

MULTIFREQUENCY EDDY CURRENT INSPECTION
WITH CONTINUOUS WAVE METHODS

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ABSTRACT

This paper describes the application of continuous wave, multifrequency eddy current methods to nondestructive inspection of materials. A generalized description of the technology is included, followed by some results obtained in multifrequency examination of tubing. A major advantage of multifrequency inspection is the ability to discriminate against unwanted test parameters. The discrimination process is effected by combining the data from individual frequencies in a manner similar to simultaneous solution of multiple equations. Multifrequency tests are described showing how discrimination has been achieved against parameters such as probe motion, tube support plates and magnetic surface deposits.

INTRODUCTION

Continuous wave multifrequency eddy current inspection can provide substantially improved characterization of material parameters in a variety of applications. This is primarily due to its ability to eliminate unwanted parameters from test data. The basic approach relies on the skin effect phenomenon of current flowing in the specimen to provide independent information at different frequencies. The test results from individual frequencies can be combined in real time so as to obtain outputs which are free of certain parameters but which preserve other test data. The ability to select individual frequencies inherent in the continuous wave approach plays an important part in successful elimination of unwanted parameters.

This paper describes some field results of multifrequency testing and addresses some of the technology used in implementing the tests.

BACKGROUND

Continuous wave multifrequency testing is the direct equivalent of operating more than one single frequency unit with a common search coil. Two parameters are output from each frequency -- the in-phase and quadrature components of coil impedance. These components are directly relatable to Fourier amplitude coefficients of eddy currents flowing in the test specimen.

Implementation of a single-frequency test is shown in Fig. 1.

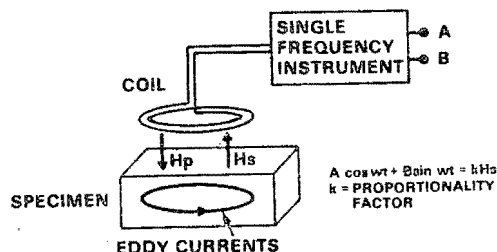


Fig. 1. Implementation of a single frequency eddy current test.

The test is based on the following events:

1. The search coil is excited with alternating current at the test frequency and positioned over the specimen.
2. The primary field (H_p) of the coil links with, and produces potential differences in, the conducting specimen. The potential differences cause circulating or eddy currents to flow in the specimen.
3. The eddy currents produce a secondary electromagnetic field (H_s) which links with the coil and induces a secondary voltage in it.
4. The secondary voltages are detected by most commercial instruments as a change in the equivalent impedance of the coil. The coil is connected as one leg of an impedance bridge in the instrument, and the secondary voltages alter the current delivered to the coil by the bridge, resulting in a change in equivalent impedance of the coil. Alternately, the secondary voltages may be detected directly by a second coil (send-receive method).
5. The Fourier amplitude coefficients A and B of the secondary voltage are detected and output by the instrument. These are used to interpret a variety of material properties, including conductivity, permeability, thickness, flaws (voids or inclusions), and probe-to-specimen spacing (liftoff).

In a continuous wave multiple-frequency test as shown in Fig. 2, the amplitude coefficients from each frequency are simultaneously output in real time. They can then be combined in real time by analog arithmetic circuitry to obtain the desired cancellation of unwanted parameters. The combination process may be likened to the simultaneous solution of multiple equations in which variables are eliminated by multiplying certain equations by an appropriate constant and adding the result to other equations. Hardware methods for implementing signal combination or mixing will be addressed in a following section of this paper.

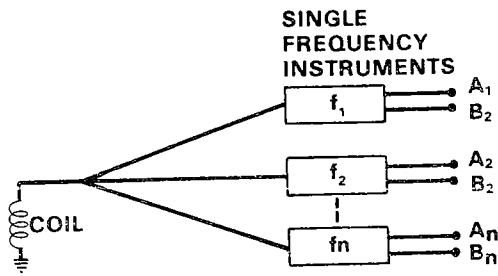


Fig. 2. Simple implementation of a multi-frequency eddy current system

Depending upon the test requirements, the optimal signal combination must be selected with a certain amount of caution. In general, there can be a wide variety of ways to combine outputs from various frequencies to cancel a given parameter, but not all of these combinations will provide meaningful or high sensitivity information on desired specimen parameters. Computer optimization techniques can be successfully used in many cases to determine the optimal combination.

