Numerical Simulation in Alternating Current Field Measurement

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Abstract. The present work develops a numerical simulation model to evaluate the magnetic field perturbation of a twin coil alternating current field measurement (ACFM) inducer passing above a surface-breaking crack. Model predictions show good agreement with experimental data, verifying the accuracy of the model. FEM simulation is then employed to in-line inspection of pipelines.

Introduction

Alternating current field measurement (ACFM) is an electromagnetic technique that permits non-destructive detection and size estimation of cracks extending to the surface of ferrous and non-ferrous metals [1]. The technique offers numerous advantages, such as little or no surface cleaning requirements, quantitative evaluation, no coupling medium, and no need for calibration, and has become a promising non-destructive testing technique in place of conventional magnetic particle and penetrant testing methods [2].

The ACFM probe contains one or more coils that induce electrical currents on the surface of a specimen, which are perturbed in the presence of an exposed crack. Associated with the perturbation of electrical currents is a magnetic field above the surface that is also perturbed in the presence of a crack [3]. The perturbation of the magnetic field is measured to both detect and estimate the size of cracks.

Experimental methods for detection effect analysis of ACFM inducer are time-consuming, costly, and include irreducible experimental errors. To overcome the shortcomings of experimental methods, the finite element method (FEM) has been employed to simulate the perturbation of the magnetic field above the crack [4]. In this paper, an FEM model of a twin coil ACFM inducer passing above a specimen with an exposed crack is constructed, and the accuracy of the model is verified by comparing the FEM simulation results with experimental data. FEM simulation is then employed to in-line inspection of pipelines.

1. Model Geometry

A twin coil inducer is employed in the model. It consists of two parallel coils comprised of multiple conductor windings around cylindrical cores [5], as shown in Fig.1, each of which carries an identical alternating current. The radius of each core is 4 mm and the length is 30
mm. Each coil is modeled as a hollow cylinder surrounding its core. The length and thickness of each hollow cylinder is 22 mm and 0.5 mm, respectively, which represents 36 turns of a wire having a diameter of 0.5 mm. The distance between the two coils is 22 mm. The specimen is modeled by a plate, and the exposed crack on the surface of the specimen is modeled as a semi-ellipse \(^6\). The dimensions of the crack are 16 mm \(\times\) 0.8 mm \(\times\) 3.2 mm (length \(\times\) width \(\times\) depth). The twin coil inducer is positioned 2 mm directly above the crack, with the core axes parallel to the longitudinal direction of the crack. The inducer and the specimen are enclosed in a cylindrical volume.

![Fig.1. A general illustration of the numerical simulation model of the twin coil inducer.](image)

### 2. Material Properties

The materials of the specimen, core, and coil are mild steel (AISI 1030 high carbon steel), Mn-Zn ferrite, and copper, respectively. Here, in general form, Mn-Zn ferrite is \(\text{Mn}_a\text{Zn}_{(1-a)}\text{Fe}_2\text{O}_4\), where \(a\) is in the range 0.4–0.6. The enclosing cylindrical volume is set as air. A small non-zero value for the conductivity of air does not substantially affect the results, but helps the solver converge. Therefore, the electrical conductivity of air was set to 50 S/m \(^7\). The properties of the materials are listed in Table 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Material</th>
<th>Relative permeability</th>
<th>Electrical conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen/Core</td>
<td>Mild steel*</td>
<td>200</td>
<td>(5 \times 10^6)</td>
</tr>
<tr>
<td>Core</td>
<td>Mn-Zn ferrite</td>
<td>2300</td>
<td>0.15</td>
</tr>
<tr>
<td>Coil</td>
<td>Copper</td>
<td>1</td>
<td>(6 \times 10^7)</td>
</tr>
<tr>
<td>Cylindrical volume</td>
<td>Air</td>
<td>1</td>
<td>50</td>
</tr>
</tbody>
</table>

* AISI 1030 high carbon steel
3. Impedance Boundary Condition

Eddy currents induced by an alternating current field in the specimen exhibit the classical skin effect \[^8\]. The current path is mainly confined to a thin layer close to the surface of the specimen. The depth of the current layer, denoted as the skin depth \(\delta\), is given by

\[
\delta = \frac{1}{\sqrt{\mu_0 \mu \sigma f}},
\]

where \(\sigma\) and \(\mu\) are the electrical conductivity and relative permeability of the specimen, respectively, \(\mu_0\) is the permeability of vacuum, and \(f\) is the frequency of alternating current, which, in the present model, is 6 kHz. Based on the specimen properties given in Table 1, \(\delta\) is 0.2 mm. The value of \(\delta\) is small compared with the thickness of the specimen (8 mm), and it is not necessary to solve the skin depth. To simulate a surface current, an impedance boundary condition is therefore adopted. This condition essentially sets \(\delta = 0\), making all induced currents flow on the surface of the specimen without penetrating into the body \[^9\]. Under this condition, the specimen interior is excluded from the model, which increases the computational efficiency by eliminating the requirement to mesh the body of the specimen.

