COMPUTATIONAL EDDY-CURRENT PROBE MODEL FOR COMPOSITES, METALS AND SEMICONDUCTORS

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INTRODUCTION

A comprehensive computer code for research and design studies in electromagnetic NDE is now at an advanced stage of development. It has the capability of predicting the impedance characteristics of fully three-dimensional eddy-current probes in the presence of metals, semiconductors and advanced composites. By using a combination of the conjugate gradient method applied to a matrix and fast Fourier transform techniques, the resulting algorithm is both efficient in CPU time and has modest storage requirements. The theoretical model was presented in [1].

The emphasis of this paper is in the validation checks and self-consistency testing by comparing results with data computed directly from available analytical expressions, and by comparing field calculations with data obtained independently from other codes, and comparing results with data collected in the lab.

NUMERICAL RESULTS

Figure 1 illustrates the variation of normalized impedance with frequency computed by modeling the cup-core probe shown in Figure 2. Four different lift-off values, z_L, were chosen, 0 mm, 0.6 mm, 1.2 mm and 1.8 mm, the lift-off parameter being the perpendicular distance from the base of probe to the surface of the workpiece. The normalized impedance is associated with a lift-off angle θ_L (Figure 1) defined in the impedance plane as the direction of the impedance change as the probe is moved incrementally away from the workpiece at constant frequency.

In [2], Vernon formulated some empirical rules governing impedance characteristics of cup-core probes. Model calculations and laboratory measurements were compared to verify these rules, which are defined in terms of a reduced impedance function [3].

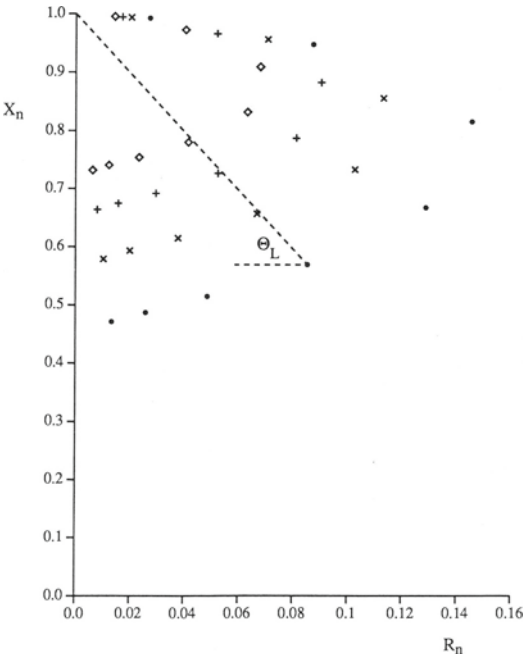

Fig 1. Normalized impedance diagram computed from the electromagnetic field theory model. The workpiece is isotropic, and the lift-off values are 0mm, 0.6mm, 1.2mm, and 1.8mm (outer to inner curves). The lift-off angle, θ_L, is also shown.

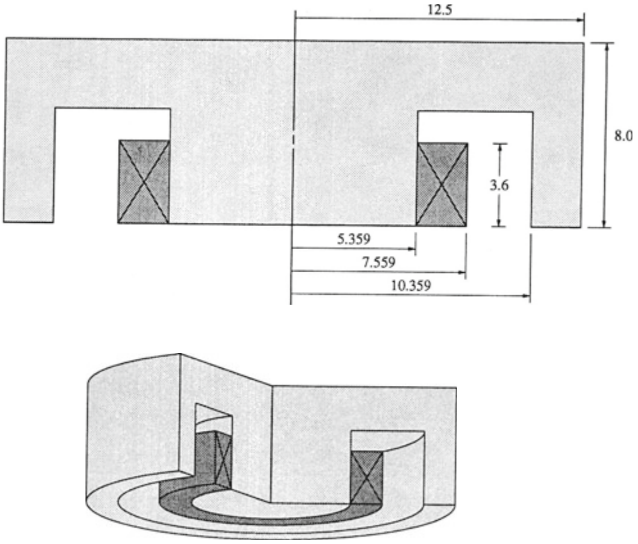

Fig. 2. Ferrite cup-core eddy-current probe. Dimensions are in mm.

Figure 3 compares the zero lift-off $\tan\theta_L$ characteristic with experimental results obtained using two different probes with an aluminum and a carbon-carbon workpiece. This plot shows the values of $\tan\theta_L$ as a function of $\bar{a}/\delta$, the ratio of probe mean radius to skin depth. Good agreement was found between the predictions and experiment. Figure 4 compares the calculation of the reduced impedance function with data derived from measurements.

