FREQUENCY DOMAIN METHODS FOR THE ANALYSIS
OF MULTIFREQUENCY EDDY CURRENT DATA

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INTRODUCTION

Eddy current techniques for nondestructive testing play a significant role in a variety of industries for evaluating the integrity of products. Any nondestructive testing system consists of five major functions as shown in Fig. 1. The test object to be examined is energized by an excitation transducer. The response of the energy-specimen interaction is picked up by a receiving transducer. The received signal is then processed and analyzed for defect characterization or Inversion. The ultimate goal of an NDT system is the inverse problem of determining the defect profiles in the test object, given the measurements from the receiving transducer. The defect characterization scheme is generally based on the solution of the partial differential equations governing the energy-test specimen interaction. As seen in Fig. 1 one of the primary steps involved in the inverse problem solution is that of signal conditioning. Pre-processing of signals is essential in certain situations in order to extract the true defect signal from the measured data. This paper describes the signal conditioning aspect of the inverse problem in the context of steam generator tube inspection using eddy current method.
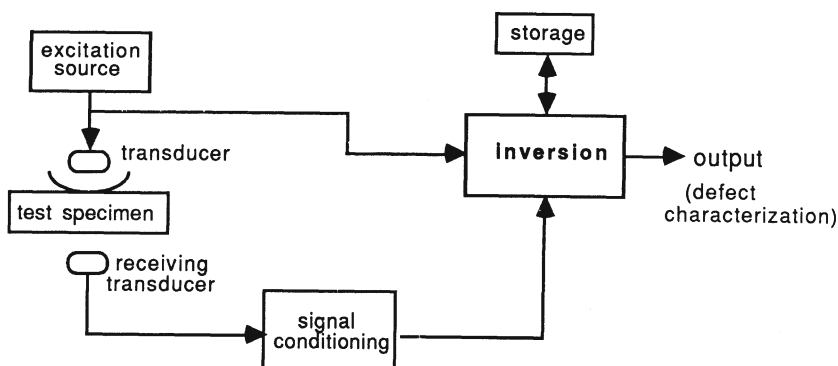

Fig. 1. Functional units of a generic NDT system.

Steam generators are the heat exchange units in a nuclear power plant. Each unit shown in Fig. 2 contains a large number of Inconel tubes through which the primary coolant from the reactor circulates. The heat from the primary coolant is transferred to a mixture of high pressure steam and water circulating outside the tubes. The steam generator tubes are anchored at intervals by support plates made of carbon steel. The support plates react with the steam and water and result in corrosion products that are deposited in the crevice gap between the tube and the support plate. The growth of this deposit over a period of time leads to denting and cracking of the tubes which can result in the contamination of the secondary coolant by the radioactive primary coolant. It is therefore of critical importance to evaluate the integrity of the tubes at regular intervals so that the anomalies can be detected in early stages.

The differential eddy current probe is one of the commonly used device for detecting defects in steam generator tubing [1]. The principles of operation of the eddy current method are reported in a number of papers [2,3]. Briefly, the eddy current method consists of exciting the probe by an alternating source of current and measuring the terminal impedance of the probe coil as it scans the test specimen. Fig. 3 shows a typical differential eddy current probe signal due to an O.D. slot in the tube wall.
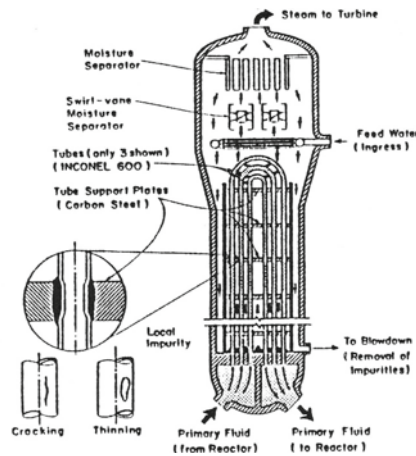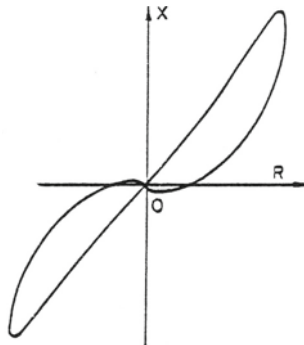

Fig. 2. Steam generator unit.

