produced when the probe is away from any metal. The middle waveform is produced when the probe is placed on a piece of brass, and the upper trace when the probe is placed on a piece of 304 stainless steel. The large divisions of the abscissa equal $0.5 \mu \text{ sec}$; the large divisions of the ordinate equal 100 volts.

Figure 11

The Waveform of the Short Pulse Current Flowing in the Outer Coil of Probe C-7. The large divisions along the abscissa are equal to $0.5 \mu \text{ sec}$. The peak current is about 1.5 amperes.

Figure 12

Photograph of the Long Pulse Current Waveform Passing Through the Outer Coil of Probe C-7. The large divisions of the abscissa equal 10μ sec in time. Peak current is about 1 amp.

Figure 13

The Voltage Waveform Developed Across the Inner Coil of Probe C-7 by the Long Pulse Current. The sequence of these waveforms from top to bottom is the same as in Figure 10. Each large division along the abscissa equals 2μ sec in time. Each large division along the ordinate equals about 20 V.

Figure 14a

Simplified Short Pulse Generator Circuit

Figure 14b

Approximate Equivalent Circuit of Short Pulse Generator

Figure 15

Calculated and Actual Waveforms of the Short Pulse Current Flowing Through the Outer Coil

L_2 denotes the inner coil inductance

R denotes coil resistance which varies with frequency

Figure 16

Simplified Inner Coil Circuit for the Short Pulse

Figure 17

The Mutual Inductance M_{12} of Coil C-7 Plotted as a Function of Frequency. The parameter is the conductivity of the material on which the probe was placed.

COIL C-7

NO METAL PRESENT			ON BRASS			ON 304 S.S.		
$f \frac{KC}{SEC}$	L_{2hy}	R	f	L	R	f	L	R
455	294	12.2	461	250	26.9	461	260	45.6
521	294	14.2	521	256	30.6	521	259	50.4
628	291	19.8	628	248	35.8	628	259	66.0
789	296	30.1	789	250	47.3	789	251	75.9
1040	300	50.6	1040	260	71.0	1040	260	107.5

Figure 18

Measurements of Inner Coil Resistance and Inductance

Figure 19

Computed Inner Coil Short Pulse Voltage Waveforms

Figure 20a

Simplified Long Pulse Generator Circuit

Figure 20b

Equivalent Circuit

Figure 21

The Computed and Actual Waveforms of the Long Pulse Current Waveform Flowing in the Outer Coil

Figure 22

Computed Inner Coil Long Pulse Voltage Waveform