APPLICATIONS

Results of three field applications of multi-frequency testing are described below. In two, steam generator tubing inspection and magnetic deposit thickness detection, output signals are directly mixed to eliminate unwanted parameters from the test data. A third application, dimensional gaging of tubing, uses two frequencies to obtain independent information on liftoff and wall thickness. Tubing ID is then obtained by combining these parameters.

Steam Generator Tubing Inspection -- Steam generator tubes in nuclear power plants are sometimes subject to corrosion mechanisms in which the amount of degradation is difficult to accurately quantify with conventional single-frequency inspection. Economic penalties to the utility are quite high if a tubing flaw inaccurately sized during routine inspection develops into a leaker during reactor operation. The plant must be shut down to plug the tube, during which the lost revenue for power sales can approach \$400,000 per day.

Battelle-Northwest has developed a multifrequency eddy current system for inspecting steam generator tubing under a research contract with the Electric Power Research Institute (EPRI), Palo Alto, California. The system has been evaluated on a steam generator mockup using two-frequency inspection. The system is currently being prepared for evaluating three- and four-frequency inspection combined with advanced probe designs. Detailed information on the system is available in References 1 and 2, and results of the mockup evaluation are contained in Reference 3. A three-frequency system manufactured by Intercontrole, a French firm, has also undergone evaluation by EPRI on their steam generator mockup; these results are also included in Reference 3.

The Battelle system has demonstrated the ability of a two-frequency test to achieve total discrimination against probe wobble and partial

discrimination against tube support indications. Alternately, if a tight-fitting or self-centering probe is used to eliminate probe wobble, total discrimination against the tube supports can be obtained. These results open substantial routes toward automated interpretation of test data, because the flaw information is no longer masked by the unwanted indications from wobble and supports.

The results described below were obtained using a two-coil differential probe of the type shown in Fig. 3. The probes are inserted through the tube past the U-bend region as shown in Fig. 4. Eddy current data are recorded as the probe is withdrawn, and then interpreted to determine the depth of flaws located in the tube. Typical support plates through which the tubes pass are made from mild steel with thicknesses up to 3/4 inch.

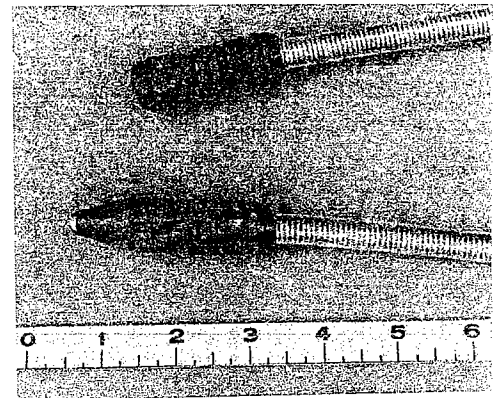


Fig. 3. Eddy current probes for steam generator tubing inspection

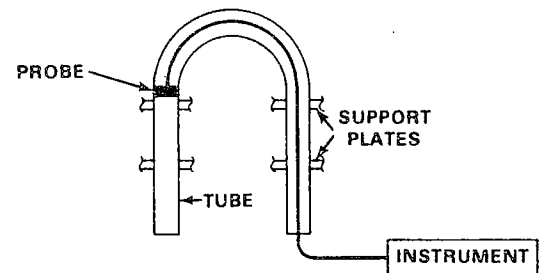
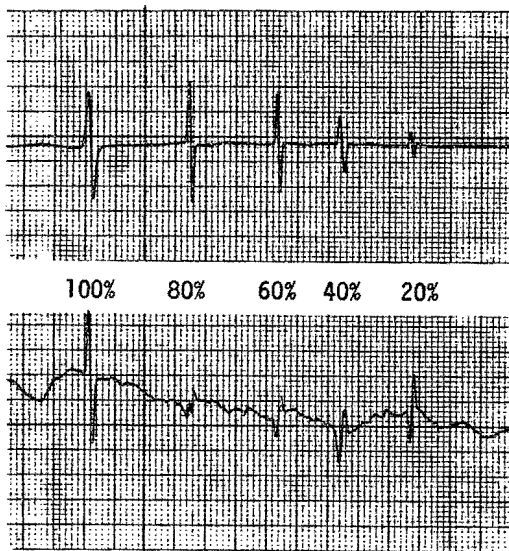


