ELECTROMAGNETIC METHODS OF DEFECT DETECTION

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Abstract - This paper serves as an introduction to the topic of detecting and characterizing defects in materials nondestructively by electromagnetic methods. All such methods rely for their operation on the interaction of an electromagnetic field with the structure under test and can thus be classified as elliptic, parabolic or hyperbolic depending upon the governing partial differential equation type describing the underlying physics. This classification has particular significance for modeling studies based on finite element or boundary integral analysis and also affects the solutions of the corresponding inverse or defect characterization problem.

INTRODUCTION

It is unfortunate that the nondestructive testing community has chosen to classify electromagnetic nondestructive evaluation (NDE) techniques into subgroups such as magnetic particle and eddy current, because such terminology is far from exhaustive, tends to trivialize the subject matter, and fails to take full advantage of the physical insight to be gained from a comprehensive analysis based on classical electromagnetic field theory. The analysis of electromagnetic NDE methods is a challenging field of research, not only because of the wide variety of physical principles involved but also because the generic forward and inverse problems to be solved are concerned with arbitrarily shaped defects in complex engineering structures.

Figure 1 illustrates the major components constituting all NDE systems. The forward problem then in this context relates to the prediction of the NDE system response of a known defect shape to a known excitation function, whereas the inverse problem is concerned with characterizing the structural defect as to location and shape, given both excitation and response signals.

Developments in the modeling of electromagnetic NDE phenomena have closely paralleled those used in the analysis of other electromagnetic devices. Starting with analytical solutions for simple static [1] and quasi-static [2,3] NDE geometries, researchers have since recognized the inherent advantages of numerical methods [4]. It is now necessary to quantify the relative advantages and disadvantages of numerical techniques such as finite element, boundary integral and hybrid methods, not only to develop individual NDE technologies but also to integrate NDE concepts effectively into computer-based product design procedures.

In the following sections of this paper, the basic electromagnetic NDE phenomena are discussed and classified according to the governing partial differential equation type. This then sets the stage for a brief discussion of the relative merits of competing numerical modeling schemes.

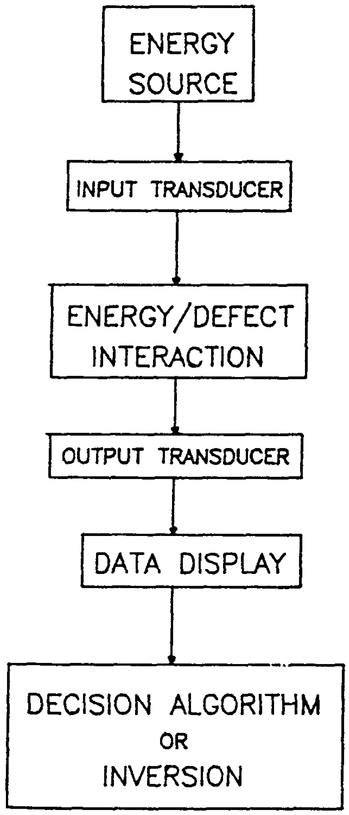

Figure 1. The "generic" NDE system has the energy/defect interaction at the very heart of the process.

STATIC FIELD NDE METHODS

Laplace's and Poisson's equations govern a variety of NDE methods from the measurement of fatigue crack length using potential drop techniques [5] illustrated in Figure 2 and governed by

$$\nabla^2\phi = 0 \tag{1}$$

where ϕ is the electrostatic scalar potential, to the variable reluctance measurement of magnetite buildup in a pressurized water reactor (PWR) steam generator [6,7] illustrated in Figure 3 and governed by the elliptic partial differential equation

