BROADBAND ELECTROMAGNETIC
TESTING METHODS

PART V

PULSED EDDY CURRENT METHOD

JANUARY 1969

AEC RESEARCH &
DEVELOPMENT REPORT

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UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

BROADBAND ELECTROMAGNETIC TESTING METHODS

PART V - PULSED EDDY CURRENT METHOD^{*}

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RECEIVED JAN 14 1969

January 1969

^{*}This paper is based on work performed under United States Atomic Energy Commission Contract AT(45-1)-1830.

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BROADBAND ELECTROMAGNETIC TESTING METHODSPART 5 - PULSED EDDY CURRENT METHOD

by

H. L. Libby

INTRODUCTION

Improved nondestructive testing techniques are needed as serviceability requirements of materials and parts increase as a result of advances in nuclear and metals technology. The main objectives of the broadband electromagnetic testing methods study are to obtain more information from test specimens than can be obtained by conventional electromagnetic or eddy current methods, and to use this information to discriminate better against signals caused by test specimen irregularities of little or no interest. Studies include both multifrequency and pulsed test coil excitation methods.

This report, the fifth in a series, describes some general aspects of a pulsed eddy current technique which has a four parameter separating capability.

The first report⁽¹⁾ established the uniqueness of the test coil input impedance over a range of frequencies by an analytical study of an equivalent electrical circuit representing test specimen conductivity and layer thickness. It also summarized the information content characteristics of multifrequency signals. The second report⁽²⁾ treated the analysis of broadband test coil output signals by expansion of the signals into orthogonal components, reviewed

associated techniques and outlined a proposed approach to the problem of parameter extraction. The third report⁽³⁾ described the multiparameter test method and gave test results of a four frequency, four parameter instrument. The fourth report⁽⁴⁾ gave several different explanations of the multiparameter test and showed some test results to illustrate the potential of the method. Another report,⁽⁵⁾ not in this series, describes a two frequency eddy current tubing tester which also uses the multiparameter method.

SUMMARY AND CONCLUSIONS

A pulsed eddy current nondestructive test method is described which has the capability of reading multiple parameters of a test specimen. Preliminary results show the separation of signals from irregularities in a short section of $\frac{1}{2}$ -in. diameter 304L stainless steel tubing with 0.050-in. wall. An inside circular test coil about 7/16-in. diameter was used. Signals from two parameters, probe wobble and the presence of a small piece of ferrous material on the outside of the tubing, were discriminated against. Signals caused by two other parameters, a fabricated notch on the inside wall and a fabricated notch on the outside wall, were separated and read on separate output channels.

Much exploratory work remains to be done in evaluating variations of the spectrum analysis technique. However, it is concluded that the method has been developed sufficiently to proceed with the development of either a plating thickness test or a tubing test using the principles described.

DISCUSSION

The method used follows the general principles of the multiparameter eddy current tests previously described.⁽²⁻⁴⁾ In the tests described here, the test coil is excited by pulsed currents and pulse analysis techniques are used. Figure 1 shows a functional diagram⁽²⁾ of the method.

FIGURE 1
Approach to the Broadband Problem

CIRCUIT DESCRIPTION

A pulsed eddy current system was assembled as shown in block diagram form in Figure 2. The system comprises a solid state pulse generator A, eddy current tubing test coil B, matching reference inductor C, balance trimmers D, artificial transmission line balance (nulling) circuits E and F, signal amplifier G, gating circuit H, orthonormal generator (filter) I, adjustable time delay circuit J, time domain sampler K, and analyzer or summing network L. A delay multivibrator circuit M provides timing (drive) signals for the solid state pulser, gate, and time domain sampler.

In this test the solid state pulser delivers an impulsive signal to the test coil bridge circuit. The output of the bridge at points a and b, applied to a transformer (not shown) in box G, gives a differential output. Adjustments of trimmers D and artificial transmission line balance trimmers F and E provide near null balance. In some applications these trimmers D provide sufficient adjustment. However, when a closer null is required the artificial transmission line trimmers F and E have been found to provide the additional degrees of freedom required. For very fine adjustment, especially for signal components near the origin in the time domain, $t \rightarrow 0$, it has been found advantageous to parallel lines F and E with two shorter lines designed to give vernier adjustment in the region immediately following the pulse epoch.

