DEVELOPMENTS IN THE NUMERICAL MODELING OF STEAM GENERATOR EC NDT PHENOMENA

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ABSTRACT

A brief description is given of developments in the use of finite element analysis techniques to model eddy current probe phenomena encountered in the testing of PWR steam generator tubing. Progress has been made during the past year in applying axisymmetric code to simulate both absolute and differential probe geometries, and more recently 3-D eddy current code has been developed which will be applied to the study of EC probe responses to realistic tube defect shapes.

ANALYTICAL APPROACHES to the solution of the electromagnetic equations describing eddy current NDT phenomena are replete with simplifying assumptions which tend to invalidate the use of such techniques for attacking the general defect characterization or inverse problem[1].

This situation is not unique to the problems of electromagnetic nondestructive testing however, in that the underlying field equation

$$\nabla\times(\nabla\times\bar{A}) = \mu\bar{J} - j\omega\mu\sigma\bar{A} \qquad (1)$$

also describes low frequency eddy current phenomena in electrical machines, accelerator and fusion magnets, etc.

In order to study the electromagnetic fields associated with such complex devices extensive use has been made of numerical analysis. Finite difference[2] and finite element[3] schemes have been particularly successful in modeling fields in magnetic structures and earlier work at Colorado State University has shown the feasibility of applying such methods to a variety of electromagnetic NDT techniques[4,5,6].

This paper reports on recent progress made in applying finite element analysis to the study of PWR steam generator tube testing using eddy current probes.

THE FINITE ELEMENT MDTHOD

Rather than solving Eq. (1) directly as in analytical approaches, or modeling the partial derivatives as in finite difference algorithms, the finite element method uses the following recipe to arrive at values of the magnetic vector potential $\bar{A}$ which satisfy Eq. (1):

1. discretization of the EC test geometry into a finite element mesh,
2. minimization of an appropriate energy function with respect to each component of the magnetic vector potential,
3. solution of the resulting "global" matrix to yield values of the magnetic vector potential at each mesh node,
4. calculation and plotting of desired output variables such as probe flux lines, eddy current densities, etc., from the nodal magnetic vector potential values.

During the initial stages of the work, two dimensional and axisymmetric code was developed and applied to a study of differential eddy current probe impedance plane trajectories for those steam generator geometries which have axisymmetry[7]. In a parallel study two dimensional and axisymmetric code was developed for studying the magnetostatic fields associated with direct current probes[8]. Both sets of code have been documented and delivered to the EPRI NDE Center in Charlotte for operation on the Center's VAX 750 computer[9]. The NDT probes in these studies are characterized by having well-defined boundary conditions and well-behaved magnetic fields which remain close to the probe. This has been a significant factor in the accuracy with which the developed FE code has been able to predict EC probe impedance plane trajectories. The inherent axisymmetry of steam generator tubing geometries has also had a significant impact on the relatively rapid development and application of the FE code.

APPLICATIONS

A variety of uses have been identified for the FE code. They include:

1. comparison of alternative EC probe designs before construction,
2. studying the penetration of EC probe fields in complex test geometries,
3. predicting EC probe signals for test situations too expensive for laboratory replication, and
4. developing training data for comparing the performance of automated EC signal processing schemes.

During the past year a number of studies have been made with the axisymmetric FE code. Figure 1 shows representative results obtained from a study of alternative absolute EC probe types used for inspecting flat metal surfaces. The finite element studies (subsequently confirmed experimentally) showed the clear superiority of the double probe structure over the two single coil types.

As an example of the use of the axisymmetric finite element code for simulating those test situations too expensive for laboratory replication, consider the prediction of differential EC probe signals for various layers of magnetite buildup in the crevice gap of a PWR steam generator. Figure 2 shows typical axisymmetric code predictions which will be used as training data to determine if the Fourier descriptor technique can be used to estimate the amount of magnetite buildup present in a steam generator crevice gap from a differential EC probe signal.

Care should be taken in choosing the mesh structure for the test geometry under study, as the output of the finite element program can be sensitive to variations in the number of elements per skin depth and the shape and orientation of the mesh elements. Figure 3 gives some indication of the error which can result from an incorrect choice of mesh. Studies of this effect are continuing in an attempt to quantify the error and provide guidelines for arriving at an optimal mesh configuration.

Additional work has been done with the axisymmetric FE code in modeling absolute EC probe responses to a variety of conditions in the tube sheet region of PWR steam generators[10], and in estimating the conductivity of intergranular attack regions of Inconel tubing[9]. The axisymmetric eddy current code has now been extended to three dimensions[11]. Table I shows how the addition of just 25 layers in the 'z' direction of an axisymmetric mesh used to study steam generator support plate signals affects the computer requirements needed to produce an impedance plane trajectory.

