FE Modelling of a Pulsed Eddy Current Probe for Inspection of Steam Generator Tubes in CANDU® Reactors

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Agenda

• Introduction
• Pulsed Eddy Current Technology
• Analytical Model
• Finite Element (FE) Model
• Experimental Validation
• Current Work
• Conclusions
Introduction

• Steam Generators are a critical component of nuclear power plants
• Inspection of thousands of tubes required
• Support structures are designed to prevent excessive vibration of tubes
Introduction

• Corrosion can occur in support structures
• Loss of support can result in excessive tube vibration
  – Leads to tube fretting
• Other issues associated with build-up of corrosion products including
  – Hydrodynamic cavitation
  – Intergranular attack & tube OD cracking
Introduction

Hydrodynamic Cavitation

Yao, Z. Holt, R. Steam Generator Design and Degradation Mechanisms [PowerPoint Slides].
Introduction

Corrosion

SG Tubes

Broach Support

Degraded Tube Sheets

5th International CANDU In-Service Inspection Workshop 2014 Conference
Broach Support Corrosion
Eddy Current Technology

- Current inspection methods use conventional eddy current technology
- Bobbin probe, X-probe
- Not as effective for inspection of external support structures
Pulsed Eddy Current Technology

• PEC uses a square pulse excitation
• Near DC magnetization of ferromagnetic materials
• Greater depth of penetration than conventional eddy current
• Sensitive at greater lift-offs than conventional eddy current
Pulsed Eddy Current Technology

• PEC takes advantage of the long diffusion time of electrodynamic fields

\[ \tau \sim \mu \sigma l^2 \quad \rightarrow \quad \delta \approx \sqrt{\frac{\tau}{\mu \sigma}} \]

• \( \mu \) is the permeability
• \( \sigma \) is the conductivity
• \( l \) is the characteristic length
• \( \delta \) is the depth of penetration
Probe Design

- Pick-up Coil
- Drive Coil
Analytical Model

- Probe can be simplified and modeled as a circuit
- Simplified circuit showing drive coil which has resistance and inductance
Analytical Model

- Circuit can be solved to find current

\[ i_1 = \frac{v_0}{R_1} \left[ 1 - e^{-t/\tau} \right] \]

\[ \tau = \frac{L_1}{R_1} \]
Analytical Model

• From solved circuit, modifying $R_1$ and $L_1$ will change shape of the excitation
• Using different inductances, rise time of the drive coil can be increased
• Inductance can be modified by the addition of a ferrite core
Analytical Model

- Three different sizes of Ferrite core
- Ferrite permeability = 2300 [H/m]
- Ferrite resistivity = \(2 \times 10^8\) [\(\mu\Omega \cdot \text{cm}\)]
- Copper resistivity = 1.72 [\(\mu\Omega \cdot \text{cm}\)]

<table>
<thead>
<tr>
<th>Core</th>
<th>Outer Diameter [mm]</th>
<th>Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>25</td>
</tr>
</tbody>
</table>
Analytical Model

Current [A] vs. Time [ms] for different core sizes:

- Air Core
- 5 mm OD
- 4 mm OD
- 3 mm OD

Legend:
- Blue: Air
- Red: Core 5 mm OD
- Green: Core 4 mm OD
- Purple: Core 3 mm OD

Graph showing the impact of core size on current over time for an analytical model.
FE Model

- Modelled in COMSOL Multiphysics
- 2D half model created to simplify computations and decrease computation time
- Axis showing distance in mm
FE Model (Mirrored)

- SG Tube
- Drive Coil
- Ferrite Core
FE Model

• From the COMSOL model, it was found that the length of the ferrite core could be reduced and still provide the same flux density at the pick-up coil locations
FE Model

Current [A] vs. Time [ms]

- Air Core
- 5 mm OD
- 4 mm OD
- 3 mm OD

Core 1
Core 2
Core 3
Comparison of analytical response and FE response in excellent agreement.
• Experimental response of single coil with three different cores in Alloy-800 tube
FE Model

- Experimental setup has an internal resistance
- Resistance shown in circuit as $R_{cir}$
- $R_{cir} = 2.3 \, \Omega$
- This additional resistance can be added to the FE model
Comparison of Models with Experiment

Air Core

- Comparing cases with air core
- Shows excellent agreement
Comparison of Models with Experiment
3 mm OD Ferrite Core

- Comparing cases with ferrite cores
- Excellent agreement between FE and Experiment
Comparison of FE Model with Experiment

- Inductance of coil with different ferrite cores
- Measured and FE are in good agreement

<table>
<thead>
<tr>
<th>Core</th>
<th>Measured L1 [μH]</th>
<th>FE L1 [μH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Core</td>
<td>232</td>
<td>233</td>
</tr>
<tr>
<td>1</td>
<td>769</td>
<td>768</td>
</tr>
<tr>
<td>2</td>
<td>634</td>
<td>627</td>
</tr>
<tr>
<td>3</td>
<td>498</td>
<td>500</td>
</tr>
</tbody>
</table>
FE Model

FE modelled response from pick-up coil

![Graph showing current vs. time for different core sizes with LOI marked]

- Air
- Core 5 mm OD
- Core 4 mm OD
- Core 3 mm OD
Comparison of FE Model with Experiment

• Frequency analysis can be conducted to examine effect of frequency on inductance
• Using tubes with comparable dimensions
• Two materials were examined:
  – Alloy-800 (resistivity 107 [µΩ·cm])
  – Aluminum (resistivity 4.0 [µΩ·cm])
Comparison of FE Model with Experiment

![Graph showing inductance vs. frequency for different materials and conditions.](image)

- No Tube
- Alloy-800 Measured
- Aluminum Measured
- Alloy-800
- Aluminum

**Probe Equivalent Frequency**
Current Work

- Optimizing probe design
- Modifying current probe from 4 coils to 6 coils
- Designed to inspect trefoil broach support structures more effectively (120° separation)
- Examining pick-up coil response with ferrite core present
FE Model

Pick-up Coil
Drive Coil
FE Model

- Sample broach support structures were built
- One trefoil hole
- Trefoil hole array
- The broach support was simulated using COMSOL
Finite Element Model

Tube

Trefoil hole
Finite Element Model

- Flaws were added to broach support to determine if detection is possible
- A tapered flaw was generated on the top surface of the support structure
Finite Element Model of Corroded Trefoil

Tube
Trefoil hole

Trefoil hole array
Corroded Trefoil hole

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Finite Element Model Results

The graph shows the current [mA] as a function of time [ms] for different conditions:
- **Flaw**
- **No Flaw**

The inset graph provides a closer view of the current and time for both conditions, highlighting the differences.

- **Current [mA]**
  - Flaw: 4.5, 5, 5.5, 6
  - No Flaw: 4.5, 5, 5.5, 6

- **Time [ms]**
  - Flaw: 0.008, 0.028, 0.048
  - No Flaw: 0.008, 0.028, 0.048
Conclusions

• Addition of ferrite core will increase rise time and total flux permitting greater depth of penetration and larger signal response
• COMSOL and experimental values were found to be in excellent agreement
• Further validation of probe is required
• Continued optimization of 6 coil probe to be used for inspection of broach support structures
Questions?