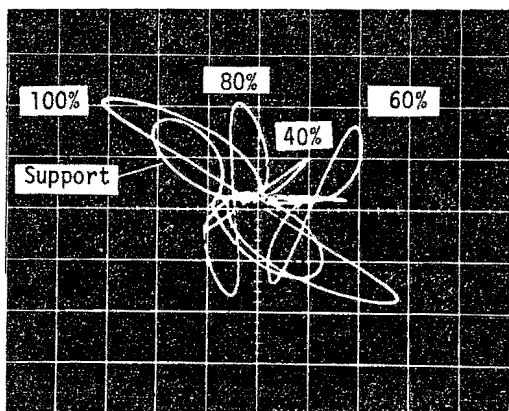
Fig. 4. Inspection of a steam generator tube

Flaw data are currently interpreted from a single-frequency test by observing the two tester outputs on an X-Y oscilloscope. A typical flaw will trace a figure-eight pattern on the oscilloscope due to the differential nature of the test. One lobe of the pattern corresponds to the first coil passing by the flaw; the other lobe is rotated 180° and is generated by the second coil. The phase angle of the flaw pattern on the display is used as a measure of flaw depth and corresponds to how far the eddy currents penetrated into the tubing wall before encountering the flaw.

Figures 5 and 6 compare the results of a two-frequency test with wobble eliminated to those of a conventional single-frequency test. In both cases, the probe was drawn through an ASME calibration tube containing a simulated support and flat bottom drill holes of the depths indicated in percent wall thickness. Figures 5a and 6a show the flaw outputs recorded on strip chart, and Figs. 5b and 6b show the same outputs plotted on an X-Y oscilloscope with support indications included. The probe wobble effect shows up on the horizontal axis of the single-frequency data in Fig. 5b as a random baseline variation which is larger than some of the flaw indications. In the two-frequency combined data of Fig. 6b, the wobble indications have been eliminated and all the flaw patterns originate from a common point. This permits electronic assessment of flaw depth by measuring and outputting the phase angle at the peak amplitude point of the flaw pattern. In contrast, the single frequency test requires visual interpretation of flaw pattern phase angle after the pattern has been stored on the screen of a memory X-Y oscilloscope.

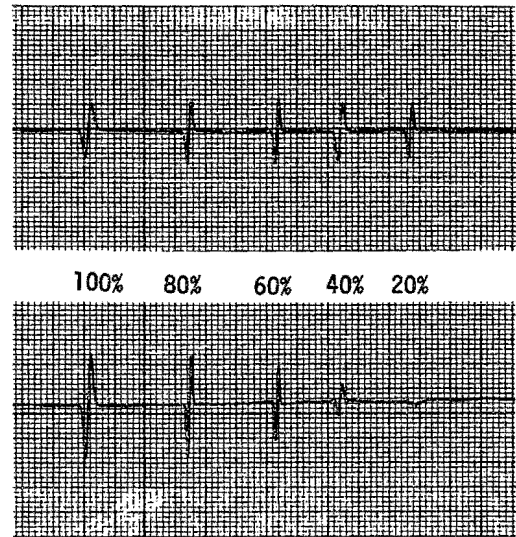


5a. Single Frequency Strip Chart Data

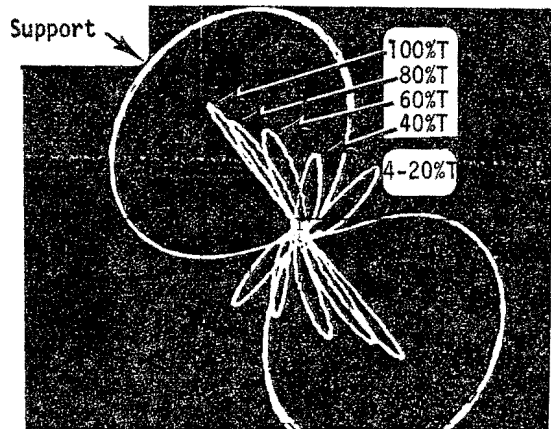


5b. X-Y Presentation of Above Data

Fig. 5. Single frequency inspection of steam generator calibration tube (400kHz). Defects are scaled in % wall thickness.