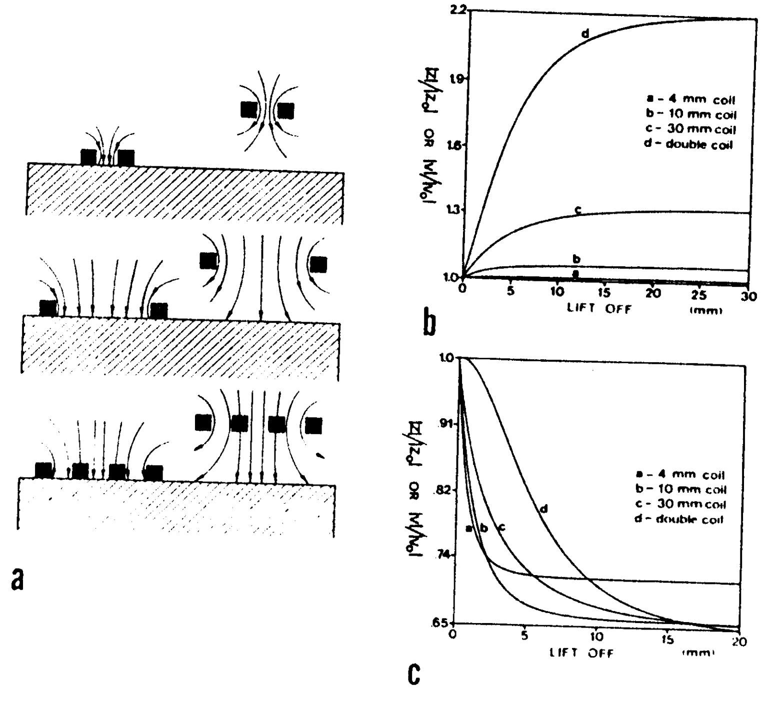

Figure 1. Axisymmetric finite element code study of surface probes.

a) Probe geometries and effect of lift-off for small diameter, large diameter and double coil structures.
b) Finite element prediction of the effect of lift-off on probe normalized impedance for coils above stainless steel.
c) Finite element prediction of the effects of lift-off on probe normalized impedance for coils above carbon steel.

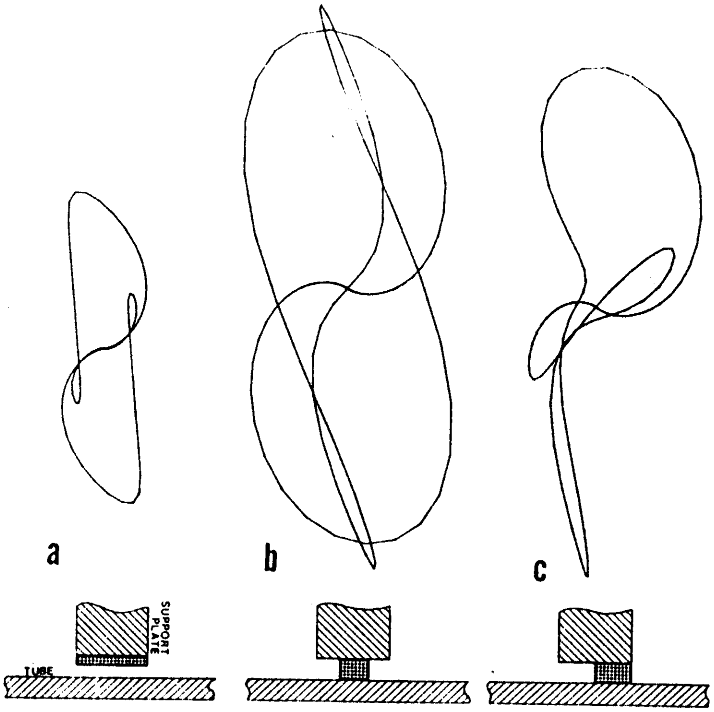

Figure 2. Axisymmetric FE code predictions of differential EC probe impedance plane trajectories for different magnetite deposits in a steam generator crevice gap.
a) 40% radial magnetite buildup.
b) 50% axial magnetite buildup.
c) 50% flushed condition.