Fig. 3. A typical eddy current probe signal due to a defect in the tube wall.

Conventional eddy current inspection techniques involve the use of eddy current probe responses due to a single excitation frequency. One of the limitations inherent in single frequency testing [4] is the sensitivity of the response signal to a variety of test variables such as specimen electrical conductivity, magnetic permeability, test specimen thickness, coupling between probe coil and specimen resulting in unwanted contributions to the signal as the probe moves along the tube. Since the defects in the steam generator tubes occur invariably in the vicinity of the support plates, the resulting eddy current response is generally complex as seen in Fig. 4 caused by the vector addition of the contributions from defects, support plates, proble wobble and so on. It is therefore important to extract the desired defect information from the complex signal. This is accomplished using the multifrequency eddy current test method.
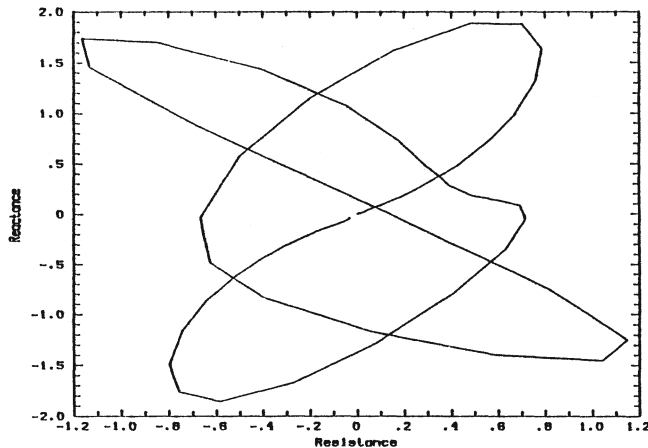

Fig. 4. Eddy current signal due to a defect in the vicinity of a support plate.

MULTIFREQUENCY EDDY CURRENT TESTING

Libby [2] developed the multifrequency eddy current test method where eddy current data is collected at several frequencies. The increased amount of information is analyzed by multifrequency techniques where the data from individual frequencies are combined in such a way that unwanted contributions are suppressed and relevant defect signals are retained. The extraneous test variable suppressed may be ferromagnetic tube supports, tube sheet, tube I.D. noise, small dents or combinations of all these variables.

Currently these principles have been implemented using mixing modules in which eddy current signals at two frequencies are mixed appropriately. The in-phase and quadrature components are combined linearly for selectively suppressing an unwanted test parameter [5]. However, the complexity of the design and problems of optimizing the combination parameters increases as the number of parameters and frequencies increase.

An alternate approach for implementing the multifrequency eddy current algorithm using affine transformations is proposed here. This approach is similar to procedures used in image registration and can be formulated in the time domain as well as the frequency domain, as described on next page.

The fundamental assumption made in the multifrequency eddy current analysis is that eddy current signals at two frequencies are RST (rotation, scaling, translation) transformations of each other.

The steps involved in the analysis of the eddy current data at two different frequencies are described below, for suppressing the contribution due to the support plate.

1. Let $\underline{S}_a$ and $\underline{S}_b$ be the support plate signals at frequencies f_a and f_b.

2. Let $\underline{S}_b = \{T\}\ \underline{S}_a$ where the transformation T is a function of

   S_x: scaling in x direction

   S_y: scaling in y direction

   t_x: translation in x direction

   t_y: translation in y direction

   ϕ : rotation about the origin

   Estimate the transformation parameters using $\underline{S}_a$ and $\underline{S}_b$

3. Let $\underline{C}_a$ and $\underline{C}_b$ be the composite (support plate + defect) signals at frequencies f_a and f_b.