6a. Two Frequency Strip Chart Data



6b. X-Y Presentation of Above Data

Fig. 6 Two frequency (200 and 400 kHz) test results on calibration tube

The multifrequency data shown in Fig. 6 were obtained by combining the four outputs from a two-frequency test to obtain three outputs which are free of wobble information. A second iteration reduced these three outputs to the two outputs shown which contain maximum available sensitivity of phase angle of flaw depth. Note that this sensitivity is still substantially less than that available with single-frequency data, but it is wobble-free.

Another second iteration was performed in parallel on the three wobble-free outputs to obtain one final output which was free of support information. This result is shown in Fig. 7. The evaluation showed that a third frequency would be required to obtain two output channels which were both wobble- and support-free, but which still contained flaw depth information.

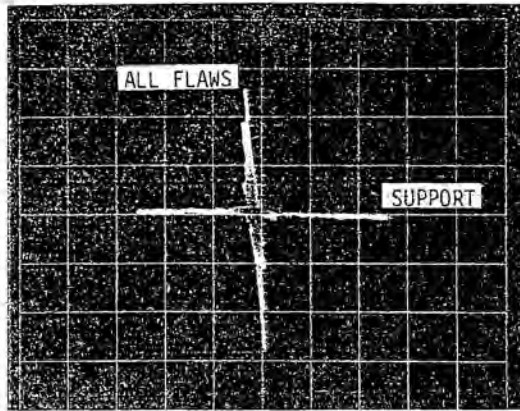


Fig. 7. Multifrequency output in which the vertical channel is free of tube support and wobble information.

In an alternate operating method, a tight-fitting or self-centering probe was used to eliminate probe wobble. This resulted in almost total elimination of the support signal while preserving flaw depth information. These results are shown in X-Y format in Fig. 8. Use of the tight-fitting probe to eliminate wobble indications is not altogether practical for steam generator inspection because the tubing may undergo diameter variations which manifest themselves as wobble indications in the output and have the potential for masking flaw indications.

The data of Fig. 8 were obtained by directly adding in-phase and quadrature test outputs from each frequency. Prior to addition, the support signals were rotated until they were 180° out of phase and sized until they were equal in amplitude. The remaining flaw information has more sensitivity of phase angle to flaw depth than does the data of Fig. 6, but possesses reduced amplitude sensitivity to shallow defects.

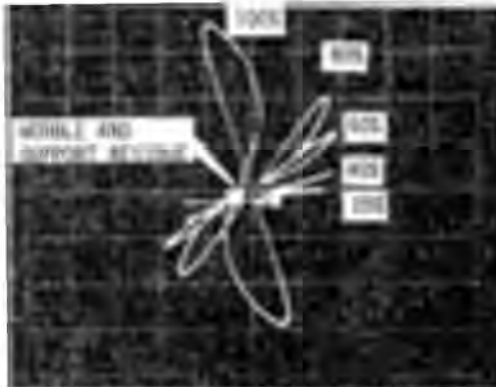


Fig. 8. Tube support discrimination with a two-frequency (200 and 400 kHz) test.

Magnetic Deposit Thickness Detection -- A two-frequency eddy current test was successfully used at Battelle to measure the thickness of an oxide containing a small percentage of magnetite which had been deposited on a base metal. A direct contact probe was used, and a frequency of 1 MHz was used to measure liftoff between probe and base metal. This relatively high frequency was chosen because its limited penetration into the base metal

would eliminate metal thickness information from the output. A second test at a frequency of 2 kHz was used to detect permeability of the oxide while remaining insensitive to the presence of the base metal. This information was then used to correct the 1 MHz data against the influence of permeability, resulting in an output which contained pure liftoff or oxide thickness information.

A block diagram of this test is shown in Fig. 9, and the results from inspecting a calibration sample are shown in Fig. 10. An accuracy of ± 0.0006 in. was obtained over an oxide thickness range of 0.0 to 0.010 in.