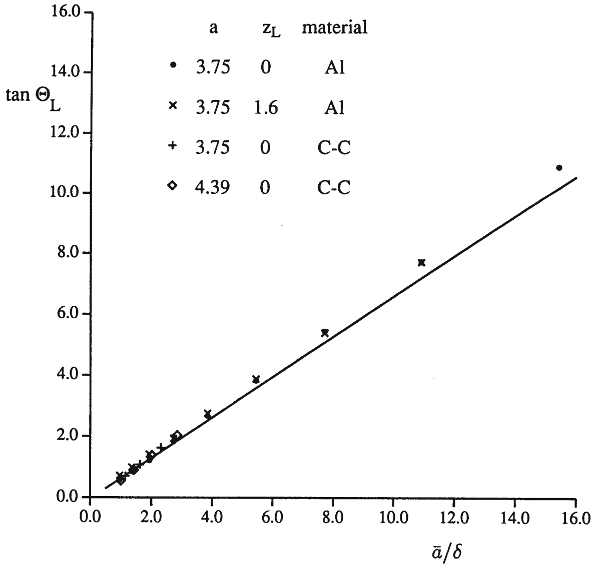

Fig. 3. Comparison of the zero lift-off $\tan\theta_L$ characteristic for the model data of Fig. 1 (straight line) with experimental results obtained using two different eddy-current probes with an aluminum and a carbon-carbon composite workpiece. Lift-off parameter, z_L, and mean radius, $\bar{a}$, given in mm.

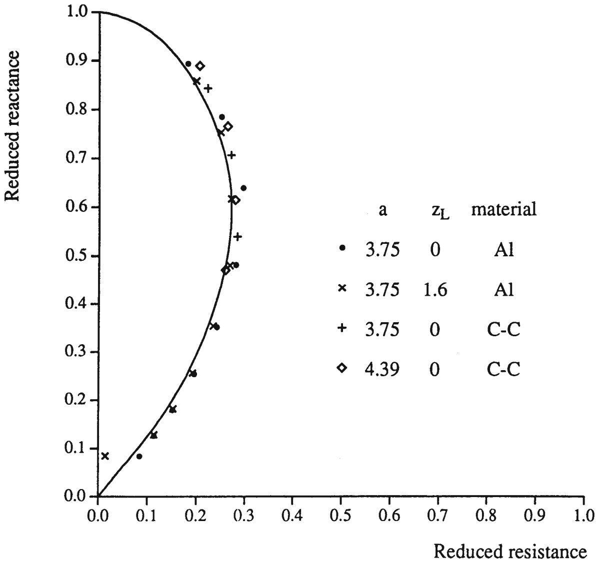

Fig. 4. Comparison of field theory calculation of reduced impedance (solid curve) with experimental data. Lift-off parameter, z_L, and mean radius, $\bar{a}$, given in mm.

An extensive program of validation checks was carried out to ensure that the results are correct and accurate within the limitations of a discrete model of a continuous system. One simple, but important, test was to compute the magnetization of a permeable sphere in a uniform incident magnetic field.

Figure 5 shows the z-component of the magnetization vector due to an incident field H_0 in the z-direction, for infinite permeability and a permeability of 2. These results are compared with the expected constant values of $M/H_0 = 3$ and $M/H_0 = 1.5$, respectively. Figure 6 gives a comparison of the external field computed from the code and from an analytical expression for the dipole field due to a uniformly magnetized sphere.

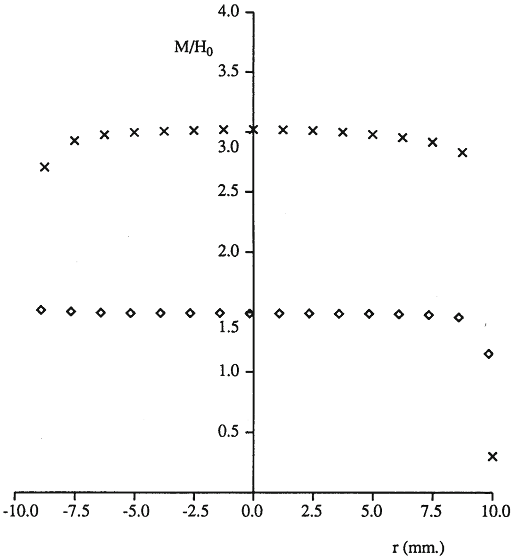

Fig. 5. Magnetization of a 20 mm. diameter sphere in free space due to a uniform incident magnetic field H_0. Crosses correspond to infinite relative permeability case (theoretically $M/H_0 = 3.0$), and diamonds represent the computed solution for a relative permeability of 2 (for which theory gives $M/H_0 = 1.5$).

