COMPUTER ASSISTED EDDY CURRENT PROBE DESIGN

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INTRODUCTION

For many years, the inspection of components using eddy current (EC) techniques has been playing an important role in the nondestructive evaluation (NDE) industry. There are many factors which affect the probability of detection (POD) of flaws. One important consideration is how to select suitable EC probes to inspect a given test component with certain class of flaws. Commonly, the performance of an EC probe design for a scan is evaluated experimentally by physically constructing prototype probes and perform test scans. This approach is both time-consuming and expensive. In particular, the EC probe has to be reconstructed each time the probe design is changed and the design cycle typically requires a number of iterations before a satisfactory performance is achieved.

It will be possible to minimize this design cycle if one can numerically simulate the performance of a probe design on a computer. The process is relatively simple and cost-effective whereas the design changes are done in a CAD environment. The probe performance may be evaluated based on, for instance, the interrogating electromagnetic (EM) fields produced by the designed probe, which are easily calculated by, e.g., the boundary element method (BEM) at critical locations.

This paper is intended to be a progress report of a project for developing computer-aided EC probe design software. In this work, we develop a BEM-based software package which is interfaced to a commercial CAD package. As a part of the probe design cycle, trial probes are constructed from various components such as cores, coils and shields in the CAD package. Design output is then read by the BEM package to calculate the interrogating EM fields produced by the EC probe, the result of which will be used by the probe designer for probe field optimization.

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The main progress this year is that, compared to the last year, the model can now include arbitrarily shaped parts and compute induced eddy currents in the part bodies. We have achieved this capability by extending the magnetic scalar potential method introduced last year for ferrite cores so that the method works with conducting materials also. The resulting BEM formulation is what we call the extended magnetic potential (EMP) formulation [1,2], which, we believe, is the best BEM approach for our target application.

In the following section, we will list the governing boundary integral equations (BIEs) which have been implemented into BEM software. We will then present several examples of CAD-BEM-code exercises for different probe constructions. The subsequent section is devoted to a description of a code validation effort against experimental B-field measurements. The last section is for the project status summary.

BOUNDARY ELEMENT METHOD

The BEM is a numerical method for solving boundary integral equations (BIEs). Here, we have chosen the extended magnetic potential (EMP) formulation, as described in References [1,2]. In the EMP formulation, most of the unknown surface density functions are scalar functions and the interface continuity conditions are enforced only on the scalar-like unknowns. For this reason, the EMP formulation is applicable for arbitrarily shaped geometries including edges and corners. Readers are invited to see Reference [2] for further details on this topic.

The EMP formulation requires to solve the following set of the governing BIEs: when the collocation point \( p \) is on the air/ferrite core interface,

\[
\int_S \left[ \frac{\partial}{\partial n} \phi(q) - \phi(p) \right] dS_q = \int_S H_n^{(0)}(q) dS_q, \quad (1)
\]

\[
-\phi(p) + \left( \mu_0^{-1} - \mu_0^{-1} \right) \int_S G_0 B_n(q) dS_q
+ \int_S \left[ G_0 \phi(q) + G_0 \left( \mu_0^{-1} B_n(q) - h_n(q) \right) - G_0 \left( \mu_0^{-1} B_n(q) - H_n^{(0)}(q) \right) \right] dS_q = 0, \quad (2)
\]

and when the collocation point \( p \) is on the air/shield core interface,

\[
-\frac{1}{2} \phi(p) + \int_S \left[ \frac{\partial}{\partial n} \phi(q) + G_0 \left( \mu_0^{-1} B_n(q) - h_n(q) \right) \right] dS_q = 0, \quad (3)
\]

\[
-\phi(p) + \left( \mu_0^{-1} - \mu_0^{-1} \right) \int_S G_0 B_n(q) dS_q
+ \int_S \left[ \frac{\partial}{\partial n} \phi(q) + G_0 \left( \mu_0^{-1} B_n(q) - h_n(q) \right) - G_0 \left( \mu_0^{-1} B_n(q) - H_n^{(0)}(q) \right) \right] dS_q = 0, \quad (4)
\]

\[
\frac{1}{2} H_n^{(0)}(p) - \frac{1}{2} h_n(p) + n \cdot \int_S \left[ \nabla (G - G_0) \times (n(q) \times H_n^{(0)}(q)) - \nabla G h_n(q) + \nabla G_0 H_n^{(0)}(q) + \nabla G_0 (\nabla \cdot (\nabla \times H_n^{(0)}(q) + \kappa^2 G_0 (\nabla \times E_q(q)) \right] dS_q = 0, \quad (5)
\]

\[
\vec{n}(p) \times \int_S \left[ \nabla (G - G_0) \times (\vec{n}(q) \times \vec{R}_n^{(0)}(q)) - \nabla G h_n(q) + \nabla G_0 H_n^{(0)}(q) + \kappa^2 G_0 (\nabla \times E_q(q)) \right] dS_q = 0, \quad (6)
\]

where \( G_0 \) and \( G \) denote, respectively, the static and dynamic Green’s functions.

\[
G_0 = 1/4\pi R, \quad G = e^{\delta R} / 4\pi R, \quad k = (1 + j) / \delta,
\]
Table I. The variables in the governing equations (1)-(6) and their definitions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^{(0)}$</td>
<td>incident magnetic field due to the coil in the absence of other objects</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>scalar magnetic potential function</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>permittivity</td>
</tr>
<tr>
<td>$\mu$</td>
<td>permeability</td>
</tr>
<tr>
<td>$G_0$</td>
<td>static Green's function</td>
</tr>
<tr>
<td>$G$</td>
<td>Green's function associated with conductive regions</td>
</tr>
<tr>
<td>$h$</td>
<td>auxiliary vector function</td>
</tr>
<tr>
<td>$E$</td>
<td>electric field vector</td>
</tr>
<tr>
<td>$n$</td>
<td>outward pointing normal vector</td>
</tr>
<tr>
<td>$B_n$</td>
<td>normal component of the magnetic flux density</td>
</tr>
</tbody>
</table>

for a given skin depth $\delta$. The definitions of the variables in Equations (1)-(6) are tabulated in Table I.

