Finite Element Modeling of Transient Eddy Currents in Multilayer Aluminum Structures

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Background

- Transient (or pulsed) eddy current inspection employs a pulsed excitation to induce a transient response from electromagnetic field interactions within a conducting structure.

- Useful for detection of defects in thick multilayered non-ferromagnetic structures at greater depths with higher resolution than conventional EC technique.

- Fatigue induced crack growth at ferrous fasteners is a common mode of failure in aircraft wing structures. Locations of cracks in the second layer are not normally inspectable by conventional techniques (EC or UT).
  
  - Typical crack depth ~ 0.10” or less
  - Thickness of wing structure ~ 0.25”
  - Geometry may be locally varying with only one side access, under installed fasteners.
Driver Signal

\[ I = \frac{\mathcal{E}}{R} \left(1 - e^{-\frac{t}{\tau_C}}\right) \quad \tau_C = \frac{L}{R} \]

Pickup signal depends on the interaction between the two coils as well as between the coils and the sample.
Experimental Set-Up

<table>
<thead>
<tr>
<th></th>
<th>Driver</th>
<th>Pickup Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, mm</td>
<td>20.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Inner diameter, mm</td>
<td>18.9</td>
<td>5.9</td>
</tr>
<tr>
<td>Outer diameter, mm</td>
<td>20.9-23.9</td>
<td>8.2</td>
</tr>
<tr>
<td>Number of turns</td>
<td>400-1600</td>
<td>300</td>
</tr>
<tr>
<td>AWG</td>
<td>34</td>
<td>44</td>
</tr>
<tr>
<td>Resistance, Ω</td>
<td>26.0-122</td>
<td>64.0</td>
</tr>
<tr>
<td>Length of ferrite core, mm</td>
<td>20.0-30.0</td>
<td></td>
</tr>
<tr>
<td>Diameter of ferrite core, mm</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Permeability of ferrite</td>
<td>1500-3100</td>
<td></td>
</tr>
<tr>
<td>Conductivity of ferrite, S/m</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Conductivity of aluminum, S/m</td>
<td>$2.46 \times 10^7$</td>
<td></td>
</tr>
</tbody>
</table>
Smoothed Heaviside function
```
flc2hs(x, scale)
```
- a step function that smooths within the interval
  -scale < x < scale

scale: \( 5 \times 10^{-7} \) s
Time range: 0 to \( 1.00 \times 10^{-3} \) s
Step size: \( 2 \times 10^{-7} \) s
2D Finite Element Mesh
Total Surface Current Density

Modeling of LOI for multilayered structure
Number of Aluminum plates used = 10
Total thickness = 4mm
Model:
coil_plate_2d_ver02_10plates_lift23
Lift = 0.23 mm
Driver and Pickup Voltages (Experiment vs. Model)
Model Verification of LOI Point for Flat Plates

-0.5
-0.4
-0.3
-0.2
-0.1
-0.0
0
0.0002
0.0004
0.0006
0.0008
0.0010

Pickup Voltage (V)

Time (s)

0 mm
0.4 mm
1.0 mm
2.0 mm
Air Signal

2.0 mm
1.0 mm
0.4 mm
0 mm
3D Model with Hole: Surface Current Density
Defect and Reference Signals for 1 Plate

- Voltage (V)
- Time (s)

Graphs showing the voltage over time with different signals:
- Background minus defect
- Defect
- No Defect (background)
Subtracted Defect Signal vs. Probe Position
Modeled vs. Experimental Signal (5 Plates)

![Graph](image)

- Voltage (V)
- Time (s)

- **5 plates (experiment)**
- **5 plates (model)**

**Note:**
- Data from 9 Oct 2009
- COMSOL Conference, Boston
3D Half Model with Fastener and Crack

**Current Density, \( J_x \)**

- \( t = 1.1 \times 10^{-4} \) s
- \( t = 1.0 \times 10^{-3} \) s

\[ \mu_{\text{ferrite}} = 2300, \quad \mu_{\text{fastener}} = 66 \]
Underside Views of Crack Near Fastener
Summary

- COMSOL Multiphysics software has proved very successful for modeling the pulsed eddy current response in conducting plates in the presence of defects. Modeling in the presence of ferrous fastener has also produced important information.

- The models have been validated against experimental data.

- The interaction of pulser, drive coil and transient response of pick-up coil in air and in the presence of conducting material is successfully modeled.

- FE Modeling helped in investigating the effect of changing probe parameters on the probe characteristics. It also provided useful information on the diffusion of current density with time in conducting plates.

- FE modeling can potentially help in theoretical understanding of transient eddy current phenomenon, designing of new probes, and dealing with a variety of complex physical situations.