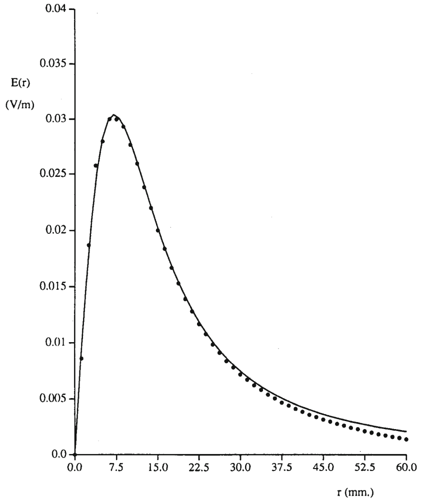

Fig. 6. Azimuthal electric field of the magnetized sphere in a plane tangential to its surface at one pole. Solid line has been derived from the analytical result.

Figures 7 and 8 illustrate the variation of normalized impedance with frequency for a cup-core probe similar to the probe in Figure 2 over an isotropic and anisotropic half-space, respectively. Note the difference in the shape of the impedance characteristic for the anisotropic material. These impedance predictions help quantify the coupling of the probe to the workpiece.

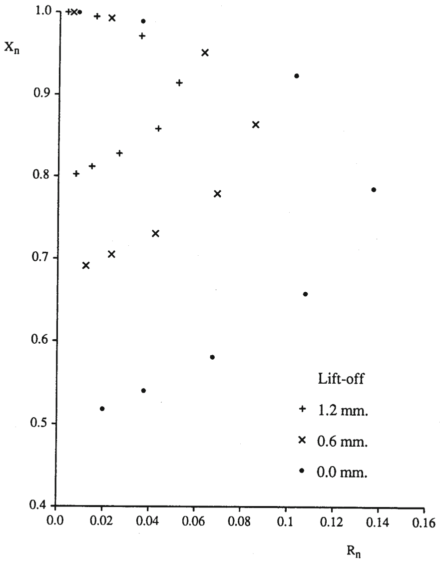

Fig. 7. Normalized impedance diagram for a cup-core probe above an isotropic half-space for various lift-off values. Points are plotted for $\bar{a}/\delta = 2^n \times 0.175$, $n = 1, 2, ...8$, and $\bar{a}$ is the ''mean'' probe radius.

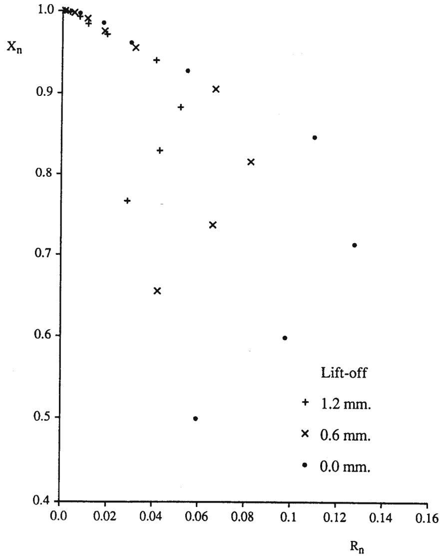

Fig. 8. Normalized impedance diagram for a cup-core probe above a uniaxial half-space ($\sigma = \sigma_{yy} = \sigma_{zz}$, $\sigma \neq \sigma_{xx}$) for various lift-off values. Conductivity ratio $\sigma_{xx}/\sigma = 200$. Points are plotted for $\bar{a}/\delta_{xx} = 2^n \times 0.175$, $n = 1, 2, ...9$, and $\bar{a}$ is the ''mean'' probe radius.

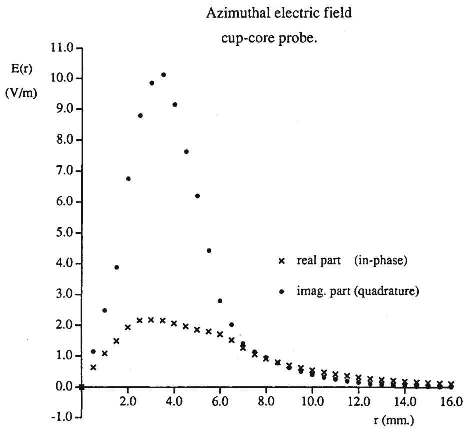

Fig. 9. Azimuthal electric field at the surface of the workpiece due to a cup-core eddy-current probe.

Figure 9 shows the azimuthal electric field at the surface of the workpiece (isotropic) as a function of distance from the axis for the cup-core probe. Note that the field is largely confined within the probe region.

ACKNOWLEDGEMENT

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