4. Then the defect signal

$$\underline{d}_{f_b} = \underline{C}_{f_b} - T \cdot \underline{C}_{f_a}$$

Time Domain Implementation

In time domain, the basic transformation of rotation scaling and translation (RST) can be combined to yield a single transformation matrix [6].

$$T = \begin{bmatrix} S_x\cos\theta & S_y\sin\theta \\ -S_x\sin\theta & S_y\cos\theta \\ S_x(t_x\cos\theta - t_y\sin\theta) & S_y(t_x\sin\theta + t_y\cos\theta) \end{bmatrix} \qquad (1)$$

Using the support plate signals $\underline{S}_a$ and $\underline{S}_b$, the transformation parameters are obtained by least squares estimation procedure, i.e. by minimizing the error function

$$E = \|\ \underline{S}_b - T \cdot \underline{S}_a\ \|^2 \qquad (2)$$

with respect to the transformation parameters. This results in a set of five nonlinear equations to be solved simultaneously [6].

Initially the method was implemented using only rotation and scaling parameters (θ, S_x, S_y) and the results of implementation looked very promising [6]. An alternate method for estimating the transformation parameters is in the frequency domain via the Fourier descriptors [7].

Frequency Domain Implementation

The principal advantage of this method is that in the frequency domain, the transformation equations are decoupled in the parameters and

significantly easier to solve. In order to implement the transformation in the frequency domain the signals are first represented in the frequency domain using the Fourier descriptors [7].

Since the impedance plane trajectories obtained from eddy current probes are closed curves, a point (x,y) on the signal can be represented as a function of the arc length ℓ (from an arbitrary starting point), in terms of the complex contour function

$$u(\ell) = x(\ell) + j\ y(\ell) \tag{3}$$

Since

$$u(\ell) = u(\ell) + L) \tag{4}$$

where L is the total arc length, the periodic function $u(\ell)$ can be expanded in a Fourier series

$$u(\ell) = \sum_{n=-\infty}^{\infty} C_n e^{j2\pi n\ell/L} \tag{5}$$

where the Fourier series coefficients

$$C_n = \frac{1}{L} \int_0^L u(\ell)\ e^{-j2\pi n\ell/L}\ d\ell \tag{6}$$

The linearity property of the Fourier series expansion yield a simple relation between the Fourier series coefficients of two curves that are transformed versions of each other. Let τ be a simply closed curve with Fourier series coefficients $\{C_n\}$. Let τ' be obtained by rotation (θ), scaling (s) and translation (p) of the curve τ. Let $\{\underline{C}_n'\}$ be the Fourier series coefficients of τ'.

Using properties of Fourier transform the relation between

$\{\underline{C}_n\}$ and $\{\underline{C}_n'\}$ is given by

$$C_0' = C_0 + p \tag{7}$$

$$C_n' = se^{j\phi}C_n \qquad n = 1,2,\ \ldots \tag{8}$$

The transformation parameters s, θ, and p for the multifrequency algorithm are obtained by considering just one of the Fourier series coefficients of the two support plate signals at frequencies f_a and f_b.

