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EDDY CURRENT MULTIPARAMETER TEST
FOR TUBE FLAWS IN SUPPORT REGIONS

H. L. Libby and C. R. Wandling

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EDDY CURRENT MULTIPARAMETER
TEST FOR TUBE FLAWS
IN SUPPORT REGIONS

By

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ABSTRACT

Laboratory tests at Battelle-Northwest show that a two-frequency multiparameter eddy current nondestructive test offers a way to dramatically reduce interfering tube test signals caused by simulated tube supports made of stainless steel or mild steel. An analysis of complex plane data of the tube support signals and a signal caused by a suspected region of intergranular corrosion in a stainless steel tube confirms the discrimination which we observed experimentally. The test described appears to be a workable system which represents a compromise between 1) full application of the multiparameter test principles (with the resulting complexity of circuits and adjustments and 2) a test system of reasonable complexity which may meet the needs of a practical field problem. Further tests are needed using real tube supports to determine optimum operating conditions.

CONTENTS

LIST OF FIGURES	vii
INTRODUCTION.	1
SUMMARY	1
EDDY CURRENT MULTIPARAMETER TEST.	2
Description	2
Equipment	3
Test Specimens	3
Test Results.	6
THEORETICAL CONFIRMATION*	12
Vector Cross Product Approach	13
Matrix Algebra Approach	18
CONCLUSIONS	22
REFERENCES.	23
DISTRIBUTION.	24

LIST OF FIGURES

1	Functional Diagram of Test Equipment	4
2	Tubing Specimen and Simulated Supports	5
3	Two-Channel Output of a Single Frequency Eddy Current Tester Showing Null Against the Mild Steel Tube Support Signal on the Lower Trace	7
4	Two-Channel Output of a Single Frequency Eddy Current Tester When the Outside Notch is Under the Mild Steel Tube Support	7
5	Multiparameter Eddy Current Tester Output Showing Discrimination Against Mild Steel and Stainless Steel Tube Support Signals on the Lower Trace.	8
6	Multiparameter Eddy Current Tester Output Showing the Outside Notch Signal and the Intergranular Corrosion Signal When the Mild Steel Tube Support is Over the Outside Notch and the Stainless Steel Tube Support is Over the Inside Intergranular Corrosion Flaw.	8
7	Multiparameter Eddy Current Tester Output Showing Discrimination Against Outside Notch Signals, Mild Steel Tube Support Signals and Stainless Steel Tube Support Signals on the Lower Trace When the Signals Occur Separately.	9
8	Multiparameter Eddy Current Tester Output Showing the Intergranular Corrosion Signal When the Stainless Steel Tube Support is Over the Intergranular Corrosion Flaw	9
9	Complex Voltage Waveforms for Single Frequency Eddy Current Test at 125 kHz	11
10	Complex Voltage Waveforms for Single Frequency Eddy Current Test at 250 kHz	11
11	X-Y Chart Record of Multiparameter Eddy Current Tester Phase Detector Output; Frequency: 125 kHz.	14
12	X-Y Chart Record of Multiparameter Eddy Current Tester Phase Detector Output; Frequency: 250 kHz	15
13	Calculated Instrument Output Showing Discrimination Between Flaw Signal and Support Signals	21

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INTRODUCTION

When installed tubes are inspected with the eddy current test method, large test signals are often caused by structural elements such as tube supports or other objects or materials adjacent to the tubes. For example, the tube supports in steam generators give such large eddy current signals that it is often impossible to inspect for flaws within the tube in the vicinity of the tube supports. This report, based on a laboratory study at Battelle-Northwest using simulated tube supports, shows that the multiparameter eddy current test offers a way of inspecting these regions. Included is a description of the test equipment and its operation, the test results, and an analytical confirmation supporting our observations.

The multiparameter eddy current test method is based upon excitation of the test coil assembly with currents that have more than one frequency component. The method has been explained⁽¹⁾ 1) as a generalization of the single-frequency phase discrimination technique to more than one frequency, 2) as the algebraic solution or decoupling of variables in a set of simultaneous equations, and 3) as the manipulation of signals in vector space.