The gate H, an FET transistor, gates out any remaining signal near the pulse epoch which has not been balanced out with the balancing circuits and which could overdrive the orthonormal filter circuits. The use of this gate feature makes the null balance requirements less strict and under some conditions makes it possible to eliminate the need for the adjustable artificial transmission lines F and E.

FIGURE 2
Pulsed Multiparameter Eddy Current Nondestructive Testing Device

The filter used is of the Laguerre type with transfer functions from input to successive outputs, $c_0, c_1, c_2, \dots, c_n$ being:

$$F_n(s) = \frac{as^n}{(s+a)^{n+1}}.$$

The time domain sampler samples the various output channels of the filter simultaneously at a selected time to obtain the Fourier coefficients. The time of sampling is chosen, depending upon the waveform of the signal being analyzed, to give good sensitivity to the waveform characteristics for the few coefficients used.

The signal analyzer used in this test was the computer section of the Multichannel Eddy Current Tubing Tester.⁽⁵⁾ This was used because of the ease of adjustment in elimination of one parameter at a time. Of course, other, more general forms of summing networks could also be used such as the one used in a four frequency multiparameter eddy current tester.⁽³⁾ In the present test, the effects of two parameters are eliminated and two others read out on separate channels. This limitation results from the use of a two channel computer section. The same basic computer (analyzer or transformation circuit) section design can be used and extended to permit reading out additional channels. All that is required are additional operational amplifiers and potentiometers interconnected in a pattern following that already established in the present design.⁽⁵⁾

TEST RESULTS

The test specimen used was a section of 304L stainless steel tubing, $\frac{1}{2}$ -in. diameter with 0.050-in. wall. The test coil was an inside, circular type of about 7/16-in. diameter. In the test, whose results are shown in Figure 3, two parameters, probe wobble, and the presence of a small amount of ferrous material taped to the outside wall were discriminated against. Signals due to

FIGURE 3
Test Results Illustrating four Parameter Separating Capability of Pulsed Eddy
Current Test Device

a fabricated notch on the inside wall were read on one output channel (lower trace) and signals due to a fabricated notch on the outside wall were read out on the other channel (upper trace). Estimated dimensions of the notches are 1/8-in. long by 0.015-in. deep for the inside notch and 1/8-in. long by 0.023-in. deep for the outside notch. Width of both notches was less than 0.005-in. The alignment of both notches was such that the 1/8-in. length was parallel with the tubing axis.

In addition to the artificial flaws already mentioned there was also a region of suspected intergranular corrosion on the inside wall and a dent. It is noted that the corrosion signal, as expected, appears mainly on the channel for inside wall flaws with a small residue signal appearing on the other channel. The dent signal appears on both channels as it was not factored into the calibration, all of the separating capability of the system having already been used.

Discussion and Theory

A signal may be expanded in the form known as a generalized Fourier Series^(6,7)

$$h(t) = \sum_{k=1}^n c_k \phi_k(t) \quad (1)$$

where c_k are the Fourier constants or coefficients and $\phi_k(t)$ are the basis functions. The $\phi_k(t)$ are orthogonal functions of t .

Since the $\phi_k(t)$ are orthogonal functions we can write:

$$\int_a^b \phi_k(t) \phi_m(t) dt = \begin{matrix} R_{kk} & \text{for } k = m \\ 0 & \text{for } k \neq m \end{matrix} \quad (2)$$

(the $\phi_k(t)$ may be normalized by choosing their values (or by including a weighting function) so that $R_{kk} = 1$ for all k).

The coefficient c_j is⁽³⁾

$$c_j = \int_0^{\infty} h(t) \phi_j(t) dt \quad (3)$$

This can be demonstrated by substituting Equation (1) into Equation (3) assuming equivalence of summation and integration in the limit, giving

$$c_j = \int_0^{\infty} c_k \phi_k(t) \phi_j(t) dt \quad (4)$$

The right hand side of Equation (4) is always zero, when $k \neq j$, due to the orthogonal relationships and is equal to c_j when $k = j$.