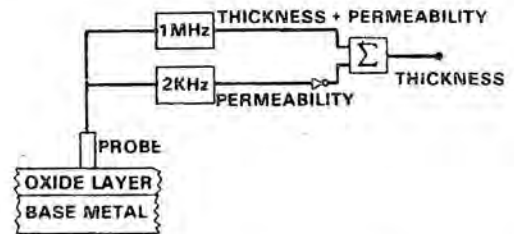


Fig. 9. A two-frequency test for thickness measurement of a magnetic oxide layer

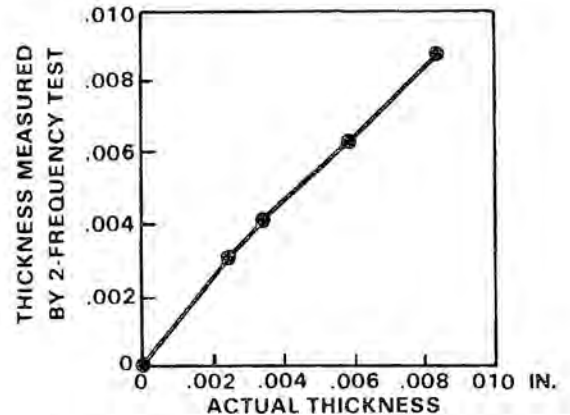


Fig. 10. Response of two-frequency test for thickness of magnetic oxide on metal

Dimensional Gaging of Tubing -- A two-frequency test has been demonstrated for measuring ID, OD and wall thickness in nonferrous tubing. The technique is easier to implement than its ultrasonic counterpart because there is no need for a water bath or other couplant to facilitate transferring energy into the part. It is, however, not quite as accurate as ultrasonic techniques, which can measure tubing dimensions with typical accuracy of 0.0001 in.

A block diagram of the test is shown in Fig. 11. A pair of diametrically opposed point probes was simultaneously excited with a high and a low frequency. The high frequency was chosen such that only shallow penetration of the tube wall occurred, while the low frequency was selected so that the nominal wall thickness was equal to one penetration depth. The high frequency tests were

used to measure liftoff. Both their outputs were subtracted from an adjustable offset constant to obtain a measure of the OD. The two low frequency outputs were processed to obtain liftoff-free measurements of wall thickness. These two values were summed together to obtain total wall thickness; this sum was then subtracted from the OD to obtain ID dimensions. The addition and subtraction was performed in real time with analog arithmetic circuitry.

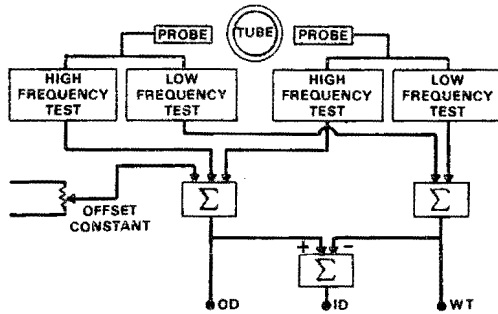


Fig. 11. Implementation of a two-frequency dimensional gaging test for tubing

MULTIFREQUENCY DATA ACQUISITION INSTRUMENTS

The basic approach in multifrequency data acquisition is to parallel an additional electronic channel onto the probe system for each additional frequency. The two main design differences between a single frequency system and a multifrequency system are: 1) the probe driver is usually a summing device which sums together sinusoids from all test frequencies, and 2) each output of the instrument must be generated in such a manner that it responds only to its particular test frequency while remaining insensitive to other frequencies.

This second requirement may be met in a variety of ways. One approach is to employ band-pass filtering for each frequency prior to detection of the amplitude coefficients. A second approach uses sequential commutation or multiplexing of individual test frequencies onto the probe system so that only one frequency at a time is present on the probes. A third method uses either analog or digital means to precisely multiply the composite probe signal by sine and cosine waves of each test frequency, followed by low pass filtering, to obtain individual amplitude coefficients. A fourth method, used in a Walsh function scheme by Battelle as described in References 1 and 2, employs simple synchronous detectors driven by square wave reference signals. Individual outputs are rendered free of amplitude coefficients from the other test frequencies by either:

- a) requiring all test frequencies to be related to each other by an even integer, or
- b) permitting test frequencies to be related by both even and odd integers and then combining the detector outputs in a pre-determined manner to eliminate unwanted amplitude coefficients from other frequencies.