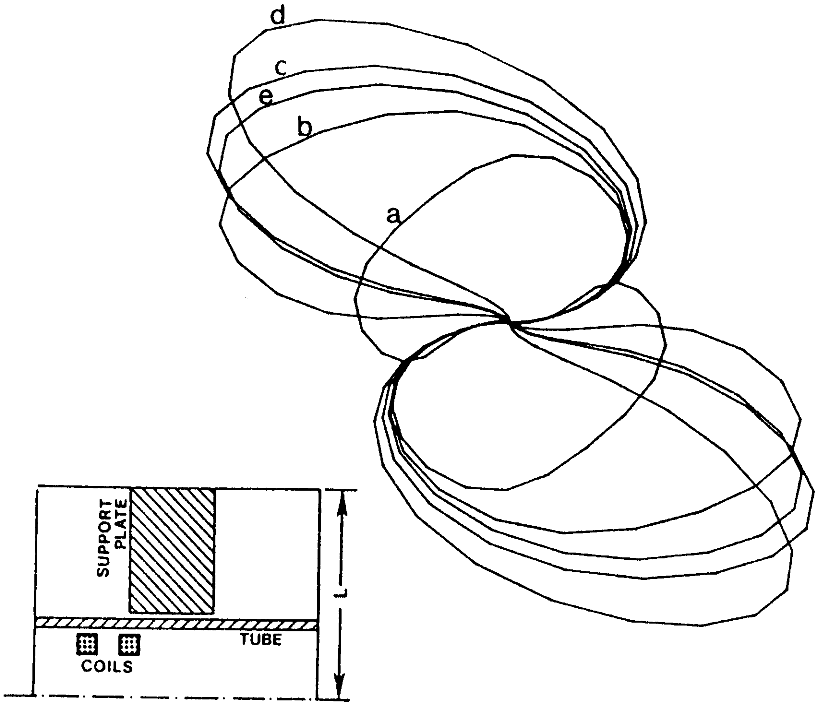

Figure 3. Effect of boundary conditions and mesh structure on the finite element prediction of impedance plane trajectories. a) Mesh boundary at L=1-1/2". b) Mesh boundary at L=4". c) Mesh boundary at L=5". d) Mesh boundary at L=9". e) Correct solution for cases a) thru d) obtained by adjusting the mesh structure in the first few skin depths of the support plate.

Table I - Comparison of Computer Requirements Needed for 2-D and 3-D Finite Element Studies of the Same Steam Generator Geometry

2-D Problem (70 Probe Positions)	3-D Problem
Mesh - 120 x 25 (Triangles)	Mesh - 120 x 25 x 25 (Hexahedra)
6000 Elements	75,000 Elements
3146 Variables	245,388 Variables
Semibandwidth - 28	Semibandwidth - 2112
Matrix - 3146 x 28	Matrix - 245,388 x 2112
(88,088 words of memory)	(5.18 x 10^8 words or memory)

Despite the enormous number of variables in such 3-D models, computer code has been successfully developed and run on a VAX 780 computer. Figure 4 shows a typical 3-D mesh for studying defect responses in steam generator tubing and the first finite element predicted differential EC probe impedance plane trajectory for a square through wall hole. Work remaining to be completed includes vectorization of the code to run on a Cyber 205 machine and additional studies of conical pits in the vicinity of a support plate.

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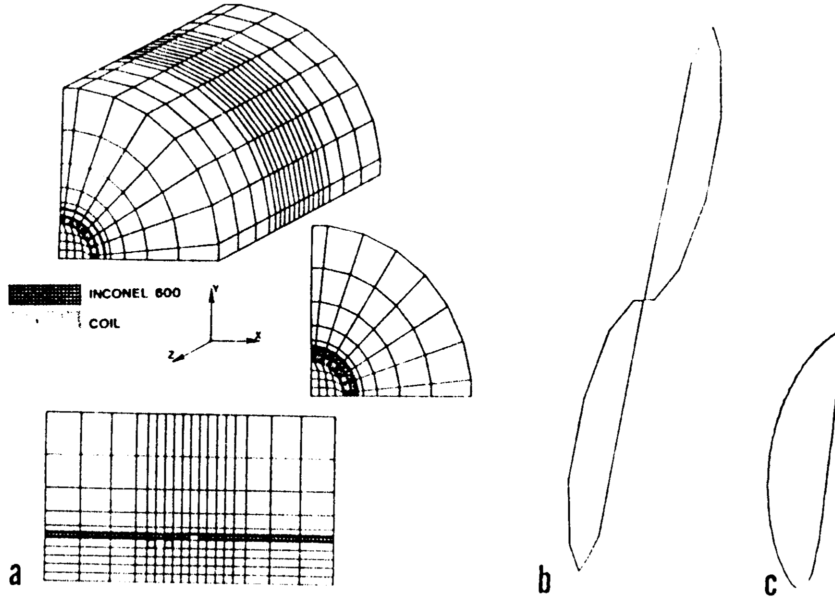

Figure 4. Development of 3-D axisymmetric finite element code.
a) Steam generator mesh structure.
b) Finite element prediction of EC probe impedance plane trajectory for a square through-wall hole (only eight points plotted).
c) Corresponding experimental EC probe trajectory.