$$\nabla^2\bar{A} = -\mu\bar{J} \tag{2}$$

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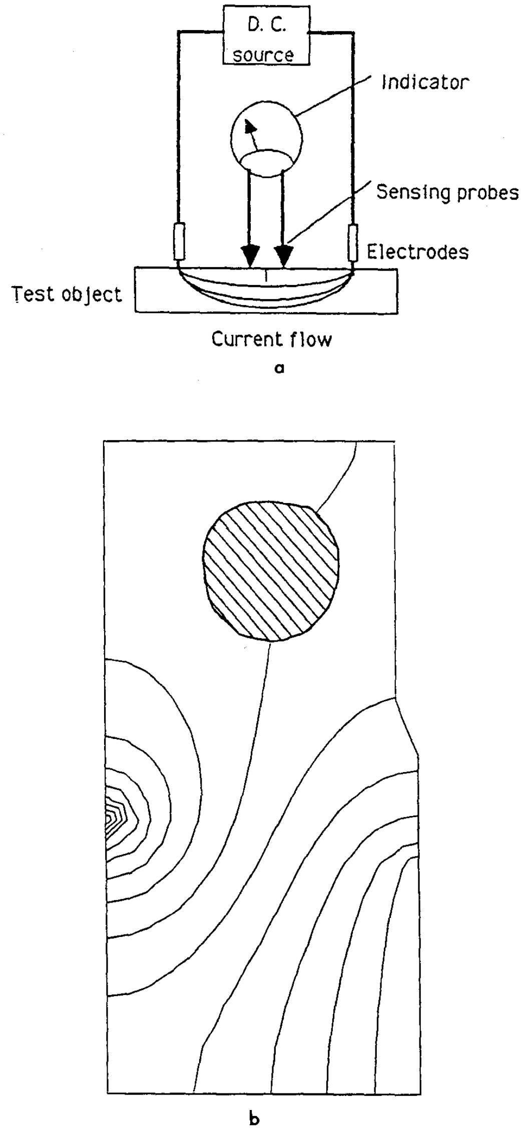

Figure 2. Potential drop method of measuring crack length.
a) Physical arrangement of probes.
b) Equipotential plots for one-half of a compact tension specimen.

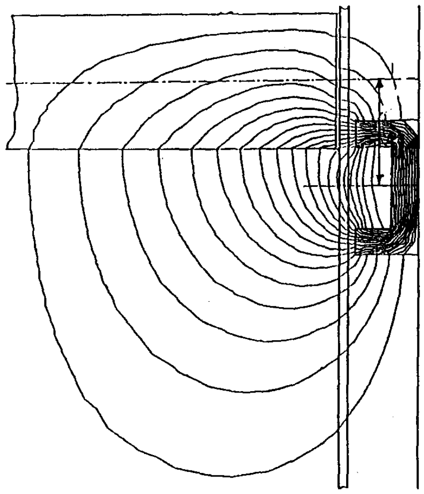

Figure 3. Variable reluctance probe for inspection of steam generator tubing.

where $\bar{A}$ is the magnetic vector potential and $\bar{J}$ the applied d.c. current density. Both Figures 2 and 3 take advantage of symmetry to reduce the computational requirements for the finite element field solutions. In Figure 3, the tubing and support plate geometry are symmetric about the tube axis.

Other electromagnetic NDE techniques based on equation (2) include magnetic particle testing, magnetography and flux leakage methods [8] where a d.c. current is used to magnetize the ferromagnetic material under test, and any flux density sensitive transducer (magnetic particles, magnetic tape, Hall elements, magneto-resistors, moving coils, etc.) can be used to detect the leakage fields set up around material flaws or inhomogeneities [9]. Such leakage field profiles are characteristic of particular flaw shapes, and hence it is possible to solve the inverse problem based on calibration curves relating profile measurements to flaw dimensions [10,11]. The magnetic permeability of equation (2) can often be modeled by the initial permeability value in situations where excitation levels are low, otherwise iterative solution techniques are necessary for finite element and finite difference modeling.

Direct application of the nonlinear B/H characteristics for ferromagnetic materials is made in micromagnetic and Barkhausen NDE methods [12,13]. Although such phenomena are more associated with dynamic magnetization and the domain behavior of ferromagnetic materials, they are finding some application to problems of residual stress and case hardening measurements [14], whereas the magnetostatic defect detection methods are used widely in any industry where the catastrophic failure of steel products is a possibility [15].

