DEVELOPMENTS IN THE FINITE ELEMENT MODELING OF EDDY CURRENT PHENOMENA AT COLORADO STATE UNIVERSITY

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ABSTRACT

Traditionally, eddy current nondestructive testing phenomena have been modeled analytically, the describing partial differential equations being solved by classical techniques after appropriate assumptions have been made with regard to material nonlinearities and geometrical constraints. To date, the analytical modeling approach has not produced the kind of results which are directly applicable to the prediction of eddy current signals obtained in steam generator tubing NDT. The major purpose of the work described in this paper is to determine if finite element analysis (a numerical rather than analytical technique), originally developed for the study of magnetic fields in electrical machinery, can be applied to the study of eddy current NDT phenomena. Various stages of development in the finite element modeling of eddy current NDT phenomena at Colorado State University are described in this paper. Comparison of finite element model results with the results obtained by analytical solutions and experimental observations show clearly the applicability of this model for steam generator support plate/tubing inspection problems.

INTRODUCTION

Inverting NDE signals to obtain quantitative information concerning surface and/or subsurface conditions of a test piece is possible only with the development of a viable theoretical model capable of describing the interactions of various factors influencing the measured signal. Classical approaches using integral solution techniques to provide direct solutions of the electromagnetic diffusion equations describing field/flaw interactions have not been successful in handling material nonlinearities (magnetic permeability μ, and electrical conductivity σ) complicated defect geometries, etc.[1] Where closed form mathematical solutions do exist, the underlying assumptions of the theories with regard to the number of dimensions, linearity of material properties, symmetry in problem geometry, boundary conditions and defect size, shape and location tend to invalidate any realistic application of the results to the problem of 'defect-characterization'.

The principal uses of a good theoretical model in any NDE technique are:[2]

- describe the physics of interaction between the applied ac field, induced eddy currents and 'defects' in the test specimen,
- serve as a 'theoretical test bed' for situations difficult or impossible to replicate experimentally,
- generate eddy current probe output signals for a wide variety of defect shapes (avoiding costly sample preparation), thus aiding in the determination of defect characterization parameters, i.e. train automated signal analyzers such as the adaptive learning network (ALN) system, and
- aid in the design of eddy current probes.

Fig. 1 shows how a reliable theoretical model can replace conventional machine made defect standards; thus avoiding expensive, time consuming and less accurate (because of machining tolerance) sample preparation. In this regard it is difficult to fabricate subsurface defects without affecting the surrounding material integrity and properties. No such limitation exists with a valid theoretical model.

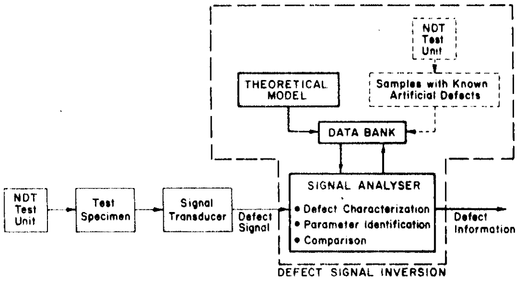


Fig. 1. Block diagram of a general automated NDE system.

An approach which does show promise of providing all the above listed capabilities is a numerical model employing finite element analysis techniques. The following sections of this paper describe the developments in finite element modeling of electromagnetic NDT phenomena in general and the eddy current method in particular at Colorado State University.

ACTIVE, RESIDUAL AND EDDY CURRENT METHODS

The common basis of the seemingly different forms of electromagnetic methods of NDT--active leakage field and residual leakage field measurements in ferromagnetic materials, and eddy current technique in the case of electrically conductive materials--is their B/H characteristics as shown in Fig. 2.[3-5] The commonality is emphasized further when one considers the corresponding diffusion equation in two-dimensions (x,y). That is active leakage case:

$$\frac{\partial}{\partial x}\left(\nu\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu\frac{\partial A}{\partial y}\right) = -J \qquad (1)$$

residual leakage case:

$$\frac{\partial}{\partial x}\left(\nu\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu\frac{\partial A}{\partial y}\right) = 0 \qquad (2)$$

eddy current case:

$$\frac{\partial}{\partial x}\left(\nu\frac{\partial \bar{A}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu\frac{\partial \bar{A}}{\partial y}\right) = j\sigma\omega\bar{A} - \bar{J} \qquad (3)$$

where

ν = reluctivity (m/Henry)