RESULTS

The results of implementing the proposed algorithm using time domain equations are presented in [6]. The estimation of the transformation parameters in frequency domain using just one of the harmonics, is less optimal than in the time domain where the parameters are obtained using least squares estimation. Some initial results of the frequency domain implementation are presented. Fig. 5a and 5b are the finite element predictions of the support plate signals at frequencies 100KHz and 50 KHz respectively. Representing these signals by the complex contour function, the Fourier series expansion was computed. The Fourier series coefficients were used to determine the transformation parameters s and θ using Eqn. (8). Since these signals were obtained using the finite element model, translation was neglected.
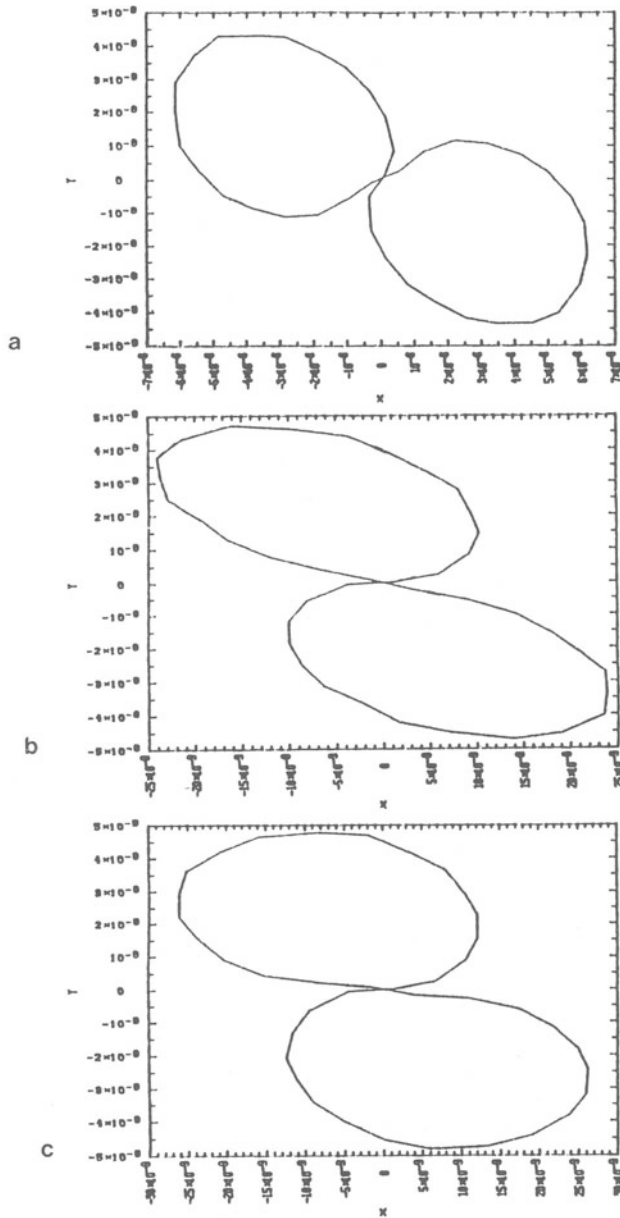
Fig. 5. Eddy current probe signal of a support plate at (a) 100KHz
(b) 50KHz (c) Signal in (b) transformed.

The transformation parameters s and ϕ were used to transform the 50
KHz signal and the transformed signal is presented in Fig. 5c. The next
step was to generate a composite signal due an O.D. slot located in the
vicinity of a support plate. The composite signals at 100 KHz and 50 KHz
are shown in Figs. 6a and 6b respectively. Using the transformation
parameters estimated earlier, the signal in Fig. 6b was transformed as
seen in Fig. 6c. Subtracting the signal in Fig. 6c from the signal in
Fig. 6a the resulting defect signal due to the O.D. slot alone is shown
in Fig. 6d. The finite element prediction of the defect signal due to
the O.D. slot, shown in Fig. 7, compares reasonably to the signal in Fig.
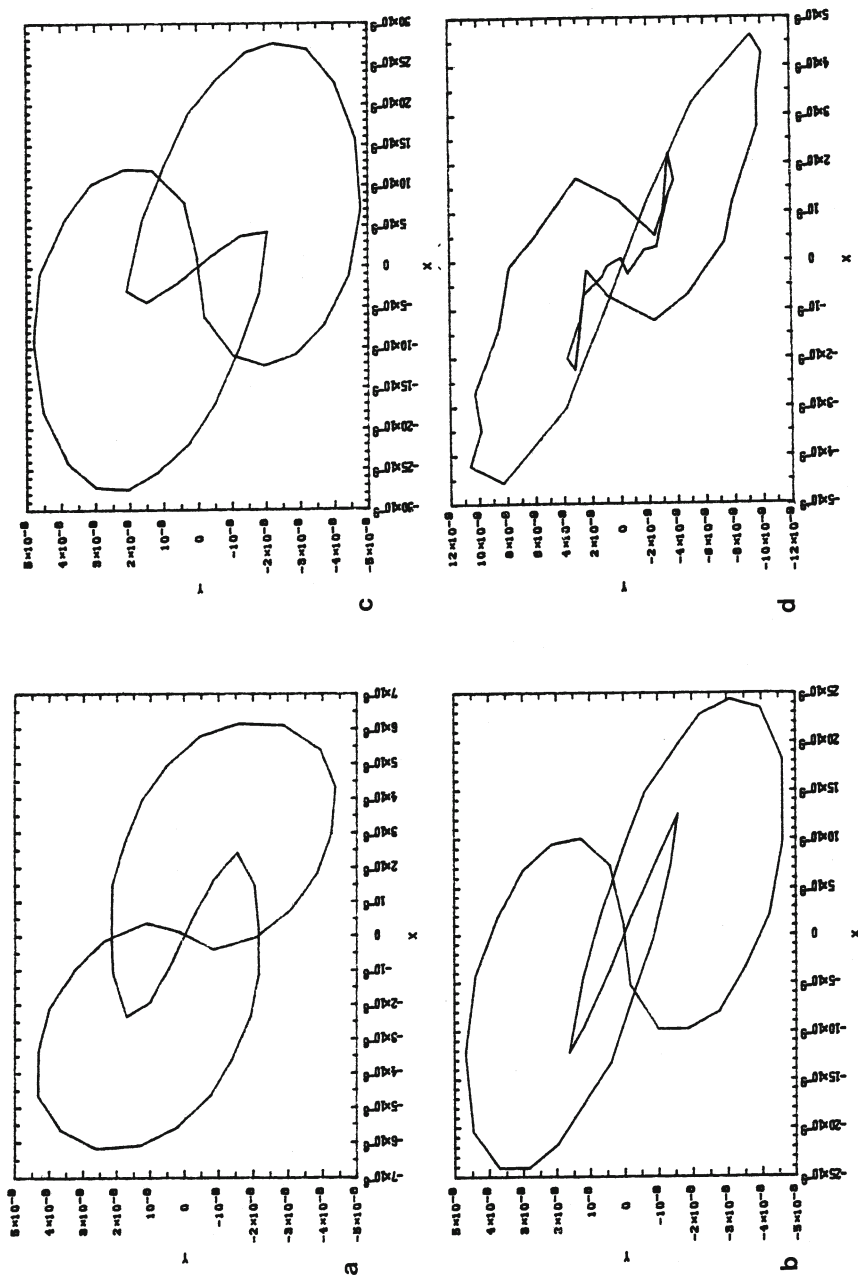6d.

