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TRANSFORMATION (ANALYZER) DEVICE
USING POST-DETECTOR SIGNAL PATTERN
ROTATORS FOR MULTIPARAMETER
EDDY CURRENT TESTER

H. L. Libby and C. R. Wandling

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TRANSFORMATION (ANALYZER) DEVICE USING
POST-DETECTOR SIGNAL PATTERN ROTATORS
FOR MULTIPARAMETER EDDY CURRENT TESTER

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ABSTRACT

An alternate transformation (analyzer) device which can replace the generalized transformation section of the Multiparameter Eddy Current Tester is described. The new device uses a series of sine-cosine potentiometers and associated amplifiers instead of the linear potentiometers used in the original multiparameter tester. The new circuit provides a simpler method of adjustment, permitting the desired signal decoupling calibrations to be made in simple steps rather than in one more complicated step. Results of our laboratory tests show the separation of tube flaw signals from those caused by simulated tube supports.

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TRANSFORMATION (ANALYZER) DEVICE USING
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INTRODUCTION

This report describes an alternate transformation (analyzer) device which can replace the generalized transformation section of the Multiparameter Eddy Current Tester.^(1,2) Test results of the new device are shown in which tube flaw signals are discriminated from those caused by simulated tube supports. The new device provides a simpler method of adjustment than the generalized transformation circuit.

SUMMARY AND CONCLUSIONS

An alternate transformation or analyzer section has been developed for the multiparameter eddy current tester. The new device uses a series of sine-cosine potentiometers and associated summing amplifiers instead of the linear potentiometer summing circuits in the generalized transformation section of the original multiparameter testers. The sine-cosine potentiometers are connected in a series of coordinate transformation circuits and are used to transform the vector signals. The final output is the same as in the original multiparameter testers, but the new device (in a two frequency system) permits the desired signal decoupling adjustments to be made in two simple steps rather than one more involved step. Thus, it retains the signal discriminating advantages of the original multiparameter test. In addition, the simplicity of adjustment is an advantage in proposed field applications of the test method.

Results of laboratory tests of the new device are given which show the separation of tube flaw signals from those caused by simulated tube supports.

PRINCIPLE OF OPERATION AND DESCRIPTION

The new device uses a series of post-detector signal pattern rotators (sine-cosine type coordinate transformation devices) in place of the linear potentiometer summing circuits of the original transformation circuit shown by the line diagram (Channels 1, 2, 3, and 4) in Figure 1. The inputs to the transformation circuit consist of signals on lines labeled c_1 , c_2 , c_3 , and c_4 which are the outputs of the eddy current tester phase detectors. The rotators are called post-detector signal pattern rotators because they are located in the circuit following the detectors.

Let us consider a four parameter problem in which we wish to read one parameter (variable) on output Channel 1 in Figure 1 and to discriminate against the other three parameters. The inputs c_1 , c_2 , c_3 , and c_4 are summed in different proportions by the potentiometers R_i and the associated summing circuits Σ_i to give the desired discrimination. In the present example only output Channel 1 is involved. One of the potentiometers, R_1 , can be set at a fixed trial value, and the remaining three potentiometers, R_2 , R_3 , and R_4 are then adjusted to give the discrimination against the three parameters whose signals are to be discriminated against. This adjustment is made by alternately or simultaneously adjusting the potentiometers until the proper settings are found. The adjustment is aided some by displaying output Channel 1 and the sum of c_1 , c_2 , c_3 , and c_4 , output Channel 5, on an X-Y oscilloscope giving Lissajou patterns. In contrast, the new device, whose principle will be described in more detail in the following paragraphs, permits the vector signals from the three unwanted parameters to be projected in one straight line by simply adjusting (alternately or simultaneously in a converging series of adjustments) two of the post-detector signal pattern rotators. The effect of these three parameters can then finally be minimized (nulled or eliminated) by the rotation of the shaft of a third rotator. The simplification of adjustment results from breaking the adjustments into two parts. The first involving two controls, places all of the undesired signals into a straight line in an X-Y presentation. The second adjustment then rotates

Figure 1. Generalized Transformation Unit

this line to a horizontal position so that it has no vertical component. The signal of the fourth parameter does have a vertical component in this display and is read independently of the other three parameters.

In summary, the new device permits the desired decoupling adjustments to be made in two simpler stages rather than in the single more involved stage required by the original transformation unit.