ACKNOWLEDGMENTS

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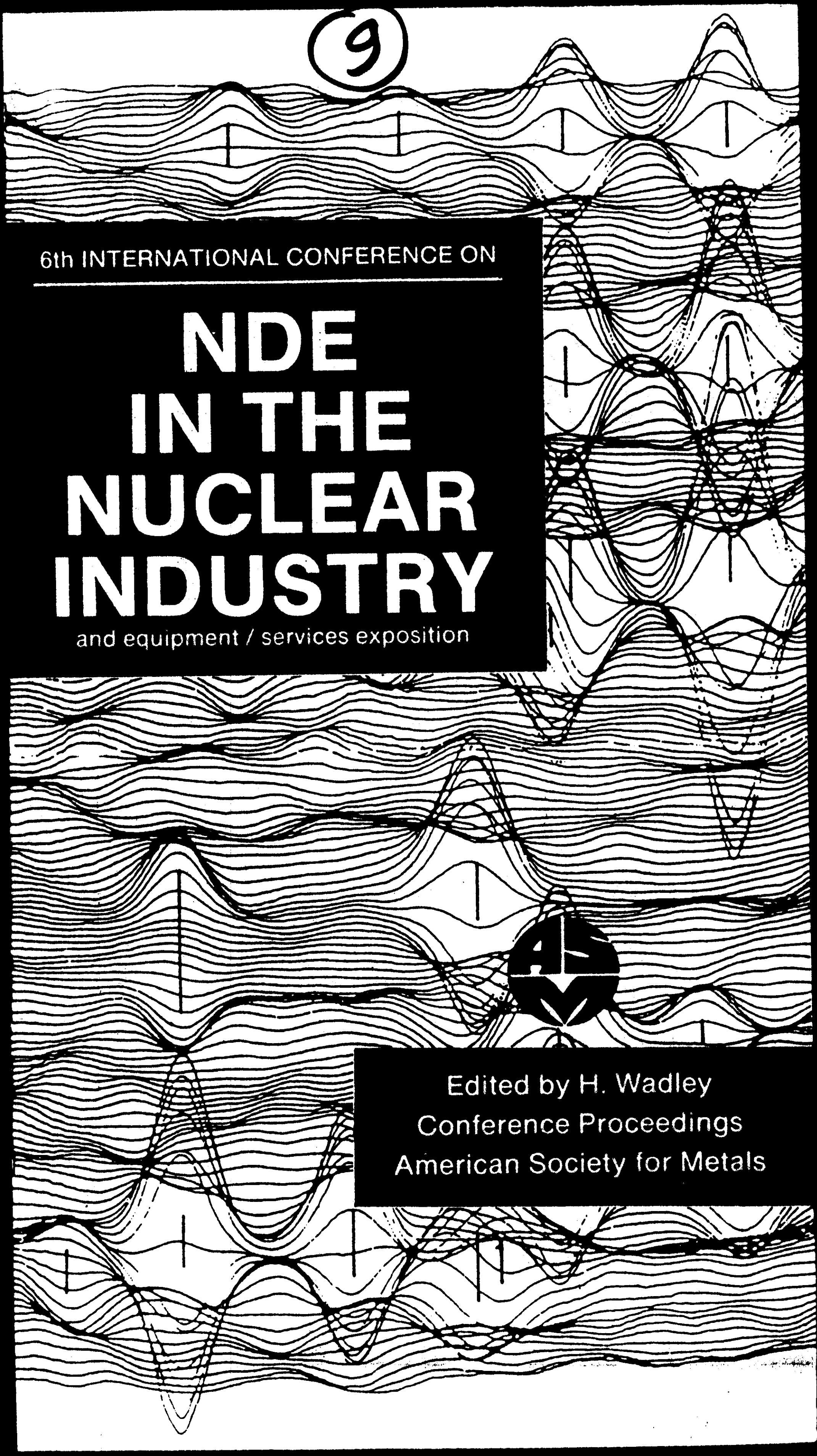

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