QUASI-STATIC FIELD METHODS

The quasi-static form of Maxwell's equations (displacement current negligible) governs all skin effect or diffusive NDE phenomena associated with a.c. potential drop and eddy current (single frequency, pulsed, remote field and multi-frequency) inspection techniques. In this case a parabolic p.d.e. of the form

$$\nabla^2\bar{A} = -\mu\bar{J} + \mu\sigma\dot{\bar{A}} \tag{3}$$

can be shown to govern the energy/defect interaction, where σ is the material conductivity. The first term on the righthand side of equation (3) is associated with the source current density and the second term with the induced eddy current distributions. Pulsed eddy current methods [16] have found limited application in industry, whereas single and multi-frequency methods [17] are used extensively for tubing inspection and aerospace applications. Remote field eddy current NDE methods [18,19] are contrasted with the operation of a single frequency differential eddy current probe in Figure 4. Unlike conventional eddy current (EC) methods (Figure 4a) which are often used for the inspection of stainless steel narrow bore tubing, remote field eddy current (RFEC) methods are finding application in the testing of large diameter ferromagnetic pipes (Figure 4b). When passing a tube wall defect, the differential EC probe produces an impedance plane trajectory similar to that shown in Figure 4c, whereas the RFEC probe monitors the steady state a.c. phase difference between excitation and sensor coils, thus producing the "double bump" signal shown in Figure 4d.

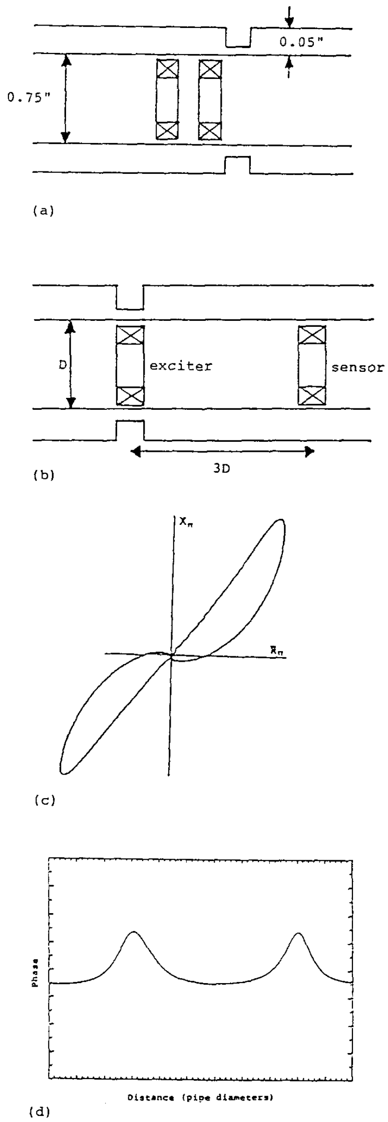

Figure 4. Single frequency and remote field eddy current methods.
a), b) Probe dimensions.
c), d) Probe signals.

Both finite element [20-22] and boundary element [23,24] methods are being used for modeling purposes. Typical finite element field plots of differential EC probe fields and induced eddy current densities are shown in Figure 5. In all such cases the steady state A.C. version of equation (3) is solved

$$\nabla^2\bar{A} = -\mu\bar{J} + j\omega\mu\sigma\bar{A} \tag{4}$$

where the $\bar{A}$ and $\bar{J}$ terms are now phasor vectors and the partial differential equation is elliptic rather than parabolic. In cases where equation (3) is solved directly for the modeling of pulsed EC phenomena [16], a mixed approach has been adopted with finite difference time stepping and finite element spatial discretization. In conventional EC testing, both amplitude and phase information can be used to aid in solving the inverse problem.

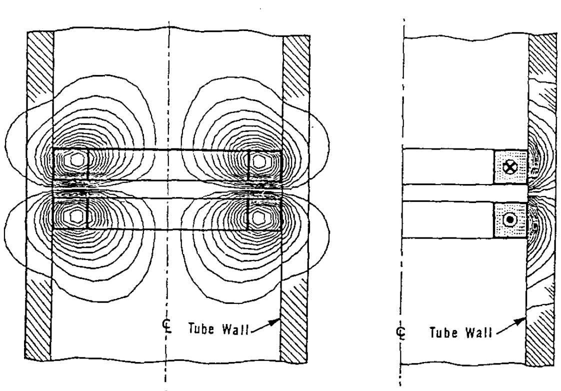

Figure 5. Finite element prediction of differential probe fields.
a) Probe flux lines at 100 KHz.
b) Corresponding eddy current density contours.