SIGNAL PATTERN ROTATOR

The basic component of the new transformation circuit consists of two sine-cosine potentiometers connected in a well-known configuration to provide transformation of Cartesian coordinates. This transformation of coordinates produces a rotation of the vector (or phasor) signals when the output of the device is displayed on an X-Y oscilloscope or X-Y recorder.

The principle of operation of the signal pattern rotator is best explained by referring to the functional diagram in Figure 2. The circuit comprises four input operational amplifiers A, B, C, and D, two ganged sine-cosine potentiometers E and F, and two output operational amplifiers G and H. The inputs to the rotator are designated x and y . For the present discussion these inputs are assumed to be obtained from the amplitude-phase detector outputs c_1 and c_2 shown in Figure 1. (It will be shown later in this report that various combinations of signal pattern rotator input and output signals are actually used.)

The input amplifiers A, B, C, and D provide balanced signals $+x$, $-x$, $+y$, $-y$ for the two sine-cosine potentiometers. The sine-cosine potentiometers are ganged on a single shaft with sliders phased as shown. The position of the shaft is denoted by the angle ϕ measured in the counter-clockwise direction from the 3 o'clock position.

The output amplifiers sum the potentiometer outputs as indicated by the summation symbol $\oplus$. Signals on each line of the diagram are identified so that the formation of signals can be followed step-by-step through the circuit. It is noted that each amplifier inverts the signal applied to it.

Figure 2. Post-Detector Signal Pattern Rotator

Given the input signals x and y , the transformed output signals x' and y' are

$$x' = x \cos \phi - y \sin \phi \quad (1)$$

$$y' = x \sin \phi + y \cos \phi \quad (2)$$

Transformation Equations (1) and (2) rotate a point having coordinates x, y through a positive angle ϕ about the origin to a new point having coordinates x', y' .

Note that such a device used with a single frequency eddy current tester performs the same function as the phase discrimination control (phase shifter) of the conventional single frequency tester.

TRANSFORMATION DEVICE AND ITS OPERATION

Figure 3 is a block diagram of the multiparameter type eddy current tester using rotated signal projection techniques. The only difference between this multiparameter eddy current tester and the generalized multiparameter eddy current tester⁽¹⁾ is the signal transformation (analyzer) unit. This transformation unit consists of 3 post-detector phase rotators labeled $T_{\phi 1}$, $T_{\phi 2}$, and $T_{\phi 3}$ and interconnected such that 3 degrees of rotational freedom are obtained. The output of this unit when displayed on an X-Y oscilloscope is a two dimensional projection of the four input signals. The four input signals can represent any number of test parameters, but this discussion will emphasize a maximum of four. The four input signals labeled c_1, c_2, c_3 , and c_4 represent the vectorial components of signals caused by one or more specimen parameters. Since c_1 and c_2 are the components of a signal vector P_1 projected on the C_1, C_2 plane (Figure 4a), this vector projection can be rotated in the C_1, C_2 plane. This rotation is accomplished with phase rotator $T_{\phi 1}$. Since this rotated vector has new rectangular coordinates, it will have new signal component values. One of these new component values can be represented by c'_x and applied as a signal input to phase rotator $T_{\phi 2}$ along with the P_1 vector signal component c_3 . The signal vector is now projected on the C_1, C_3 plane (Figure 4b), and rotated in this plane. The signal vector rotation

Figure 3. Multiparameter Eddy Current Tester Using Signal Rotation-Projection Device

Figure 4. Rotation of Vector Signal P_1 with Rotators T_{ϕ_1} , T_{ϕ_2} , T_{ϕ_3}

with T_{ϕ_2} creates two new signal components, one of which is labeled c'_x (Figure 3) and applied to phase rotator T_{ϕ_3} along with P_1 signal vector component c_4 . We now have the signal vector P_1 projected on the C_1 , C_4 plane (Figure 4c). This signal vector can be rotated in the C_1 , C_4 plane with rotator T_{ϕ_3} . The P_1 signal vector components c'''_x and c'''_y are then fed to the respective X and Y inputs of an X-Y oscilloscope and to the inputs of a two channel strip chart recorder as shown in Figure 3. If signals caused by other parameters (P_2 , P_3 , P_4 --- P_n) were applied singly to this signal processing unit, they would be rotated in the same manner as described above for P_1 . Discrimination against certain unwanted parameter signals is accomplished by rotating the signals until the unwanted parameter signals appear projected on the C_1 axis (Figure 4c) and components of the parameter signal to be read out appear on the C_4 axis. The following mathematical operations developed from Equation (1) and (2) describe the rotated signal vector components:

