Detection of second layer fatigue cracks around ferrous fasteners in lap joints of a CP-140 Aurora

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Agenda

• Introduction
• Eddy Current Testing
• Principal Components Analysis
• Custer Analysis (Mahalanobis Distance)
• Samples
• Notch Information
• Experimental Set-up and Technique
• Results
• Conclusion
Introduction

- Cyclic fatigue cracks emanate from around ferrous fasteners in lap joints of CP-140 Aurora and CC-130 Hercules.
- Goal is to detect the cracks without fastener removal (saving time and money) using NDT.
- Conventional Eddy Current encounters difficulties detecting second layer cracks.
- PEC offers advantages such as deeper penetration of eddy currents.
  - Signals require more sophisticated analysis.

![Diagram of crack detection](image)
Introduction
Current Methods of Second Layer Detection

• Conventional Eddy Current: CAF Eddy Current Procedure (Hocking Fast-scan)
  – Capable of reliably detecting 2.54 mm cracks in second layer
  – Fasteners retained
  – Probe requires rotation
  – Has shortfalls detecting cracks in 4 orientations

• Bolt Hole Eddy Current:
  – Requires fastener removal
  – Can cause surface damage
  – Min detectable flaw size < 0.76mm

• Minimum Detectable Flaw Size for Second Layer Flaws not Defined using PEC
  – To be competitive, goal is to detect a 0.76 mm flaw in second layer using PEC, **not** requiring fastener removal
Introduction
Probability of False Positive (False Call)

• System response: detecting a flaw when none is present at inspection location
• Difficult to define acceptable false call rate
• Cost of false call high: low false call rate desirable
  – Time and money involved in re-inspecting flaw site or removing component from service is high
<table>
<thead>
<tr>
<th></th>
<th>Conventional Eddy Current</th>
<th>Pulsed Eddy Current</th>
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<tbody>
<tr>
<td><strong>Magnetic Field Excitation</strong></td>
<td>Sinusoidal</td>
<td>Step Function, use leading edge</td>
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<tr>
<td><strong>Crack Detection</strong></td>
<td>Impedance plane display</td>
<td>Analysis of raw signal features (i.e., peak amplitude) using PCA, to address subtle differences</td>
</tr>
<tr>
<td><strong>Depth of Penetration of Eddy Currents</strong></td>
<td>Limited</td>
<td>Deeper, compared with conventional ET</td>
</tr>
<tr>
<td><strong>Probe Design</strong></td>
<td>Fast, reliable method for multiple inspections</td>
<td>Tailored to application</td>
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Signal Analysis
Differences are too subtle to consistently and reliably determine which are from fasteners with notches at their bore
Principal Components Analysis (PCA)

- Statistical technique used to re-express multivariate data (such as PEC or EC signals) by finding linear combination of original variables with max variation
  - $Y = S_1V_1 + S_2V_2 + S_3V_3 + \cdots$
- PCA reduces large data sets (signals) to 3 or 4 PCA scores and eigenvectors
- Eigenvectors are orthogonal (independent)
Data Reconstruction using Eigenvectors

Sum-product of scores and vectors reproduce the original signal. Only takes approximately 4 vectors to represent 99.9% of the original signal.
PCA Scores
Cannot distinguish between tracks (solid circles) and blanks (hollow circles) without rotating the view
How do we separate clusters?
Cluster Analysis

• Another statistical technique, Malahanobis distance (MD), describes the proximity of a point, $y$, to the centroid of a group of points.
• MD adjusts for covariance in the data.
  \[ MD = \sqrt{(y - \bar{x})'\Sigma^{-1}(y - \bar{x})} \]
• In the PCA space, it is a relative measure of a notch’s distance from a common point (blanks) in standard deviations.
• Notch/Blank categorization: compare MD to critical Hotelling $T^2$ value (uses population size, # of PCA scores and F test @ 95%)
  – If $MD > T^2$, then it is a notch
  – If $MD < T^2$, then it is a blank
Mahalanobis Distance
Relative measure of distance in standard deviations
Samples

NAVAIR Sample

Test Piece #1

Ferrous Fasteners

CP-140-TT-1B Aurora Sample
**Notch Orientation**

Notches in NAVAIR and Aurora test pieces are EDM notches, Lab test piece notches cut with jewellers blade, by hand, Length measured using picture microscope

Notch sizes vary from 0.8mm to 5.5mm and are at 45° angle (1:1 aspect ratio) to the surface (i.e. large notches become through cracks)

Can be in bottom of first layer, or in top of second layer
**Probe Design**

Central driving coil wound around ferrite core
8 pick-up coils – Either absolute or differentially connected
Probe takes advantage of ferrous fastener which acts as a flux conduit allowing deeper penetration into the sample
Experimental Technique

Centering errors can occur, 1 mm
Results: Eddy Current Density in Sample

Highest concentration of Eddy Currents occurs between 0.4 – 1.0 ms
4\textsuperscript{th} and 5\textsuperscript{th} eigenvectors have largest contribution
Results: Logistic Regression

Using 5 eigenvectors yields better $a_{50}$ (0.90mm) than using 3 or 4 eigenvectors.