SUMMARY

Laboratory tests show that a two-frequency multiparameter eddy current nondestructive test offers a way to dramatically reduce interfering tube test signals caused by simulated tube supports made of stainless steel or mild steel. Comparative tests were made of a conventional single frequency technique and the multiparameter test method.

These tests show a large improvement in the discrimination against the undesired simulated tube support signals by the multiparameter method. A single calibration of the test device gives discrimination against signals from two simulated tube supports, one made of stainless steel and one made of mild steel. An analysis of complex plane data of the signals involved confirms the discrimination which we observed experimentally.

The test described appears to be a workable system which represents a compromise between 1) full application of the multiparameter test principles (with the resulting complexity of circuits and adjustments) and 2) a test system of reasonable complexity which may meet the needs of a practical field problem. The present tests using simulated supports should be followed by tests in which real supports are used. Further tests are needed to determine factors affecting choice of optimum operating frequencies.

EDDY CURRENT MULTIPARAMETER TEST

DESCRIPTION

A Hanford prototype multiparameter eddy current tester is used in an operating mode which provides a main readout channel and a secondary output channel. This is in contrast to the use of several readout channels when it is desired to read several parameters independently. In the arrangement described in this report, the equipment is adjusted so that the signals caused by tube flaws appear on the main readout channel, while the signals caused by the simulated tube supports are discriminated against on this same channel. The secondary output channel is used for convenience in making the required instrument adjustments and to give an auxiliary chart record.

EQUIPMENT

The test arrangement is shown in the block diagram in Figure 1. The instrument operates at 125 and 250 kHz simultaneously. An inside type differential test coil is driven at these two frequencies simultaneously. Near null signals from the test coil and null adjust bridge circuit are applied to two tuned amplifiers. These amplifiers drive two sets of phase detectors which produce signals (at points C_1 , C_2 , C_3 and C_4) representing the coefficients of the Fourier series expansion of the test signal. The signals at points C_1 , C_2 , C_3 and C_4 are summed at point A (through a summing circuit consisting of sign changing amplifiers, potentiometers and amplifiers) in the proper proportion to produce the desired discrimination of signals on output Channel 1. This summation is indicated by the solid lines connecting the points C_1 , C_2 , C_3 and C_4 to the point A. The dotted lines leading from the points C_1 , C_2 , C_3 and C_4 indicate summations of signals to feed additional output channels used in other applications of the multiparameter eddy current test. These channels are not used in the test described in this report.

Channel 1 (point A) is the main readout channel and is applied to one channel of a strip chart recorder and to the vertical deflection channel of a cathode ray oscilloscope. Channel 2, the secondary output channel, is used for convenience in providing a two-dimensional oscilloscope display which aids in obtaining the desired adjustment of the potentiometers feeding point A. The signal on output Channel 2 is generated by summing the signals at points C_1 , C_2 , C_3 and C_4 at point B. The output of Channel 2 is applied to the horizontal input circuit of the oscilloscope. The resulting two dimensional display serves as an aid in obtaining the desired adjustment of the potentiometers feeding point A.

TEST SPECIMENS

The tube and simulated supports used are illustrated in Figure 2. The tube is a section of Type 304 stainless steel tubing, 0.5 in. diameter, 0.054 in. wall thickness, which has several flaw conditions at locations shown approximately in Figure 2. These flaws are

Figure 1. Functional Diagram of Test Equipment

Figure 2. Tubing Specimen and Simulated Supports

1) an outside notch 1/8 in. long by 0.023 in. deep, 2) a region of suspected intergranular corrosion, 3) a kink, and 4) an inside notch 1/8 in. long by 0.015 in. deep. Two simulated tube supports are used. One is made of mild steel (3/8 in. thick) and the other is made of stainless steel (1/2 in. thick). Each has a 41/64 in. diameter hole for receiving the tube. The simulated supports fit the tubes loosely enough so that the supports may be positioned along the tube as desired.

