

IMAGING OF ELECTROMAGNETIC NDT PHENOMENA

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INTRODUCTION

Practical solutions of the defect characterization or NDT inverse problem still continue to be sought by researchers in a variety of industries where the location and sizing of material flaws is important to successful plant operation. The exact type of 'imaging' which can be used to characterize defects found by electromagnetic NDT methods depends very much on the underlying physics governing the electromagnetic field/defect interactions. All such phenomena are describable by Maxwell's equations

$$\int_C \bar{E} \cdot d\bar{l} = -\iint_S \dot{\bar{B}} \cdot d\bar{s} \quad (1)$$

$$\int_C \bar{H} \cdot d\bar{l} = \iint_S (\bar{J} + \dot{\bar{D}}) \cdot d\bar{s} \quad (2)$$

$$\iint_S \bar{B} \cdot d\bar{s} = 0 \quad (3)$$

$$\iint_S \bar{D} \cdot d\bar{s} = \iiint_V \rho_v dv \quad (4)$$

and the constitutive relationships

$$\bar{B} = \mu \bar{H} \quad (5)$$

$$\bar{D} = \epsilon \bar{E} \quad (6)$$

$$\bar{J} = \sigma \bar{E} \quad (7)$$

These equations are modified considerably by the operating frequency and material properties [1] and represent the governing equations for all electromagnetic NDT phenomena. Their importance to the subject of imaging as applied to electromagnetic NDT methods, lies in the different systems of equations associated with the different frequency regimes and material properties. The following section discusses these different regimes and their importance to the imaging of electromagnetic NDT phenomena.

Leakage Field Phenomena

Active and residual leakage field phenomena [2,3] associated with magnetic particle, magnetography, flux perturbation and variable reluctance NDT methods occur under d.c. (zero frequency) or magnetostatic conditions. All the time derivatives are thus zero in Maxwell's equations which now become:

$$\int \bar{E} \cdot d\bar{l} = 0 \tag{8}$$

$$\int_C \bar{H} \cdot d\bar{l} = \iint_S \bar{J} \cdot d\bar{s} \tag{9}$$

$$\iint_S \bar{B} \cdot d\bar{s} = 0 \tag{10}$$

$$\iint_S \bar{D} \cdot d\bar{s} = 0 \tag{11}$$

Defining the magnetic vector potential by the equation

$$\bar{B} = \nabla * \bar{A} \tag{12}$$

and converting the magnetostatic form of Maxwell's equations (8 through 11) into differential form gives

$$\nabla * \left(\frac{1}{\mu} \nabla * \bar{A} \right) = -\bar{J} \tag{13}$$

as the governing equations for all leakage field NDT phenomena. To the author's knowledge there is no controversy surrounding the validity of this equation. However, its solution for realistic defect geometries is fraught with difficulty and the implications of this for leakage field imaging are discussed in the section on imaging and a companion paper [4].

Microwave Phenomena

At microwave frequencies, the full set of Maxwell's equations (1 through 4) is valid and with some vector algebra, the differential form reduces to

$$\nabla^2 \bar{E} = \mu\sigma \dot{\bar{E}} + \mu\epsilon \ddot{\bar{E}} \tag{14}$$

$$\nabla^2 \bar{H} = \mu\sigma \dot{\bar{H}} + \mu\epsilon \ddot{\bar{H}} \tag{15}$$

These are the general electromagnetic wave equations governing the propagation of the electric field intensity \bar{E} and the magnetic field strength \bar{H} . Such waves can be used to interrogate ceramic materials for inhomogeneities but cannot penetrate metals. As this paper is primarily concerned with the imaging of defects in conducting media, the importance of equations (14) and (15) would be limited if it were not for the fact that they are often perceived as the starting point for eddy current analysis. Herein lies a significant controversy, for if indeed eddy current NDT phenomena are truly electromagnetic wave phenomena, then one should be able to apply imaging techniques based on wavefront measurements such as holography and tomography. The following section shows why this is not the case.

Eddy Current Phenomena

Most textbooks dealing with electromagnetic field theory pay scant attention to that region of the frequency spectrum between the magnetostatic and microwave. This is particularly significant for eddy current NDT phenomena as all operating frequencies lie in this region. Those textbooks devoting more than a page or two to the topic clearly point out the quasi-static nature of the phenomena [5 to 8].