$$c'_x = c_1 \cos \phi_1 - c_2 \sin \phi_1 \quad (3)$$

$$c_x''' = (c_1 \cos \phi_1 - c_2 \sin \phi_1) \cos \phi_2 - c_3 \sin \phi_2 \quad (4)$$

$$c_x'''' = \left[(c_1 \cos \phi_1 - c_2 \sin \phi_1) \cos \phi_2 - c_3 \sin \phi_2 \right] \cos \phi_3 - c_4 \sin \phi_3 \quad (5)$$

$$c_y'''' = \left[(c_1 \cos \phi_1 - c_2 \sin \phi_1) \cos \phi_2 - c_3 \sin \phi_2 \right] \sin \phi_3 + c_4 \cos \phi_3 \quad (6)$$

SIGNAL SEPARATION USING PROJECTION ROTATION TECHNIQUES

When this technique is used, signals caused by n parameters are projected in two dimensions on the screen of an X-Y cathode ray oscilloscope. For the four parameter case (as in the block diagram in Figure 3) this is a two dimensional projection of the signals in 4-space caused by the four parameters. The objective here is to find a projection of the signals (in 2-space) such that all the signals which are to be discriminated against lie in a straight line in the two dimensional projection. Two degrees of freedom are required to rotate the signals that make up this projection into a position such that an "edge" view of a plane (hyperplane) that contains the three signals to be discriminated against is displayed. The separation of signals is illustrated in Figure 5 which shows (in an idealized manner) successive views of the signals projected in two dimensions as viewed on the screen of the oscilloscope in Figure 3. At the start, signals caused by all four parameters may appear as in Figure 5a. The signals are labeled P_1 (the signal to be retained) and P_2 , P_3 and P_4 (the three signals to be discriminated against). The signal pattern rotators are next adjusted by varying ϕ_1 and ϕ_2 to successively give projections in which the signals caused by P_2 , P_3 and P_4 appear more collapsed as in Figures 5b and 5c. With some alternate adjustments of ϕ_1 and ϕ_2 , the undesired signals are projected as an edge view as in Figure 5d. It is noted that even though these signals are Lissajou patterns of some complexity at the start, all of their final projections

Figure 5. Progressive Elimination of Signals Using Rotation-Projection Transformation Device

can be made to occur essentially in the one straight line. It is also noted that, in general, the signal caused by the variable to be read has a component normal to the other three signals. One more rotation adjustment, (made by adjusting ϕ_3 , Figure 3) rotates the pattern to that shown in Figure 5e where the undesired signals give deflection only in the horizontal direction. The desired signal (and other signals, if any, which have not been discriminated against) then have components in the vertical direction. Thus, these signals can be read on output terminal c_Y''' (Figure 3) independent of the other signals which have been discriminated against.

It is understood that although we have described the elimination of signals from three selected parameters with the circuit shown in Figure 3, additional circuits of this type can be used to eliminate the three other groups of three parameters in a four parameter system to permit the individual readout of four parameters. We assume that the signals possess the degree of independence required for practical separation.

It is understood that the system described can be expanded to separate signals caused by additional parameters by using more excitation frequencies and signal rotators.

TEST RESULTS OF MULTIPARAMETER TESTER

. A practical demonstration of the functional capability of the new transformation device using signal pattern rotation and projection techniques as applied to an eddy current tester using multiparameter principles has been made.

The tubing and simulated tube supports used for this demonstration are shown in Figure 6. A 12-in. length of 304 stainless steel tubing with 0.5-in. inside diameter and 0.054-in. thick wall is shown mounted in movable, simulated, tube supports.

The tube contains: 1) a 0.015-in. deep, 1/8-in. long, 0.005-in. wide electric-discharge-machined notch, on the inside wall, parallel with the axis of the tube, 2) a 0.023-in. deep, 1/8-in. long, 0.005-in. wide electric-discharge-machined notch, on the outside wall, parallel with the axis of the tube, 3) a spot of suspected intergranular corrosion, and 4) a kink.

Two tube supports were simulated. One was made of 3/8 in. thick mild steel and the other one was made of 1/2 in. thick stainless steel. The mild steel support and the stainless steel support completely encircle the tube. Each of these simulated tube supports makes a loose sliding fit on the tube.