4. Simulation Results

Free tetrahedral elements were employed to model the specimen surface, cores, coils, and air, as shown in Fig.2. The maximum element size employed was 13.8 mm for air, and the minimum element size was 1 mm for modeling the crack. The element growth rate was 1.4, and the model employed a total of more than \(9 \times 10^4\) tetrahedral elements.

![Fig.2. Meshing employed for the model.](image)

The root mean square (rms) current was 0.6 A, and the alternating current frequency was as 6 kHz. The solutions were calculated using the biconjugate gradient stabilized (BiCGStab) linear system solver and Multigrid preconditioner, and the simulation results of the current density and the longitudinal component of the magnetic field \((B_y)\) on the specimen surface were obtained.
The resulting current density distribution on the surface of the specimen is shown in Fig.3. An elliptical area of uniform current density is observed directly beneath the twin coil inducer. However, the current density is not uniform near the crack. Fig.3 shows that the current density attains a maximum at the ends of the crack, and a minimum in the middle.

Fig.3. Current density distribution on the specimen surface (A/m).

The variation of $B_y$ on the surface of the specimen is shown in Fig.4. An approximately elliptical area of nearly uniform $B_y$ is observed directly beneath the twin coil inducer. However, $B_y$ is also not uniform near the crack, and $B_y$ is maximum at the ends of the crack, and minimum in the middle.

Fig.4. Distribution of the longitudinal component of the magnetic field ($B_y$) on the specimen surface (G).
5. Experimental Verification

The passage of an ACFM probe above a specimen is modeled by a parametric sweep. The distance along the y axis between the crack center and the center of the twin coil inducer was selected as the sweeping parameter, which was varied from −40 to 40 mm in 1 mm steps. During the scanning process, the model was solved a total of 81 times, and the value of $B_y$ at each step was also determined at a position 4.8 mm below the center of the twin coil inducer (i.e., 1.2 mm above the specimen surface), which represents the position of the magnetic sensor employed in the corresponding experiment.

To verify the simulation results, an experiment was conducted with an ACFM probe employing a twin coil inducer and a specimen with a machined crack, all of which employed dimensions and positions equivalent to those used in the sweep simulation. As shown in Fig.5, the ACFM probe was comprised of a twin coil inducer and magnetic sensor housed in a container made from Teflon, and the scanning direction of the ACFM probe was along the longitudinal direction of the crack. During the scanning process, $B_y$ was measured by the magnetic sensor.

![Fig.5. Illustration of the ACFM probe.](image)

Fig.6 presents the comparison between the experimental results and the simulation results obtained from the model, indicating good agreement between the two. However, the curves in some regions do not compare favorably. The experimental curve is not as symmetrical relative to the crack center as the simulation curve. The difference is expected to be due to experimental error and the inhomogeneity of the relative permeability of the actual specimen. The perturbations of $B_y$, described by the peak to peak values (i.e., the differences between the minimum and the greater of the two maxima), are given as 2.27 and 2.35 G for the experimental and simulation results, respectively, and exhibit a rather small relative difference of 3.6%. As such, the observed differences are not considered to be a major drawback of the simulation.
6. Simulation in Pipeline In-line Inspection

Another simulation model is built for pipeline in-line inspection, which consists of a pipeline segment with a crack and 120 uniformly distributed coil inducers. The shape of the crack is rectangle. The outer diameter of the pipeline is 610 mm, and the wall thickness is 12.5 mm. The length of the segment is 300 mm. The dimensions of the coil inducers are the same with the model in section 1. The materials of the pipeline is also AISI 1030 high carbon steel.

![Fig.7. A general illustration of the pipeline in-line inspection model.](image)

Distribution of $B_y$ on inter surface of the pipeline is shown in Fig.8. An annular area of nearly uniform $B_y$ is observed on the inter surface, and $B_y$ is maximum at the ends of the crack, and minimum in the middle.
The curves of $B_y$ 1.2 mm above the crack is shown in Fig.9. The characteristic of the curve is two peaks and a trough, a classical characteristic of ACFM, and the peak to peak values of $B_y$ is 3.03 G, greater than that in twin coil inducer. The results show that ACFM is applicable in in-line inspection of pipelines.

**Fig.8.** Distribution of $B_y$ on inter surface of the pipeline (G).

**Fig.9.** Curves of $B_y$ above the crack.

### 7. Conclusions

A numerical simulation model of a twin coil ACFM inducer was constructed to model an ACFM probe passing above a specimen having an exposed crack. The model was verified by
comparison with experimental data, where generally good agreement was obtained. FEM simulation is then employed to in-line inspection of pipelines and shows ideal results.

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References