To solve the BIEs, the bounding surfaces of the cores are first discretized into a set of surface elements (mesh). Each element can be either a quadrilateral or a triangle. By expanding the unknown density functions in terms of the shape functions and nodal density functions on each element, the continuous BIEs are transformed into a set of linear algebraic equations. Once the unknown density functions at the nodes are determined, it is straightforward to calculate the interrogating fields elsewhere. For instance, the H-fields produced by the probe can be computed by the integral formula

$$
\bar{H}(P) = \bar{H}^{(0)}(P) - \left(\mu_c^{-1} - \mu_0^{-1}\right) \int_{\partial\Omega} \left[\nabla G_0 B_n(q)\right] dS_q + \left[\nabla \left(\frac{\partial G}{\partial B_n}\right)\varphi(q) - \nabla G\left(\mu_0^{-1} B_n(q) - h_n(q)\right)\right] dS_q + \left(\nabla G_0\left(\mu_0^{-1} B_n(q) - H^{(0)}_n\right)\right] dS_q. \tag{8}
$$

NOVEL EDDY CURRENT PROBE DESIGN

To illustrate the versatility of the BEM-based EC probe design package, a number of complex shaped EC probes were constructed using the CAD package PATRAN\textsuperscript{TM}. The CAD output file is then read by the BEM software to simulate the resulting electromagnetic fields produced by the probe. Figures 1 - 3 illustrate several novel probe constructions and their corresponding field maps. In addition to these probe designs, a list of typical probes including both absolute and differential probes are under investigation.
Figure 1. Probe design exercise for split-D differential probe. (A) is the CAD output of the probe design geometry, and (B) is the vector plot of the H field distributions as computed by the BEM code.

Figure 2. Similar probe design exercise for a shielded differential probe. As above, (A) is the probe geometry, and (B) is the vector plot of the computed H field distributions.

Figure 3. The BEM code can compute E fields also. These are E-field vector plots induced by a cylindrical-core probe. (A) is for the real parts of the E field, and (B) illustrates the imaginary parts of the E field vectors.
Table II. The probe parameters used in the validation experiments.

<table>
<thead>
<tr>
<th></th>
<th>Probe #1</th>
<th>Probe #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Type</td>
<td>Air</td>
<td>Ferrite</td>
</tr>
<tr>
<td>Permeability ($\mu_r$)</td>
<td>1</td>
<td>110</td>
</tr>
<tr>
<td>Wire Size</td>
<td>44 AWG</td>
<td>44 AWG</td>
</tr>
<tr>
<td>Turns</td>
<td>200 / layer</td>
<td>200 / layer</td>
</tr>
<tr>
<td>Layers</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Radius</td>
<td>0.250&quot;</td>
<td>0.250&quot;</td>
</tr>
<tr>
<td>Length</td>
<td>0.750&quot;</td>
<td>0.750&quot;</td>
</tr>
<tr>
<td>Frequency</td>
<td>100 Hz</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Axial Lift-Off</td>
<td>0.6 mm</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Transverse Lift-Off</td>
<td>2.9 mm</td>
<td>2.9 mm</td>
</tr>
</tbody>
</table>

BEM MODEL VALIDATION

As a part of the effort to validate the BEM-based probe design model, we have performed B-field measurements using Hall sensors attached to a gauss meter. The measurement results are then compared with the simulation results predicted by the BEM model. Our specific validation procedure involved two solenoidal probe designs. The specifications for the two EC probes are outlined in Table II. Due to the geometry of the Hall sensor, the two B-field components (axial and transverse) are measured at different lift-off distances. Examples of the 2-D field profile maps are shown in Figure 4. Quantitative comparisons were made among slices of the 2-D profiles, the examples of which are given in Figure 5. It turned out that the preliminary measurement apparatus had a high background noise from the gauss meter and the Hall sensor, large enough to mask the field produced by the air-core probe. Consequently, there is a wide fluctuation in the measurement. On the other hand, the B-fields produced by the ferrite-core probe have a significantly higher signal to noise ratio. As a result, the simulated field map matches very closely with the measured B-field map.

Figure 4. Example plots of the magnetic flux density profiles. The BEM code result (A) and the measurement data (B) are shown together for illustration.
Figure 5. Examples of 1D slices taken from the 2D profile data. Here, the BEM and measurement results are plotted together. The plot (A) contains the axial component of the magnetic flux B, while the plot (B) is for the perpendicular components.

SUMMARY

A cost-effective, software-based procedure to reduce the conventional EC probe design cycle is under development. The recently developed extended magnetic potential formulation has been incorporated into the BEM-based simulator code. As a result, the BEM code now admits conducting components of arbitrary shapes as constituents of test
inspection systems. For a CAD-designed probe of arbitrary shape and construction, and for a conducting part of general shape, the code can compute eddy current distributions induced on and inside the component surfaces. Several prototypical probe designs have been actually studied, with predicted field results.

An experimental effort to validate the software has been performed. The preliminary validation data on solenoidal probes exhibited a reasonable agreement between the predictions and the data within the measurement accuracies. Further efforts toward code validation using more complex EC probes are planned.

ACKNOWLEDGMENTS

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REFERENCE