Figure 6. Stainless Steel Tube with Flaws and Movable Simulated Tube Supports

Two types of eddy current tests were made: 1) single frequency with differential test coils and 2) two frequency (multiparameter) with the same differential test coils. Figures 7 and 8 show the "figure 8" patterns or two-dimensional projections of all of the flaw signals and the simulated tube support signals. Figure 7 was made using a single frequency of 125 kHz and Figure 8 was made using a single frequency of 250 kHz. The two large signals in each figure were caused by the simulated tube supports. The suspected intergranular corrosion, inner wall notch, outer wall notch

TUBE SUPPORTS:
MILD STEEL (MS)
STAINLESS STEEL (SS)

Figure 7. Single Frequency Eddy Current Tester X-Y Display (125 kHz)

TUBE SUPPORTS:
MILD STEEL (MS)
STAINLESS STEEL (SS)

Figure 8. Single Frequency Eddy Current Tester X-Y Display (250 kHz)

and the kink caused the signals that are clustered about the origin in each photograph. Note the size and nonlinearity of the simulated tube support signals compared to the other flaw signals. Figures 9 through 12 are strip chart recordings of the single frequency eddy current tests. Figures 9 and 10 were made at 125 kHz test frequency. Figures 11 and 12 were made at 250 kHz test frequency.

The bottom trace in Figure 9 shows one output channel of the eddy current tester operated at 125 kHz. A post detector phase rotator was used to rotate the phase of all signal vectors to a position such that minimum mild steel support signal residue appears on this trace. Note that all of the signals occur separately, indicating unique flaw and tube support locations along the length of the tubing. Also note the large amounts of residue signal from both the mild steel and the stainless steel tube supports as compared to the other signal indications on the trace. The top trace in Figure 9 shows the signal components that are in quadrature with those shown on the bottom trace. Normally both of these traces would be used to predict flaw characteristics from flaw signals. However, all flaw signals are apparent and can be interpreted from these two traces.

Figure 10 shows the result of moving the simulated tube supports over other flaws. The stainless steel support was physically placed over the spot of suspected intergranular corrosion and the mild steel support was placed over the 0.023-in. deep notch on the outside wall. All other test conditions remain unchanged. The signals from these two flaws are now coincident with the signals from the respective tube supports. Note that it is now difficult to detect the presence of these flaws and interpretation of their characteristics is no longer possible.

Figures 11 and 12 are respectively similar to Figures 9 and 10 except that the test frequency has been changed from 125 to 250 kHz. At this test frequency it is somewhat easier to detect the presence of the notch on the outer wall when it is coincident with the mild steel tube support by examining the lower trace, but in general it is still difficult and interpretation is very difficult, if not impossible. The intergranular corrosion signal is even more difficult to detect and interpret at either test frequency.

Figure 9. Single Frequency Eddy Current Test with Simulated Tube Supports Not Over Flaws (125 kHz)

Figure 10. Single Frequency Eddy Current Test with Simulated Tube Supports Over Flaws (125 kHz)

Figure 11. Single Frequency Eddy Current Test with Simulated Tube Supports Not Over Flaws (250 kHz)

Figure 12. Single Frequency Eddy Current Test Results with Simulated Tube Supports Over Flaws

Figures 13 and 14 show the test results obtained using a two frequency multiparameter test. All test conditions remain the same as for the single frequency tests. The only changes made were that the test coils were driven at 125 and 250 kHz simultaneously and the output signals were processed using rotated signal projection techniques before being recorded.

The top trace in Figure 13 is the signal readout trace. The bottom trace is still a quadrature signal component readout channel, but is included here only to show the relative position of flaws and tube supports along the length of the tube. Note that both tube support residue signals are small compared to the flaw signals on the top trace. Figure 13 can be compared to Figures 9 and 11.

Figure 14 can be compared to Figures 10 and 12. Note that the flaw signals that occur simultaneously with the tube supports are now readily distinguishable. Compare the signals on the top trace, from the notch on the outer tube wall and the suspected intergranular corrosion on the inner wall, to these respective signals on the top trace in Figure 13. Note that these respective signals appear approximately the same in each figure, thus demonstrating nearly independent **flaw** readout with respect to the tube supports.

Figure 13. Multiparameter Eddy Current Test Results with Tube Supports Not Over Flaws (125 and 250 kHz). Top Trace is Readout Trace

Figure 14. Multiparameter Eddy Current Test Results with Tube Supports Over Flaws (125 and 250 kHz). Top Trace is Readout Trace

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