Equation (3) is also seen to be in agreement with the specific coefficient equation of the Fourier series where the coefficients a_n and b_n are

$$a_n = \int f(t) \sin \omega_n t dt$$

$$b_n = \int f(t) \cos \omega_n t dt$$

where $f(t)$ corresponds to $h(t)$ and $\begin{matrix} \sin \omega_n t \\ \cos \omega_n t \end{matrix}$ correspond to the $\phi_k(t)$.

Error of approximation, though not discussed here, is important in the application of these principles. Weighting functions likewise are not discussed but are used to emphasize errors over the desired region.

To explain the operation of the orthonormal filter let us apply an impulse to a series of circuits so designed that the outputs of these circuits are the $\phi_k(t)$ basis functions described earlier. Thus, $\phi_1(t)$, $\phi_2(t)$, $\phi_3(t)$. . . are the impulsive responses of the circuits at the various terminals. From

the convolution theorem the output at any terminal for an input $f(t)$ is⁽²⁾

$$m_k(t) = \int_0^{\infty} f(t - \tau) g_k(\tau) dt \quad (5)$$

$f(\tau) = \text{input}$

$g_k(\tau) = \text{impulse response}$

or for our example

$$m_k(t) = \int_0^{\infty} h(t - \tau) \phi_k(\tau) dt \quad (6)$$

Comparing Equation (6) with Equation (3) it is apparent that the $m_k(t)$ of Equation (6) are the coefficients of the expansion of the reversed signal $h(t - \tau)$. Thus, when input $h(t)$ is applied to the filter the outputs of the filter represent the Fourier coefficients of the expansion of the reversed signal $h(t - \tau)$.

An important point is that in the characterization or identification of the signals, we are looking for means to describe them uniquely so that we can identify particular signals or their combinations. For our purpose it should not matter whether we identify the original signal or the reversed signal since the reversed signal should be as unique as the original as far as relating its characteristics to the test specimen parameters. Since the identification of the reversed signal can be obtained without using a time (signal) reversing section ahead of the orthonormal filter, it is simpler to operate without this added complex circuit. One disadvantage exists here which has not been fully evaluated. Analysis of the not-reversed signal is done using a filter having impulse response of decaying orthogonal exponentials; however, best identification is made for input signals having rising exponential waveforms. The present signals from the pulsed eddy current test are of the

decaying exponential type, thus being less favorable for best analysis. Two methods for correcting this disadvantage are proposed. The first provides orthonormal filters which have rising exponential response characteristics to impulse input as suggested by Mishkin⁽⁸⁾. The second technique modifies the eddy current test coil drive function so as to result in a test coil output signal better suited for identification with the decaying exponential impulse response of the present filter. Mishkins' approach is simpler than the signal reversing technique but requires unstable amplifiers which must be alternately clamped and released for proper operation. If needed, however, this is the preferred technique. Favorable test results have been obtained with the present proposed method in separating four parameters, and for many applications it may not be necessary to use the more elaborate technique which uses the unstable orthonormal generators.

Another related consequence of the foregoing is that the filter used in the expansion of the signal does not necessarily need to be adjusted to give "normalized" outputs. The orthogonal function of the filter is the important feature for parameter separation since the present application does not involve the "normalization" requirement, needed if synthesis of the original signal is desired.

However, until all facets of the foregoing conclusion are studied, it is still desirable to designate the filters used as "orthonormal".

FUTURE DIRECTION

The pulsed eddy current multiparameter nondestructive test has a great potential. As it is further developed, it may be found to require less complicated circuitry than the multifrequency test. In the meantime, further comparison of sensitivity, signal-to-noise ratios, reproducibility and parameter separation capabilities of the two systems need to be made. The

best basic functions, ϕ_k , for general and specific nondestructive test problems should be determined and the use of unstable filter systems should be evaluated. Extension of the pulse test technique should be made to cover very short pulses to evaluate the system for operation under conditions equivalent to the operation of single or multifrequency testers in the high and very high frequency region. It appears possible to extend the operation into nanosecond or shorter pulse duration times using state-of-the-art sampling techniques. Although much exploratory work remains to be done, it is concluded that the test has been sufficiently developed to proceed with the development of either a plating thickness test or tubing test using the principles described.

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