Key arguments as to why quasi-static phenomena are not wave phenomena in either free space or metals relate to the slow rate of change of the field quantities. For example, let us assume that an \vec{H} field is propagating as a plane wave along the x axis of a rectangular coordinate axis system with velocity c, thus

$$H(x,t) = H_0 e^{j\omega(t - \frac{x}{c})} \quad (16)$$

$$= H_0 e^{j\omega t} e^{-j\omega x/c} \quad (17)$$

$$= H_0 e^{j\omega t} (1 - j\frac{\omega}{c}x + \dots) \quad (18)$$

Any lag effects are thus negligible if

$$\frac{\omega}{c}x \ll 1 \quad (19)$$

but

$$\frac{\omega}{c} = \frac{2\pi f}{c} = \frac{2\pi}{cT} = \frac{2\pi}{\lambda} \quad (20)$$

So if the dimensions (x) of the NDT geometry are much smaller than a wavelength (λ), then one can ignore any lag effects.

At 30 Hz, the operating frequency for remote field eddy current phenomena [9], λ would be approximately 10,000 kilometers. Even at 1 MHz, the upper limit for most practical eddy current tests, λ would be approximately 300 meters. The implication of these wavelength values then, is that for practical NDT geometries, the excitation coils do not launch electromagnetic waves as far as the part being interrogated is concerned.

Another key factor in the quasi-static argument relates to the displacement current term \vec{D} in equation (2). This term must be present for true electromagnetic wave propagation to exist and is essential in the derivation of the propagation equations (14) and (15).

It can be seen from equation (2) that the displacement current term is negligible if compared to the conduction current density, \vec{J}

$$|\dot{\vec{D}}| \ll |\vec{J}| \quad (21)$$

$$\text{i.e., } |j\omega\epsilon_0 E_0 e^{j\omega t}| \ll |\sigma E_0 e^{j\omega t}| \quad (22)$$

$$\text{i.e., } \frac{\omega\epsilon}{\sigma} \ll 1 \quad (23)$$

For most conductors this inequality implies that the frequency of excitation would have to be almost 10^{18} Hz for the existence of appreciable displacement currents. Consequently, it is meaningless to talk of wave propagation in metals at the frequencies used in either eddy current or microwave NDT.

All that is needed then to describe eddy current NDT phenomena, is the quasi-static form of Maxwell's equations

$$\int_C \bar{E} \cdot d\bar{l} = -\iint_S \dot{\bar{B}} \cdot d\bar{s} \quad (24)$$

$$\int_C \bar{H} \cdot d\bar{l} = \iint_S \bar{J} \cdot d\bar{s} \quad (25)$$

$$\iint_S \bar{B} \cdot d\bar{s} = 0 \quad (26)$$

$$\iint_S \bar{D} \cdot d\bar{s} = 0 \quad (27)$$

where all quantities are now steady state RMS phasor vectors. With some algebra equations (24) to (27) reduce to

$$\nabla * \left(\frac{1}{\mu} \nabla * \bar{A} \right) = -\bar{J} + j\omega\sigma\bar{A} \quad (28)$$

From a phenomenological point of view then, all eddy current NDT measurements can be described in terms of Maxwell-Ampere and Maxwell-Faraday laws.

An excitation coil carrying a sinusoidally time varying current will set up a sinusoidally time varying magnetic field strength given by the Maxwell-Ampere law (equation (25)). Through the constitutive relationship of equation (5) a sinusoidally time varying B field is produced which induces an electric field E in the test specimen describable by the Maxwell-Faraday law (equation 24)). It is this induced E field which sets up the eddy currents in the conducting test specimen (equation (7)). Naturally, according to the Maxwell-Ampere law again, these induced eddy currents themselves set up a magnetic field which interacts with the excitation coil field to produce changes in the steady state A.C. impedance of the excitation coil (an extremely complicated sequence of events to describe analytically, particularly if defects are present in the test specimen and if the test specimen is ferromagnetic).

Skin effect phenomena can indeed be predicted directly from equation (28). For a cylindrical conductor carrying alternating current along its axis, the current density distribution in the radial direction from equation (28) (i.e., no D term, hence no electromagnetic waves) is

$$J_x = J_0 e^{-\frac{x}{\delta}} \sin(\omega t - \frac{x}{\delta}) \quad (29)$$

where $\delta = (\pi f \mu \sigma)^{-1/2}$, the conductor's skin depth and J_0 is the current density at the surface of the conductor. Matveyev [5] shows clearly that this tendency of alternating currents to stay near the surface of the conductor is a direct consequence of the interplay between the Maxwell-Ampere and Maxwell-Faraday laws and involves no electromagnetic wave propagation whatsoever.