TEST RESULTS

Test runs were made using single frequency operation (conventional phase discrimination technique) and two frequency operation (multi-parameter technique) for various positions of the simulated tube supports. Figures 3 and 4 illustrate the difficulty of discriminating against the support signals when using the single frequency system. In contrast, Figures 5 through 8 show the increased discrimination against the simulated support signals obtained by using the multiparameter principle.

The in-phase and quadrature signal component channels of a single frequency (125 kHz) eddy current tester are shown in Figures 3 and 4. The signals of each channel, from left to right, are caused by:

0.023 in. deep notch outside wall of the tube.

Mild steel simulated tube support.

- Stainless steel simulated tube support.
- Suspected intergranular corrosion on inside wall of the tube.
- Kink.
- 0.015 in. deep notch inside wall of the tube.

The tester is adjusted to produce minimum signal output for the mild steel tube support on the lower trace in both Figures 3 and 4. In Figure 3 all of the signals are separate, distinct signals. Notice that even though discriminated against, the mild steel tube support produces a large residue signal on the lower trace. Next, the mild steel tube support is physically placed over the outside notch giving the results shown in Figure 4. Now, the iron tube support signal and the outside notch signal appear together, and the outside notch signal is unreadable.

Figure 3. Two-Channel Output Of A Single-Frequency Eddy Current Tester Showing Null Against The Mild Steel Tube Support Signal on the Lower Trace

Figure 4. Two-Channel Output Of A Single-Frequency Eddy Current Tester When The Outside (OD) Notch Is Under With The Mild Steel Tube Support

Figure 5 Multiparameter Eddy Current Tester Output Showing Discrimination Against Mild Steel and Stainless Steel Tube Support Signals On The Lower Trace

Figure 6 Multiparameter Eddy Current Tester Output Showing Outside (OD) Notch Signal and The Inside (ID) Intergranular Corrosion Signal When The Mild Steel Tube Support Is Over The Outside (OD) Notch and The Stainless Steel Tube Support Is Over The Inside (ID) Intergranular Corrosion Flaw

Figure 7. Multiparameter Eddy Current Tester Output Showing Discrimination Against Outside (OD) Notch Signals, Mild Steel Tube Support Signals and Stainless Steel Tube Support Signals On Lower Trace When Signals Occur Separately

Figure 8. Multiparameter Eddy Current Tester Output Showing The Intergranular Corrosion Signal When The Stainless Steel Tube Support Is Over The Intergranular Corrosion Flaw

Figures 5 and 6 are strip chart recordings of the output signals from the multiparameter eddy current tester operated simultaneously at 125 and 250 kHz. The same tube test specimen, simulated tube supports and test probe are used for these tests as were used for those related to Figures 3 and 4. The top trace in Figures 5 and 6 is a reference trace and is used only to show the relative position of the tube supports with respect to the notches. Notice in Figure 5 that all flaws and supports occur at distinct (separate) positions and that both of the tube supports signals have been discriminated against on the lower trace, leaving only small residues. In comparing the lower trace of Figure 6 to the lower trace in Figure 5, notice that the outside notch signal and the inside corrosion signal in Figure 6 are essentially the same as in Figure 4, even though the mild steel tube support has been moved over the outside notch and the stainless steel tube support has been moved over the intergranular corrosion area on the tube.

Figures 7 and 8 were made with the same test equipment, test specimen and probe as Figures 5 and 6. The top traces in each figure are again only reference traces used for showing the position of the tube supports with respect to the notch signals. The lower trace in Figure 7 shows that both tube support signals and the outside notch signal have been discriminated against. The residues from these signals are very small. Here again, the tube support signals and the notch signals are separate. In Figure 8 the stainless steel support has been moved over the suspected intergranular corrosion flaw. Notice that the intergranular corrosion signal appears essentially the same on the lower trace in Figure 8 as it did in Figure 7.

Figures 9 and 10 are photographs of the complex voltage waveforms for all of the signals shown in Figures 3 through 8. Figure 9 was made using a test frequency of 125 kHz and a differential probe. Figure 10 was made using a test frequency of 250 kHz with the same probe. The probe motion or probe wobble axis is horizontal in each of these figures.