This fourth method enjoys a substantially reduced parts count and can be implemented in compact instrument packages. These four methods are described briefly below.

A multifrequency system employing one type of bandpass filtering is shown in Fig. 12. Each single-frequency channel taps the composite probe signal, buffers it with preamplification, and then eliminates the other frequencies with a bandpass filter. This method suffers from the fact that the filters must be retuned each time frequencies are changed. Additionally, a great deal of phase shift can occur in the filter outputs for slight drifts in oscillator frequency or filter center frequency.

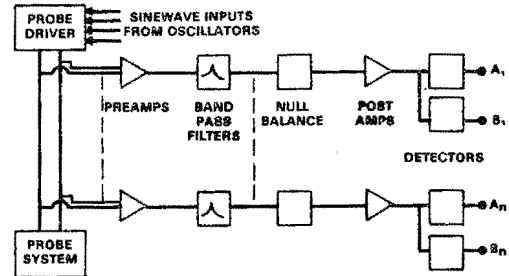


Fig. 12. A multifrequency system employing band-pass filtering

One type of multifrequency system which employs multiplexing of individual single-frequency instruments is described in Reference 4. The basic process involves using a dedicated single-frequency instrument for each test frequency; these can be off-the-shelf commercial instruments. The instruments are commutated onto the probe system one at a time in sequence. Their outputs are sampled while the probe data is being accessed and the sampled values are stored and used as system outputs. This approach is a highly expedient way to assemble an operational multifrequency system and it does not necessarily require a high degree of electronic expertise as compared to some of the other schemes. Caution must be used in multiplexing low test frequencies (1 kHz, for example) due to longer commutation times required to reach a steady state condition for sampling the data. This can force an undesirable upper limit on probe translation speed or on the rate at which probe data can change. Additionally, this approach can require substantial amounts of cabinet space to house the individual single frequency instruments.

The third method uses correlation-type phase sensitive amplitude detectors to extract amplitude coefficients of individual frequencies from a multiple-frequency waveform. This involves linear multiplication of the composite signal by sine and cosine waveforms of the test frequency to be extracted, as shown in Fig. 13. The reference sine and cosine signals must be synchronized with the test frequency and may be derived from the oscillator for that test frequency. The product of the multiplication will be a sine squared term plus a DC term. This DC term is one of the two desired amplitude coefficients and is extracted by a low pass filter. If the reference waveforms contain no harmonic distortion and the multipliers are perfectly linear, the outputs will contain no

contribution from other test frequencies in the composite waveform. In a typical analog implementation of this method, however, one can expect as much as 2% pollution of the outputs by other test frequencies. In most cases this is inconsequential.

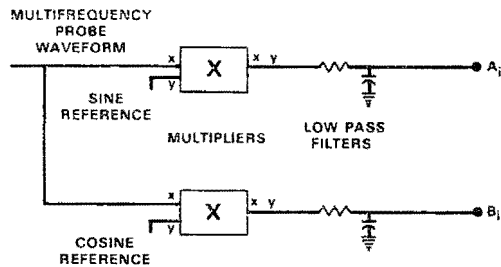


Fig. 13. Correlation type phase sensitive amplitude detection

The detection process of Fig. 13 may be implemented by either analog or digital techniques. Integrated circuit four quadrant multipliers followed by passive RC low pass filters form an analog technique suitable for some applications. This method has two main disadvantages: 1) analog multipliers are typically quite noisy devices, with some having an input noise level of 900 microvolts RMS, and 2) both a sine and a cosine reference wave must be generated for each frequency, requiring more sophisticated oscillators. In a digital implementation of the detection scheme of Fig. 13, small computers can be used to perform many or the functions in real time, including generating the probe drive and reference signals, multiplying, and averaging the product to extract amplitude coefficients. The digital probe drive signal from the computer is converted to an analog sinusoid by D/A conversion, and the probe output signal is digitized and input to the computer for processing. Computer speed determines the maximum test frequency, the maximum number of frequencies which can be used simultaneously, and the maximum translation speed of the probe.