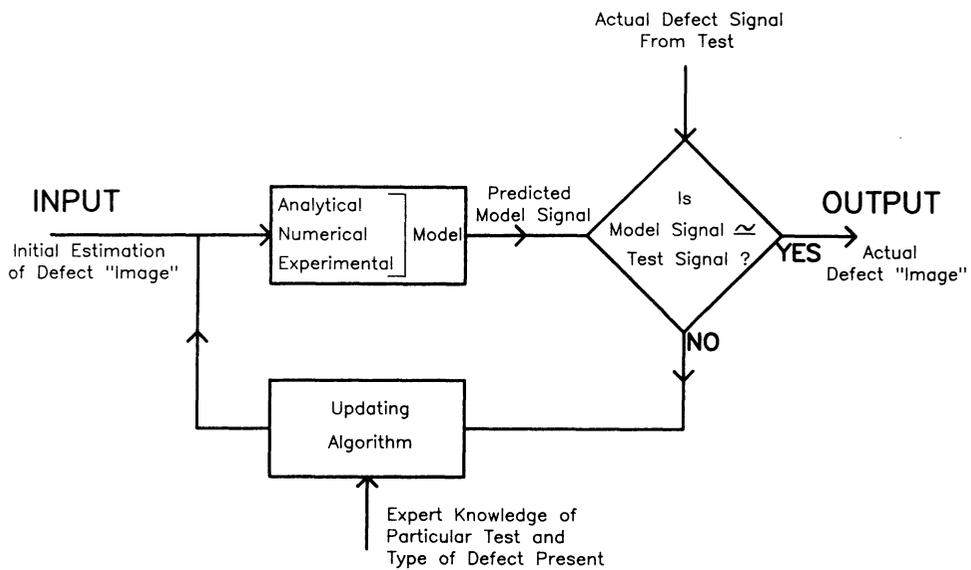


Fig. 1. An artificially intelligent expert system for "imaging" electromagnetic NDT data.

It should be noted in concluding this discussion of eddy current phenomena that equation (29) also results from considering the current distribution in a conducting half space subjected to an incident electromagnetic plane wave in the x direction. This rather surprising result should not however, be interpreted as proof of the existence of waves in metals, but as a demonstration of the consistency of Maxwell's equations across different frequency regimes. Some of the energy of the plane wave in this case is simply converted into heat in the metal by induced (quasi-static) eddy currents.

IMAGING

If indeed the electromagnetic nondestructive testing of metals does not involve the propagation of waves, then no wavefront measurements can be taken and hence optical forms of imaging cannot be utilized. This conclusion follows directly from the arguments of the previous section and presupposes a magnetostatic or quasi-static condition for all electromagnetic field/defect interactions within metals. If this conclusion is indeed correct, then the future of imaging for electromagnetic NDT methods must be closely tied to 'algorithmic' or 'calibration' schemes which rely on an intimate knowledge of the 'forward' or 'direct' problem gained via analytical, numerical and/or experimental studies. Because of the difficulties associated with solving the forward problem for realistic NDT geometries (we must seek solutions to the nonlinear, three dimensional equations (13) and (28)) [10], electromagnetic imaging may well be very problem specific, incorporating many of the features commonly associated with artificial intelligence and expert systems.

Initial efforts at solving the defect characterization problem for leakage field [11] and eddy current [12 to 14] methods clearly support this contention. The imaging algorithm proposed in a companion paper [4] and reproduced here as Figure 1 for the sake of completeness, gives a general recipe for attacking the imaging problem for electromagnetic NDT phenomena. For the near future, such an approach will prove to be computer resource intensive.

CONCLUSION

The lower the frequency, the more difficult the imaging problem.

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DISCUSSION

Chairman Heyman: It is apparent that monopoles are alive and well at Colorado State University. This is a super topic but we are running late. I'm just going to pick one question.

Mr. David Cheeke (Sherbrooke): Your analysis would imply that you could do eddy current imaging in the semiconductor. Presumably this wouldn't be of any practical interest.

Mr. Lord: I presume it would be of practical interest to manufacturers in semiconductors, but again, you might run into wavelength problems.

Mr. Cheeke: I think it would be very easy to satisfy that condition.

Mr. Lord: Okay.