Figure 9. Complex Voltage Waveforms For Single Frequency Eddy Current Test At 125 kHz

Figure 10. Complex Voltage Waveforms For Single Frequency Eddy Current Test At 250 kHz

The two largest signals in Figures 9 and 10 are caused by the simulated tube supports. The stainless steel tube support signal is the largest in both figures. The magnitude of the stainless steel tube support signal is approximately 15 times larger than the largest notch or intergranular corrosion signal at 125 kHz. All of the notch, kink, and corrosion signals appear clustered at the center of the photograph. These two figures are intended to show the relative magnitudes and nonlinear nature of the signals.

THEORETICAL CONFIRMATION

We have experimentally observed (as shown in Figures 5 through 8) that the figure 8 signals encountered in tubing tests can be discriminated against or separated by using the multiparameter eddy current test method. At first the amount of discrimination that we obtained appeared to be in excess of that allowed by the basic theory of the test. It seemed that more than the two test frequencies used would be needed to obtain the observed degree of discrimination. However, a study of the signal patterns in 4-space shows that any number of figure 8 patterns can be eliminated using a two frequency system if they all occupy the same three-dimensional subspace.

Computations based upon measurements of the signals from the two simulated tube supports and the suspected region of intergranular corrosion confirm our experimental results. Confirmation of the experimental results is shown by a vector cross-product approach and by the matrix algebra approach. Each of these approaches gives a different view of the separating or decoupling process, but each is basically equivalent. The vector cross-product approach enhances the visualization of the underlying geometrical principles of the process.

The coordinates of four points (including the zero or origin) on each of the three signals were obtained at the two operating frequencies by simultaneously recording the eddy current tester phase detector outputs using two X-Y recorders. Tracings of the two records are shown in

Figure 11 (125 kHz) and Figure 12 (250 kHz). Corresponding signal points on the two X-Y records are numbered alike. One point was near the tip of each signal lobe and the two other points were on opposite sides of the wider portion of each signal lobe (points 1, 3, 4, 6, 7 and 9). The remainder of the lobe of each figure 8 pattern is shown approximately by the dashed lines.

From observation of various projections of the signals in 2-space we know that each of the Lissajou figures (figure 8 patterns) lies mainly in a plane when described in 3-space. Thus, it seems reasonable to work with the four points on each pattern.

VECTOR CROSS PRODUCT APPROACH

As the signals have four components resulting from the two Fourier series coefficients at each of the two excitation frequencies, the signals can span, under the right conditions, a four-dimensional vector space. However, for the desired separation or decoupling of the intergranular corrosion signal from the signals caused by the simulated supports it is necessary that the support signals span a space having dimension less than 4. This requirement is next tested.

Since separation of these signals is observed experimentally using a four parameter system, we assume that the support signals may span a space having dimension 3. Next, we construct a composite vector signal by adding corresponding components of the signals caused by the stainless steel support and the mild steel support. This new signal consists of three 4-vectors. A vector M is next formed which is orthogonal to the three 4-vectors. This is done by computing the cross product of the three 4-vectors. The scalar products (dot products) of the vector M and each of the six 4-vectors of the original support signals are then computed to show that the newly formed vector M is approximately orthogonal (dot product ≈ 0) with respect to each of the 6 original vectors.

Figure 11. X-Y Chart Record Of Multiparameter Eddy Current Tester Phase Detector Output
 Frequency: 125 kHz

SS 1,2,3: Stainless Steel Simulated Tube Support
 MS 4,5,6: Mild Steel Simulated Tube Support
 IC 7,8,9: Suspected Region of Intergranular Corrosion

0.02 VOLT/INCH

Figure 12. X-Y Chart Record of Multiparameter Eddy Current Tester Phase Detector Output
 Frequency: 250 kHz

The scalar product of M and the three composite vector signals are also formed as a check on the computations. Finally, the scalar product of M and the three vectors representing the signal caused by the region of suspected intergranular corrosion is formed, with the result that this scalar product differs radically from zero. Thus, it is concluded that the intergranular corrosion signal can be decoupled or separated from those caused by the simulated tube supports. The coordinates, in inches, scaled from the original X-Y recording by using vernier calipers are given in Table 1.