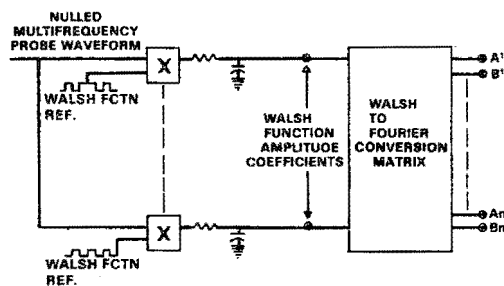


Fig. 14. A Walsh function method for implementing a multifrequency test.

Battelle has used the fourth detection method based on Walsh functions for implementing a multifrequency steam generator tubing inspection system (References 1 and 2). This method uses detectors similar to those shown in Fig. 13 except that the reference signals are binary (two state) waveforms. The gain of the multiplier is +1.0 during the

reference high state, and -1.0 during the reference low state. The multiplier is a much simpler device than that required for true four-quadrant multiplication and does not inject noise into the signal. The reference signals are Walsh function waveforms synchronized to the test frequencies. Walsh functions (Reference 5) are a series of orthogonal binary waveforms. Some are 50% duty cycle square waves; the balance have additional state changes during a period.

A block diagram of the Walsh function scheme is shown in Fig. 14. The outputs of the detectors are amplitude coefficients of Walsh functions contained in the composite waveform. As the Walsh amplitude coefficients can be made up of Fourier amplitude coefficients from more than one frequency, they are input to an analog arithmetic matrix which converts from Walsh to Fourier amplitude coefficients. The main advantage of this approach is simplification of the circuitry. A four-frequency system (100, 200, 300 and 400 kHz) was fabricated onto two circuit boards in the prototype instrument shown in Fig. 15. This approach would work equally well for Rademacher functions, which are all 50% duty cycle square waves.

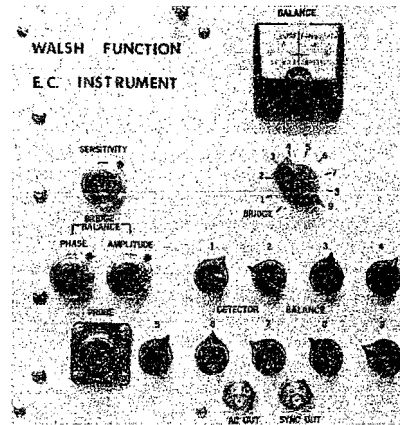


Fig. 15. A prototype four frequency eddy current instrument using Walsh function detectors

MULTIFREQUENCY DATA PROCESSING

In its simplest sense, the elimination of unwanted test parameters by processing of multifrequency data is equivalent to simultaneous solution of multiple equations. Linear combinations of output channels are performed in real time by analog arithmetic circuits. An example of this is shown in Fig. 16 where three signals containing information on three parameters are reduced to two signals which are both free of the parameter Z. This configuration could be used directly for eliminating probe wobble signals from a tubing test.

The probe wobble locus defined by any pair of outputs in a tubing test will usually plot as a straight line and can be eliminated by the simple technique shown in Fig. 16. For more complex signals such as the figure-eight pattern from a support plate, a more sophisticated approach is required. One of these is shown in Fig. 17. The support indications from two different

frequencies are rotated and sized until they are 180° out of phase and equal in amplitude. The in-phase and quadrature components are then summed to produce two support-free output signals.

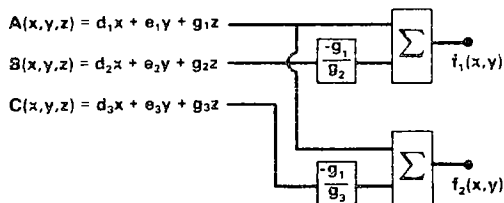


Fig. 16. Simplistic treatment of parameter elimination

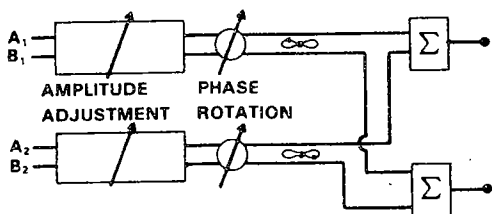


Fig. 17. Two-frequency data processing method for elimination of parameters having complex output indications