Horizontal axis is log scale.
Differential Analysis Results

- Top layer thickness: 2mm
- HL-19 Fasteners (7mm head diameter)
- 8 blanks
- 15 notch sites
- Notch size range: 0.89 – 5.46 mm (first and second layer)
- 100% Notch Detection
- 5% False Call Rate
NAVAIR Sample

**MD versus Crack Size**

- Hotelling T^2 99%
- Hotelling T^2 95%

- Mahalanobis Distance (arbitrary units)
- Crack size (mm)

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Differential Analysis Results

- Top layer thickness: 2mm
- HL-19 Fasteners (6.5mm head diameter)
- 10 blanks
- 19 notch sites
- Notch size range: 0.83 – 3.26 mm (all second layer)

- 100% Notch Detection
- 5% False Call Rate
Test Piece #1

MD versus Crack Size

- Hotelling $T^2$ 99%
- Hotelling $T^2$ 95%

Mahalanobis Distance (arbitrary units)

Crack Size (mm)
Differential Analysis Results

- Top layer thickness: 2.58mm
- HL-51 Fasteners (7mm head diameter)
- 12 blanks
- 21 notch sites
- Notch size range: 1.53 – 3.81 mm (first and second layer)
- 82% Notch Detection
- 5% False Call Rate
CP-140-TT-1B

MD versus Crack Size

Mahalanobis Distance (arbitrary units)

Crack Size (mm)

- Hotelling T^2 99%
- Hotelling T^2 95%

- 1st Layer Notches
- 2nd Layer Notches
# Results Comparison

<table>
<thead>
<tr>
<th></th>
<th>NAVAIR Sample</th>
<th>Test Piece #1</th>
<th>CP-140-TT-1B</th>
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</thead>
<tbody>
<tr>
<td><strong>Fastener Type</strong></td>
<td>HL-19</td>
<td>HL-19</td>
<td>HL-51</td>
</tr>
<tr>
<td><strong>Fastener Head Diameter</strong></td>
<td>7 mm</td>
<td>6.5mm</td>
<td>7 mm</td>
</tr>
<tr>
<td><strong>Top layer Thickness</strong></td>
<td>2mm</td>
<td>2mm</td>
<td>2.6mm</td>
</tr>
<tr>
<td><strong>Crack Detection @ 0% False Calls</strong></td>
<td>87%</td>
<td>100%</td>
<td>80%</td>
</tr>
<tr>
<td><strong>Crack Detection @ 5% False Calls</strong></td>
<td>100%</td>
<td>100%</td>
<td>82%</td>
</tr>
</tbody>
</table>
Consequences of False Call

• False Call rates of ≈ 5% are normally acceptable (in a_{90/95} analysis)
• Cost involved in false call rates is important
• Should a crack be detected: remove fastener and perform BHEC inspection
  – Capable of detecting 0.76 mm flaws (a_{90/95})
Conclusions

- Notches ranging from 0.83 to 5.5 mm were detected using the coil based probe
- Optimum results were obtained using probe in differential mode
- PCA provides mechanism for compensating for additional variables that may affect PEC signal response (lift-off, distance to edge, off-centering)
- PCA allows visualization of data in more than 2 dimensions (in this case, 5)
- 100% of cracks in 2 test pieces were detected with 5% false call rate
- 82% of cracks detected in CP-140-TT-1B Sample with 5% false call rate
- MD shown to be correlated with crack size, identifying a potential for crack sizing
Conclusions Continued

- All first layer flaws detected, improving current conventional eddy current technique
- Second layer detection using PEC technique surpasses conventional technique min detectable flaw size of 2.54 mm, and approaches BHEC min detectable flaw size
- Successfully reproduced NAVAIR sample (Test Piece #1) and crack detection results
- Should a flaw be detected, remove fastener and perform BHEC inspection
- Strong evidence that PEC technique has capability for second layer crack detection, approaching the BHEC target size of 0.76 mm
Questions?