Table 1. Signal Coordinates

Line	Artifact	Identification Number On X-Y Charts (Figures 11, 12)	Coordinates			
			c_1	c_2	c_3	c_4
a	Stainless Steel	1	6.288	0.473	5.261	-0.343
b	Simulated Support	2	7.922	0.664	6.954	-1.509
c		3	5.176	0.264	4.340	-0.426
d	Mild Steel	4	1.790	0.000	1.527	-0.288
e	Simulated Support	5	2.166	-0.544	1.974	-0.801
f		6	1.635	-0.743	1.585	-0.804
g	Suspected Intergranular	7	0.230	0.299	0.709	-0.205
h	Corrosion	8	0.545	0.438	1.400	-0.713
i		9	0.474	0.277	1.090	-0.755

A composite support signal is next found by summing the vector components on lines a and d, b and e, and c and f.

j	Sum lines a and d	8.078	0.473	6.788	-0.631
k	Sum lines b and e	10.088	-1.208	8.928	-2.310
l	Sum lines c and f	6.811	-0.479	5.925	-1.230

Vectors having components c_1 , c_2 , c_3 and c_4 are designated by upper case letters corresponding to the line designations a, b, c. For example, the three composite vectors J, K and L correspond to the signals on lines j, k and l.

The cross product $J \times K \times L$ is formed, giving a vector M which is orthogonal to each of the vectors J, K and L.

$$J \times K \times L = M = [0.5224 \quad 0.0633 \quad -0.6510 \quad -0.2669] .$$

The scalar products of M and the stainless steel support signals A, B, and C are

$$M \cdot A = -0.0186$$

$$M \cdot B = -0.0275$$

$$M \cdot C = 0.00936 .$$

The scalar products of M and the mild steel support signals D, E and F are

$$M \cdot D = 0.0179$$

$$M \cdot E = 0.0258$$

$$M \cdot F = -0.0101 .$$

The scalar products of M and the composite support signals J, K, and L are

$$M \cdot J = 0.000634$$

$$M \cdot K = 0.00204$$

$$M \cdot L = -0.00112 .$$

These scalar products have magnitudes equal to or less than 0.0275.

In contrast, the scalar products of M and the signal vectors G, H and I representing the corrosion signal are:

$$M \cdot G = -0.268$$

$$M \cdot H = -0.407$$

$$M \cdot I = -0.243 .$$

Here, the largest scalar product for the corrosion signal (0.407) is 14.8 lines as large as the largest scalar product (0.0275) for a support vector signal. It is concluded that the corrosion signal has

a component which is orthogonal to all of the components of the 6 support signals and thus it should be possible to decouple or separate the corrosion signal from those caused by the two simulated supports.

MATRIX ALGEBRA APPROACH

The basic equations relating the test parameters and instrument signals of the multiparameter test are:

$$[A] \quad P] = C] \quad (1)$$

$$P] = [A]^{-1} \quad C] \quad (2)$$

where A is the modulation matrix which transforms the parameters P_i into a vector signal C having components c_i . This transformation takes place in the field of the test coils and the test specimen through the complex behavior of the electromagnetic field. The c_i are produced at the output terminals of the instrument phase detectors and represent the Fourier series coefficients of the complex eddy current test signal. Signals proportional to the test parameters p_i are produced by transforming the c_i using Equation (2). Since the decoupling of the parameters (variables) is of primary interest, it is not necessary to obtain the complete solution as indicated in Equation (2). Rather, the decoupling can be obtained by using the adjoint A . Thus,

$$P] \cong [Adj \quad A] \quad C] \quad (3)$$

and individual calibration controls can be provided on each output channel to adjust the channel sensitivity.

We wish to determine whether the support signals can be discriminated. To do this we determine the first row of the adjoint of the matrix A and then calculate the instrument output p_i for the transformation (analyzer) section adjusted to the adjoint components.