σ = electrical conductivity $(\text{ohm-m})^{-1}$

J = current (source) density (amp/m^2)

$\bar{A}, \bar{J}$ = complex quantities

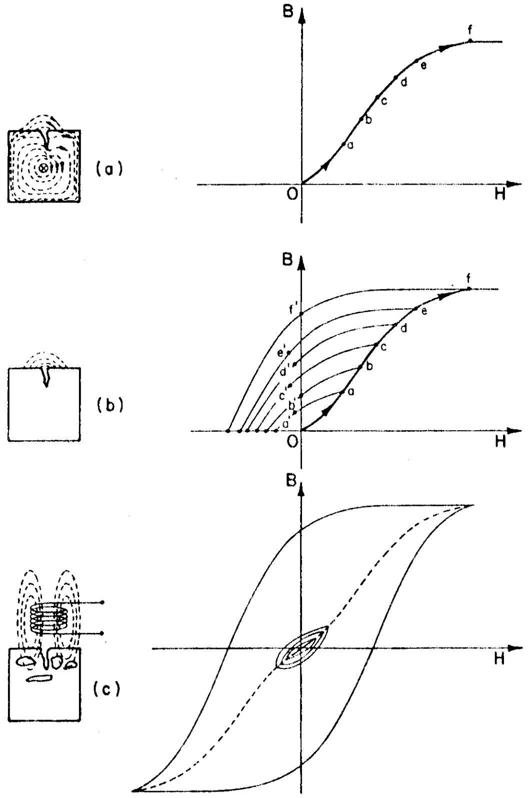


Fig. 2. Classification of Electromagnetic NDT Methods. a) Active leakage field, b) residual leakage field, and c) eddy current.

A unified approach to modeling electromagnetic NDT phenomena is possible, if one utilizes numerical analysis techniques, such as the finite element approach, to satisfy the describing partial differential equations.

The finite element modeling of electromagnetic NDT methods began with the active case at Colorado State University.[6-10] With dc excitation, the working region for each element of the ferromagnetic material under test is along the initial magnetization curve (region o-f of Fig. 2a). Project work to date with ARO sponsorship has involved the finite element modeling of two-dimensional linear and nonlinear leakage field profiles around a variety of surface and subsurface defects. In addition axisymmetric code has been developed as part of an EPRI project to study the problem of detecting magnetite buildup in the crevice gap of nuclear power plant steam generators using a variable reluctance probe.

Next, the model was extended successfully to the residual leakage field method.[11] When the dc excitation is removed, the working points a through f in Fig. 2 relax to working points in the second quadrant of the B/H plane (a' through f'). Material around a defect in the test specimen thus acts as a permanent magnet, supplying a residual leakage field which can be detected by magnetic particles or other flux sensitive devices. The results of this investigation show that the residual phenomena can be modeled, if the B/H characteristics are known accurately.

With ac excitation, as shown in Fig. 2c), the magnetization levels are normally sufficiently low that the working points of a ferromagnetic test specimen describe a family of hysteresis loops close to the origin of the B/H plane. Both two-dimensional and axisymmetric codes have been developed with constant μ and σ values. The rest of this paper describes the eddy current modeling work at Colorado State University.

EDDY CURRENT MODELING

The finite element formulation of electromagnetic diffusion equations describing eddy current NDT phenomena, minimization of the corresponding energy functional, calculation of complex magnetic vector potential at each node of the finite element mesh and the prediction of differential eddy current probe signal trajectories for axisymmetric geometries have all been reported elsewhere.[12-14] Verification of the finite element code was carried out in three steps (Fig. 3). Finite element results were compared with classical solutions obtained for an ac source above an infinite conducting plane and for an ac coil in air. In addition finite element predictions of impedance are obtained for a coil surrounding a variety of conducting rods and the results compare favorably with the integral equation solutions of ORNL workers. The finite element code has also been applied to steam generator testing problems, and predictions made of eddy current probe impedance trajectories for I.D. and O.D. axisymmetric slots in Inconel tubing, which agree well with corresponding experimental data.