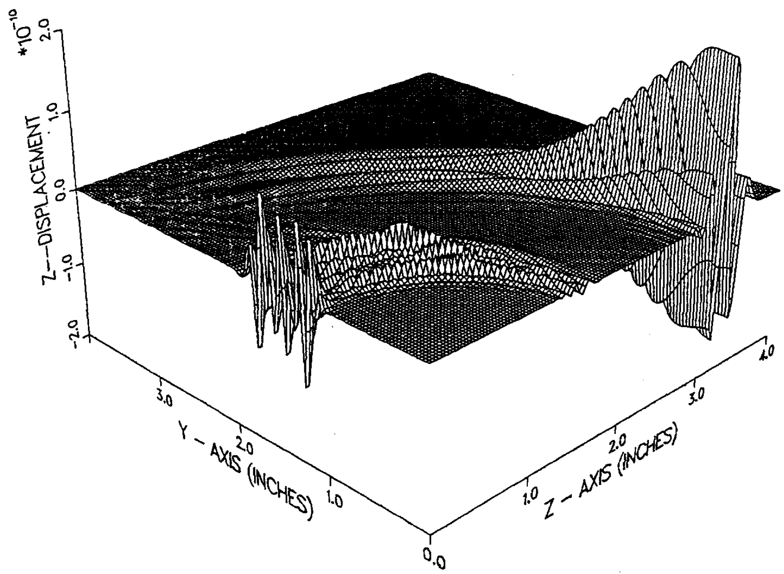

Figure 6. Finite element prediction of ultrasonic wave propagation in an aluminum block. Only one-half of the block is illustrated because of symmetry.

WAVE-BASED NDE METHODS

Including displacement current to give the full form of Maxwell's equations results in the hyperbolic wave equations

$$\nabla^2\bar{A} = -\mu\bar{J} + \mu\epsilon\ddot{\bar{A}} \tag{5}$$

$$\nabla^2\phi = -\frac{\rho}{\epsilon} + \mu\epsilon\ddot{\phi} \tag{6}$$

in terms of the scalar potential function ϕ and the magnetic vector potential function $\bar{A}$, where ϵ is the permittivity. These equations govern microwave interactions with non-conducting materials such as ceramics and composites [8]. Although both analytical and numerical solutions exist for equations (5) and (6) when applied to waveguide and antenna structures [25], very little work has been reported in the literature on the application of numerical methods to the solution of forward and inverse microwave NDE problems [26]. Ultrasonic NDE phenomena, however, are also governed by a hyperbolic partial differential equation of the type

$$\mu\nabla^2\bar{u} + (\lambda+\mu)\nabla\nabla\cdot\bar{u} = \rho\frac{\partial^2\bar{u}}{\partial t^2} \tag{7}$$

where $\bar{u}$ represents displacement, λ and μ are Lame constants and ρ is material density. Equation (7) has been successfully solved using finite difference [27], finite element [28] and boundary integral [29] methods. Figure 6 shows longitudinal, shear, surface and head waves predicted from a finite element solution of equation (7) for a 1 MHz finite aperture transducer on an aluminum block 15 microseconds after the application of the excitation pulse. The interaction of such waves with arbitrarily shaped defects is readily handled by all three numerical analysis techniques. Such waves can be generated electromagnetically using EMATs (electromagnetic acoustic transducers) [30]. All wave-based NDE methods can take advantage of holographic and tomographic reconstruction as a direct solution of the inverse problem.

MODELING ASPECTS

Numerical analysis has a significant role to play in the modeling of the electromagnetic NDE phenomena described in the previous sections of this paper because the awkward defect and NDE testing geometries preclude the use of classical analytical techniques. Just which numerical method to use in a specific situation is often left to the whim of the individual researcher or is governed by the availability of commercial software and appropriate computer resources.

In general finite element and finite difference algorithms give "full field" solutions as exemplified in Figures 2, 3, 5 and 6, which can be very useful if a major objective is to gain a fuller understanding of the underlying physics from the associated field distributions. Additionally, these techniques are not limited by material nonlinearities or anisotropy. Unfortunately, problems do arise, however, when extending finite element code to a full three dimensions. Figure 7 illustrates this point well by comparing typical dimensions of EC and RFEC geometries. Given that several mesh layers are required per skin depth and that wall pits of only 10% through wall depth can be of interest, the finite element mesh requirements for RFEC modeling of three-feet diameter pipeline (even for axisymmetric solutions) become exorbitant.