A third approach for eliminating unwanted parameters treats the signals from a perspective of N-dimensional vector space. A plane in the vector space is located which totally contains the unwanted indication. An output channel is then derived which is perpendicular to this plane and which thereby contains none of the unwanted information. This process can be implemented using a multiplicity of phase rotators of the type commonly used in commercial single-frequency instruments. A phase rotator is a four-terminal device with inputs X and Y and outputs X' and Y', and has a transfer characteristic of:

$$X' = X \cos \theta - Y \sin \theta$$

$$Y' = Y \cos \theta + X \sin \theta$$

where θ is the desired rotation angle.

A configuration of phase rotators used in the Battelle system for processing two-frequency data is shown in Fig. 18. Rotators 1, 2 and 3 are used to obtain three wobble-free indications from the four wobble-prone inputs. For tube support discrimination, rotators 4 and 5 are adjusted to obtain a two-dimensional X-Y presentation in which the plane of the figure-eight support indication is parallel to the discarded Z axis. The support indication thus appears as a straight line in an X-Y plot of these two outputs. Rotator 6 is then used to place the support line all into one of the final output channels, leaving the other one free of support information. A response of this type is shown in Fig. 7.

Some care is required in selecting the final combination of signals for a given test requirement.

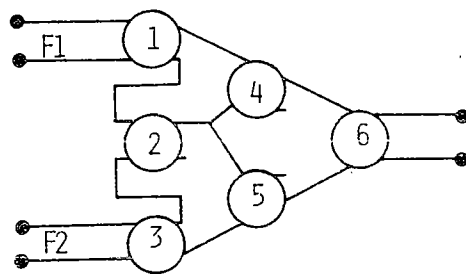


Fig. 18. A multifrequency data processing method using a multiplicity of phase rotators

There may be a variety of combinations which will eliminate an unwanted parameter, but only a few of these may provide meaningful or independent information. For example, in the arrangement of Fig. 16, outputs A and C could also be combined to achieve a third output, f_3 , which is free of parameter Z. However, these three outputs will not necessarily all contain independent information on the desired specimen parameters. They must be examined in turn to determine which of them provide the desired information. Computer optimization techniques are somewhat useful in making these selections.

FREQUENCY SELECTION

The skin effect phenomenon, which predicts amplitude and phase distribution versus depth of eddy currents flowing in a conductor, is undoubtedly the most useful criterion in selecting test frequencies. The general objective in frequency selection is to obtain frequencies which have independent information on specimen parameters so that cancellation of one parameter does not result in cancellation of other desired parameters. The skin effect plays an important role in obtaining independent information from properly selected frequencies.

A generalized approach to frequency selection is:

1. Select a frequency range in which the skin effect provides independent information on wanted and unwanted specimen parameters.
2. Select frequencies in this range for which: A) the indications from unwanted parameters are similar enough for good cancellation, and B) the information remaining after cancellation contains meaningful information on other specimen parameters.

In many cases the separation between individual frequencies should be held to as small as 2:1. For example, in the previously described test for steam generator tubing, it was found that a frequency separation greater than 2:1 would not produce support plate indications that could be effectively cancelled. Frequencies of 200 kHz and 400 kHz were thus used for support cancellation. The support indication from the 100-kHz test

evidenced enough dissimilarities from that of the 400-kHz test to the point that these two frequencies did not produce effective cancellation of the support. This was attributed to the greater penetration depth of the 100-kHz eddy currents in the tube wall material, resulting in support indications being manifested at greater distances between the probe and the support region.

CONCLUSIONS

Continuous wave multifrequency eddy current inspection provides an extremely powerful assist in certain areas of material characterization. It provides the ability to eliminate or reduce unwanted parameters that may otherwise mask desired test information. Continuous wave testing offers an advantage over pulsed techniques in that individual frequencies may be matched to the particular test requirements. The responses from individual frequencies may be observed directly during the test development and frequency selection process. Continuous wave multifrequency testing may be implemented in a variety of ways, ranging from multiplexing of commercial single-frequency instruments to assembly of compact portable instruments or to fully computerized implementations.

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