In order to explain the kind of results one can obtain using this numerical model consider an example of void growth on both sides of a tube support plate. A sectional view of such an axisymmetric geometry with differential eddy current coils is shown in Fig. 4. Starting from a tight fit and voidless carbon steel support plate around an Inconel 600 tube, finite element analyses were carried out for progressively increasing voids. The cases studied are shown in Fig. 5. Part of the finite element mesh employed in this study is given

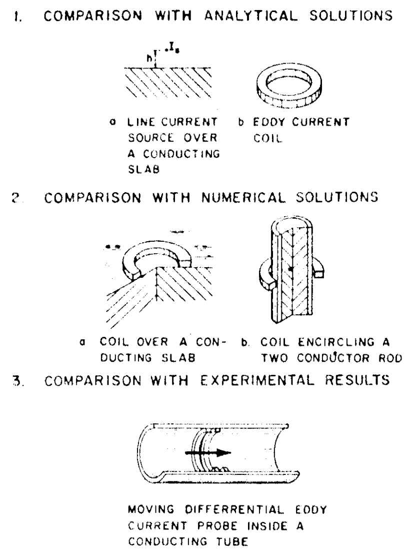


Fig. 3. 2-Dimensional and axisymmetric geometries analyzed using finite element model.

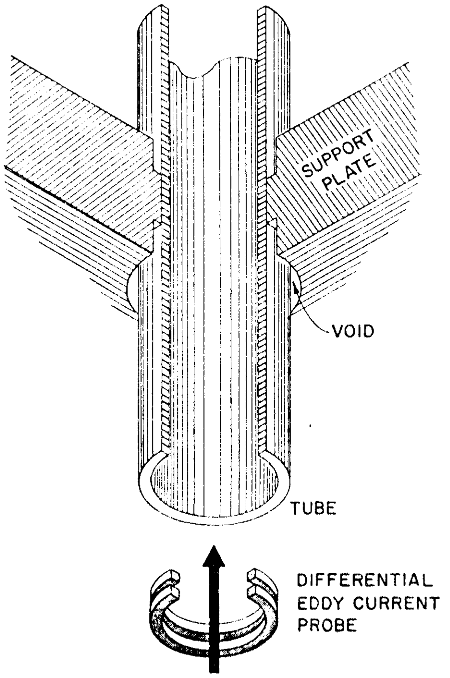


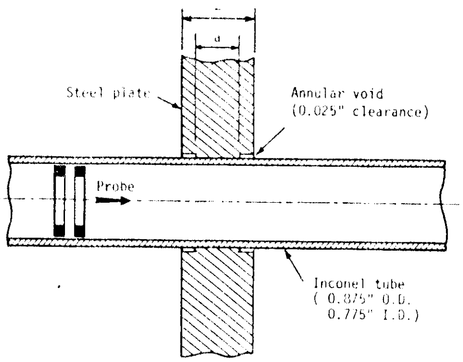
Fig. 4. Void growth in a tube support plate.

in Fig. 6 along with the corresponding geometry.

The major purpose of the numerical model is to calculate the vector potential values at the mesh nodes for a given source position (here, eddy current coils with opposing source densities). From these potential values one can calculate numerically the differential impedance of the probe. By repeating this procedure for successive probe positions it is possible to obtain a complete trajectory of the probe signal as the probe passes from one side of the plate to the other. Plots of the predicted and experimentally recorded signal trajectories for two different frequencies are given in Fig. 7. Flux plots when the probe is at the plate center are shown in Fig. 8 for three different geometries and for two frequencies in each geometry. Following are the material properties used in the analysis:

Material	Electrical conductivity $(\mathrm{ohm}\text{-}\mathrm{m})^{-1}$	Relative permeability
Air	0	1
Inconel	1.0×10^6	1
Steel	5.0×10^6	50

While contour plots (flux lines and eddy current phase angle plots) provide a visible



L 0.75"

Plate Number	$\left(\frac{d}{L}\right)$	(L-d)/2 (inch)
1	1	0.0
2	1/6	0.0625
3	1/3	0.125
4	1/2	0.1875
5	3/4	0.25
6	5/6	0.3125
7	0	0.375

Fig. 5. Void growth geometries chosen for finite element analysis.