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Fig. 6. Composite (support plate + O.D. defect) eddy current signal at (a) 100KHz (b) 50KHz (c) signal in (b) transformed and (d) signal in (a) - signal in (c).
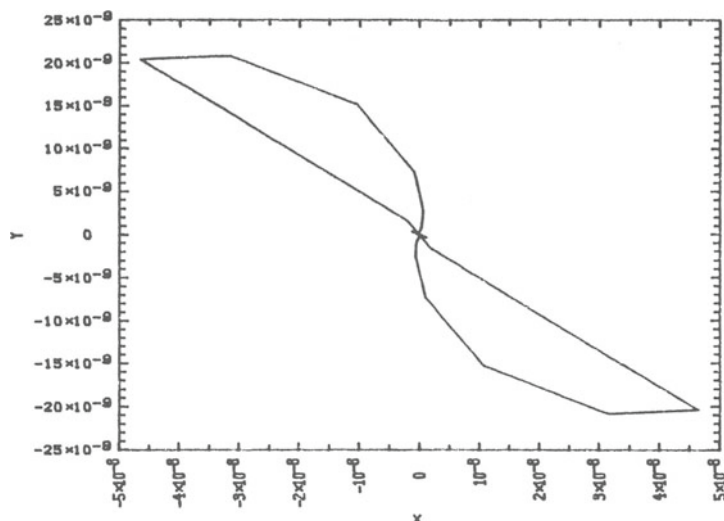
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Fig. 7. Eddy current signal due to an O.D. defect.

CONCLUSIONS

The results show the feasibility of the approach for suppressing the support plate contribution in a composite signal, obtained when a defect in the tube wall is in the vicinity of the support plate. The method is robust and the computational burden is low, particularly in the frequency domain implementation. However, the error introduced in the time domain algorithm is considerably lesser due to the more optimal nature of the least squares estimation procedure as opposed to the frequency domain algorithm where the parameter estimation was done using just one harmonic of the signals. Further research needs to be done on various combinations of defect, support plate and other extraneous effects.

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