The matrix A is first formed from the data on lines j, k, 1 in Table 1:

$$[A] = \begin{bmatrix} -8.078 & 10.088 & 6.811 \\ -0.473 & -1.208 & -0.479 \\ -6.788 & 8.928 & 5.925 \\ -0.631 & -2.310 & -1.230 \end{bmatrix} \quad (4)$$

The column corresponding to the intergranular corrosion signals is left blank as it is not required at this time. The first row of the adjoint of A is obtained by first inserting the cofactors of the missing matrix elements in the first column in Equation (4) giving the transpose of adjoint A:

$$[\text{Adj } A]^T = \begin{bmatrix} 0.5224 & - & - & - \\ 0.0633 & - & - & - \\ 0.65099 & - & - & - \\ 0.26692 & - & - & - \end{bmatrix} \quad (5)$$

$$[\text{Adj } A] = \begin{bmatrix} 0.5224 & 0.0633 & -0.6510 & -0.2669 \\ - & - & - & - \\ - & - & - & - \\ - & - & - & - \end{bmatrix} \quad (6)$$

Then, the instrument output with these values set in the potentiometer summing network of the transformation (analyzer) section of the instrument is, from Equation (3),

$$\begin{bmatrix} p_1 \\ - \\ - \\ - \end{bmatrix} \approx \begin{bmatrix} 0.5224 & 0.0633 & -0.6510 & -0.2669 \\ - & - & - & - \\ - & - & - & - \\ - & - & - & - \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} \quad (7)$$

where the values of the c_i are those in Table 1. It is noted that this produces the output of Channel 1, the only discrimination channel used in the present test. Inserting in Equation (7) the various values of the c_i for the signal vectors resulting from the stainless steel support, the mild steel support, and the suspected region of intergranular corrosion gives the output signal values shown in Table 2.

Table 2. Calculated Output Signals for Different Test Conditions

<u>Condition</u>	Identification Number On X-Y Charts (Figures 11, 12)	<u>Calculated Output Channel 1</u>
Stainless Steel Support	1	-0.0186
	2	-0.0275
	3	0.00936
Mild Steel Support	4	0.0179
	5	0.0258
	6	-0.0101
Suspected Region of Intergranular Corrosion	7	-0.268
	8	-0.408
	9	-0.243
Composite Support Signal		0.000634
		-0.00204
		-0.00112

The relative values of the output signals in Table 2 for the different test conditions are shown in Figure 13. The relative absolute magnitude of each corresponding 4-vector is also shown.

Figure 13. Calculated Instrument Output Showing Discrimination Between Flaw Signal and Support Signals

It is noted that although the peak vector signal absolute magnitude of the signal caused by the stainless steel simulated support is 6.3 times that of the corrosion signal, the calculated corrosion signal (with discrimination) is 14.8 times that of the output signal caused by the stainless steel simulated support.

CONCLUSIONS

A more detailed analysis is possible using more signal vectors from the signal patterns. Laboratory results indicate that it is easier to separate inside surface notch signals from the support signals than it is to separate outside notch signals from the support signals. The outside notch used in the tests is deep (42.5% of the wall thickness) and it was separated. However, it is expected that outside notches having less depth will be more difficult to separate. It is expected that separation difficulty will increase as the flaw signals occupy regions of signal space representing total phase angles closer to those of the support signals. In addition, small outside notches (or flaws) naturally produce smaller signals which can be masked by the residues (remaining, uncanceled portions) of the support signals.

The instrument arrangement described here, in which essentially one channel readout is used, is the multiparameter counterpart of the conventional single frequency eddy current test using the phase discrimination technique. In the multiparameter version, exemplified by the test described in this report, the support signals are discriminated against and the flaw signals are read on the single output channel. Additional channels are not provided here for further identification of the remaining flaw signals. This does remain a possibility, but because of the complexity of the support signals it may require the use of additional test frequencies with the attendant complication of circuitry and adjustment. The test described here appears to be a workable system which

represents a compromise between developing the potential of the multi-parameter test more fully (with resulting complex circuits) and providing a test system of reasonable complexity which may meet practical field operating requirements for a specific need.

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