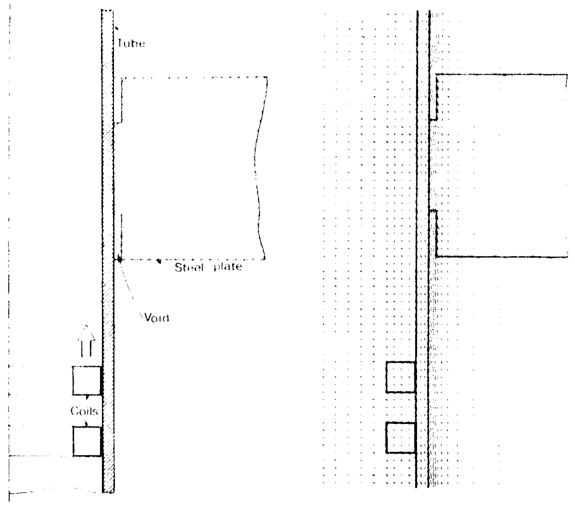


Fig. 6. Finite element geometry and the mesh.

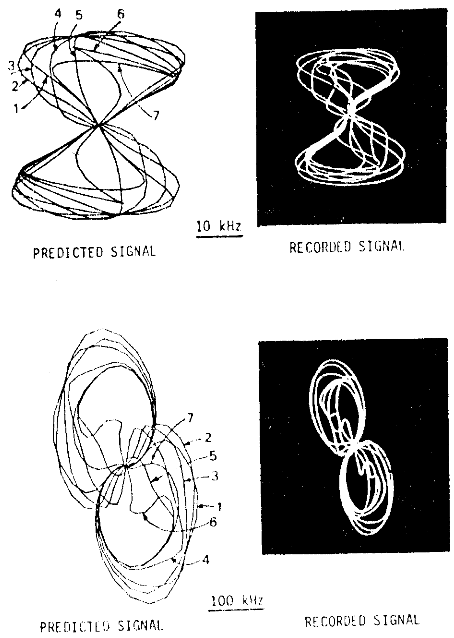


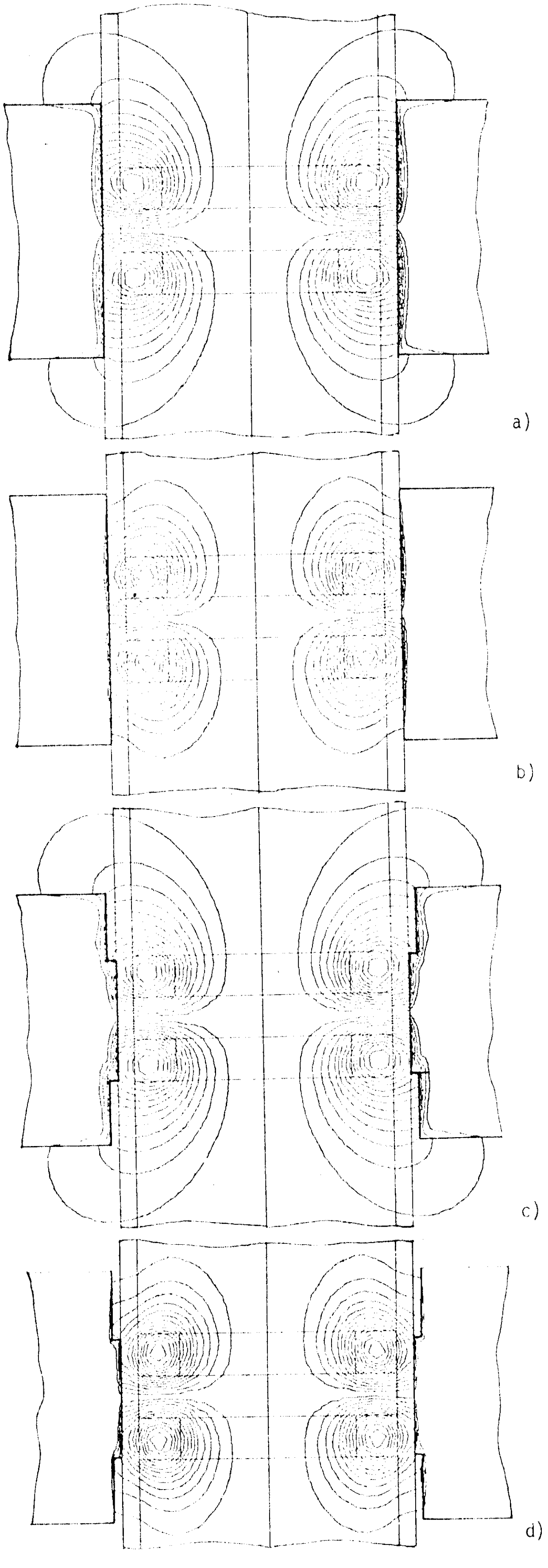
Fig. 7. Finite element predicted and experimentally recorded signals for 10 and 100kHz. (Nos. 1 to 7 correspond to void numbers in Fig. 5).

