Finite element modeling of remote field eddy current phenomenon


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Outline of presentation

- Introduction to eddy current testing
- Introduction to remote field eddy current testing
- Governing PDE of Remote field eddy current testing
- Modeling RFEC technique in COMSOL
- Analysis of model predictions
- Conclusions and further works
Eddy current testing principles

Used for nondestructive detection of defects and anomalies in metallic materials and components

- **Probe/coil**
- **Sinusoidal excitation source**
- **Sets up a Primary field**
- **Eddy currents induced in the material**

**Lenz’s law:** An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux.

Impedance change of the coil is measured with respect to defect and defect-free regions to detect them.
Introduction to RFEC technique (A variant of eddy current testing with exciter-receiver coils)

For tubular ferromagnetic components

Sinusoidal excitation of the coil establish two different fields of interest
1) Direct field/energy is due to the excitation coil
2) Indirect field/energy due to eddy currents in the tube

✓ The indirect field is dominant at the remote field zone
✓ This phenomenon happen due to the different attenuation characteristics of air and the magnetic materials
Remote field eddy current technique - Principle

- The receiver coil is kept in the remote field zone avoiding direct coupling and transition zones for detecting defects in the tube wall.
- Identification of this remote field zone is primary objective of the COMSOL model.
FE Modeling of RFEC - Formalism

Maxwell's curl equations

\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \\
\nabla \times \vec{H} = \vec{J}
\]

\[
\vec{B} = \nabla \times \vec{A}
\]

\[
\vec{J} = \vec{J}_s + \vec{J}_e
\]

\[
\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \nabla V
\]

\[
\vec{J}_e = \sigma \vec{E}
\]

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times \vec{A} \right) = -\sigma \frac{\partial \vec{A}}{\partial t} - \nabla \sigma V + \vec{J}_s
\]

\[
\nabla^2 \vec{A} = \mu \sigma \frac{\partial \vec{A}}{\partial t} + \mu \sigma \nabla V - \mu \vec{J}_s
\]

Assuming \( \mu \) to be constant and incorporating Coulomb gauge condition \( \Delta \vec{A} = 0 \)

Time harmonic fields \( (\vec{A} = e^{-i\omega t}) \)

\[
\frac{\partial \vec{A}}{\partial t} = i \omega \vec{A}
\]

\[
\nabla^2 \vec{A} = i \mu \sigma \omega \vec{A} + \mu \sigma \nabla V + \mu \vec{J}_s
\]

Source current density \((\vec{J}_s)\) is a constant value
**FE Modeling – 2D axisymmetric**

Material properties used in the model

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Size (Width x Height mm)</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exciter coil</td>
<td>2.7 x 7.5</td>
<td>Copper</td>
</tr>
<tr>
<td>Tube</td>
<td>2.3 x 100 (ID. 12.6 mm)</td>
<td>Mod. 9Cr-1Mo</td>
</tr>
<tr>
<td>Outer box</td>
<td>30 x 110</td>
<td>Air</td>
</tr>
</tbody>
</table>

Number of turns in exciter coil: 400, SWG 38
Number of turns in receiver coil: 200, SWG 38
Current in exciter coil: 100 mA
Material property and boundary condition

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Property</th>
<th>Conductivity, S/m</th>
<th>Relative permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil</td>
<td>Copper</td>
<td>6.0x10^7</td>
<td>1</td>
</tr>
<tr>
<td>Tube</td>
<td>Mod. 9Cr-1Mo steel</td>
<td>2.3 x 10^7</td>
<td>75</td>
</tr>
<tr>
<td>Outer box</td>
<td>Air</td>
<td>100</td>
<td>1</td>
</tr>
</tbody>
</table>

- The conductivity of the air chosen to be very small (not zero) to maintain numerical stability (zero on diagonal, ill conditioning of matrix)
- Electric insulation boundary condition (Neumann condition on magnetic field) used against magnetic insulation which required larger solution domain
- Solver: Direct (UMFPACK) solver for sparse matrix
- The Magnetic vector potential \(A_\phi\) values obtained after solving the model at the nodal points used for further processing.
Analysis of the predicted magnetic flux density, Magnetic field

- Close to the exciter coil the direct field is dominant and indirect or the resultant field is minimum.
- With increase axial distance the indirect fields increase and direct field decrease.
- At the remote field zone the indirect field is dominant and enters back into the tube ID.

Surface plot : logarithm Magnetic flux density (Magnitude information)
Arrow plot : logarithm Magnetic field (direction information)
Analysis of the predicted magnetic flux density and field at different frequencies

- Predicted field profiles confirm the existence of RFEC zone in the ferromagnetic tubes
Analysis methodology for obtaining the RFEC characteristics

- Further characteristics of the RFEC technique analyzed in the following manner:
  - Vector potential values inside the tube were used to calculate amplitude and phase of the induced voltage in the fictitious receiver coil at different axial positions.
  - log (amplitude) and phase angle plotted as a function of the axial position of the receiver coil.

\[
\text{Induced voltage} = -N \frac{d\phi}{dt} = -Ni \omega \oint B \cdot da = -Ni \omega \oint \nabla \times A \cdot da = -Ni \omega \oint A \cdot dl = -Ni \omega A.2\pi r
\]
Amplitude and phase of induced voltage in axially displaced receiver coil

- Clear distinction of direct, transition and RFEC zone observed.
- The phase angle shows a sudden jump of nearly 180 degrees.
- Phase angle jump signifies the back entry of indirect field due to eddy currents in the tube wall.
Quantitative characterization of RFEC zone

- Deviations in the straight line behavior in the direct and remote field zones was quantitatively analyzed to characterize the zone.
Presentation of quantitative Analysis results

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Frequency, Hz</th>
<th>Start of transition region (A), mm</th>
<th>End of transition region (B), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>21.5</td>
<td>40.0</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>20.0</td>
<td>38.0</td>
</tr>
<tr>
<td>3</td>
<td>700</td>
<td>19.5</td>
<td>36.5</td>
</tr>
<tr>
<td>4</td>
<td>800</td>
<td>19.0</td>
<td>36.0</td>
</tr>
<tr>
<td>5</td>
<td>900</td>
<td>19.0</td>
<td>35.5</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>19.5</td>
<td>35.0</td>
</tr>
<tr>
<td>7</td>
<td>1100</td>
<td>19.5</td>
<td>35.0</td>
</tr>
<tr>
<td>8</td>
<td>1200</td>
<td>20.0</td>
<td>34.5</td>
</tr>
<tr>
<td>9</td>
<td>1300</td>
<td>20.0</td>
<td>34.0</td>
</tr>
<tr>
<td>10</td>
<td>1400</td>
<td>21.0</td>
<td>33.5</td>
</tr>
<tr>
<td>11</td>
<td>1500</td>
<td>22.0</td>
<td>32.0</td>
</tr>
</tbody>
</table>

- The transition zone ends at 35 mm in most of the frequencies
- So the RFEC zone exists beyond 35 mm and consider ideal location for positioning the receiver coil.
Validation of the model in a normalized scale

- Good agreement between the experimental and model results observed.
- The deviation with respect to experimental measurements is less than 10%.
Conclusions and further works

- The RFEC characteristics in the Modified 9Cr-1Mo ferromagnetic steel was studied using COMSOL.
- The RFEC zone in this tube could be accurately identified for placing a receiver coil.
- The model was experimentally validated and deviation was found to be less than 10%.
- Further works are necessary to model the nonlinear behavior of the magnetic steel (BH characteristics).
- 3D modeling is also being explored for