Boundary integral approaches, on the other hand, based as they are on a Green's formulation of the type

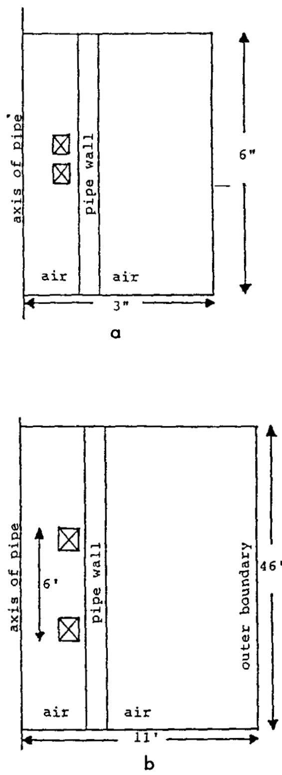

Figure 7. Comparative dimensions of the EC and RFEC geometries illustrated in Figure 4.

$$\phi(\bar{r}) = \phi(\bar{r}') = \iiint_V f(\bar{r}')G(\bar{r},\bar{r}')dv' +$$
$$+\oiint_S \left[\phi(\bar{r}')\nabla' G(\bar{r},\bar{r}') - G(\bar{r},\bar{r}')\nabla'\phi(\bar{r}')\right] \cdot d\bar{s}'(\bar{r},\bar{r}') \qquad (8)$$

where f represents the source distribution and G the free space Green's function, give point field solutions which in many NDE applications are all that is required. This is particularly obvious for the potential drop method illustrated in Figure 2 where only two field points are needed for an estimation of the potential drop. The comment also holds for other electromagnetic NDE methods, too, as the active sensor volume tends to be small compared to the overall testing geometry. Figure 8 shows finite element, boundary element and Johnson's formula [31] predictions for the ratio of actual crack length, A, to notch length, W, as a function of the actual potential drop, U expressed as a ratio of the notch length potential U_0.

As the Green's formulation of equation (8) presupposes superposition, some difficulty is experienced in handling nonlinear material properties and anisotropy.

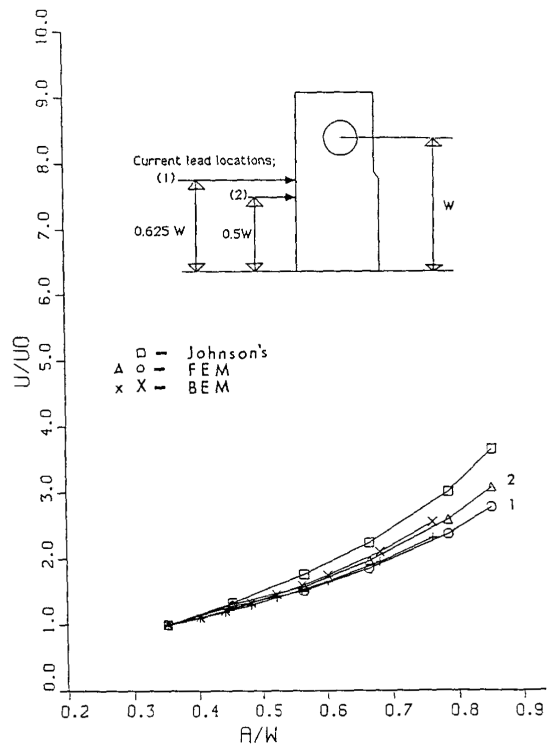

Figure 8. Comparison of boundary element and finite element solutions for the potential drop measurement of fatigue crack length.

Hybrid methods [32,33] can contribute to the solution of such problems, however, and it is quite conceivable that the future use of finite element analysis techniques in solving electromagnetic NDE problems may lie in providing the surface integral terms in equation (8). Such an approach could well combine the inherent 3-D modeling capability of the boundary integral technique with the power of the finite element method to handle nonlinearities and anisotropy.

CONCLUSIONS

A general overview is given of electromagnetic NDE methods and the numerical techniques currently in vogue for their analysis. Although finite element and boundary integral solutions will separately continue to provide additional physical insight into specific NDE phenomena, it is quite possible that a hybrid approach will be necessary to integrate NDE modeling techniques successfully into the interactive, computer-based product design environment.

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