understanding of the physics of eddy current NDT phenomena, the impedance plane information provides data necessary for training an automated NDE system. From the finite element output one can plot differential impedance, resistance, reactance and phase angle with respect to probe position inside the tube.

FUTURE WORK

The results of the work done thus far clearly show the applicability and usefulness of finite element analysis techniques to the modeling of eddy current NDT phenomena in steam generator tubing inspection. Hence, recently emphasis has been placed on extending the modeling studies to problems of practical importance. One of the major problems in nuclear power plant steam generators is the buildup of magnetite in the tube/support plate crevice gap. Work is in progress to model the magnetite buildup in the 0.015" crevice gap in steam generators. Differential eddy current probe signals will be predicted for different geometries of magnetite buildup. Similarly the modeling studies will be extended to the eddy current inspection of condenser tube/tube sheet inspection. These investigations are undertaken using axisymmetric finite element code.

Full utilization of the numerical model is possible only with a 3-dimensional computer code as the test and defect geometries encountered in the real world do not always fall into the class of 2-dimensional or axisymmetric geometries. With funding from the Electric Power Research Institute (EPRI), a 4081 Tektronix graphics system has been acquired and made operational recently at Colorado State University and work is in progress towards building up a complete 3-dimensional modeling capability to solve active, residual and eddy current NDT problems.



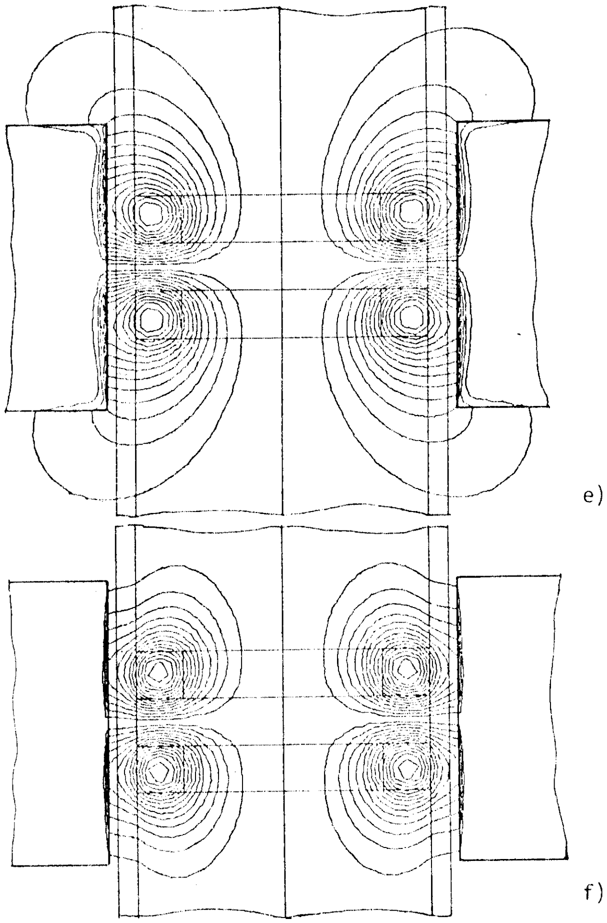


Fig. 8. Flux plots:
a) and b) 10 and 100kHz (no void)
c) and d) 10 and 100kHz (1/2 void)
e) and f) 10 and 100kHz (fully open)

ACKNOWLEDGMENT

This work was supported by the Electric Power Research Institute, Palo Alto, California under Project RP1395-2.

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Review of Progress in

QUANTITATIVE NONDESTRUCTIVE EVALUATION

Volume 1

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