Pulsed eddy current detection of cracks in CF-188 inner wing spar through insulating wing skin using modified Principal Components Analysis

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Outline

• Motivation
• Pulsed Eddy Current
• Data Acquisition & Analysis
• Results from Field Trial – NAS North Island
• Issues
• Conclusions
Introduction

• Ongoing research at RMC using PEC to detect SCC in lower cap of CF188 inner wing spar without fastener or carbon fibre reinforced polymer (CFRP) skin removal

• Currently addressed by Radiography inspections – long inspection times and costly.

*Dimensions in mm
CF-188 Inner Wing lower surface

Red=Titanium
Green=Steel
Blue=Steel
Pink=Steel

Lower Surface Wing
Thicknesses
Conventional Eddy Current Testing

- Very sensitive to lift-off distance
- Effect falls off rapidly with lift-off (~5 mm)
- Very sensitive to ferromagnetic (steel) material, generating an overwhelming response.

Pulsed Eddy Current

- Effective at large lift-offs (~20 mm)
- Can use ferromagnetic material as a flux conduit.
Experimental Setup

• Probe Design:
  – Central driver coil, dual outer pickup coils, sampled separately (absolute)
  – Centered over fastener
  – Pickup coils aligned with fastener row (spar)
Signal Response

- Traditional methods of PEC analysis are unfeasible at such large lift-off distances
  - CF188 Lift-off (skin thickness) can vary from 9 to 21 mm (0.36-0.84in) in area of interest
- Use of discrete time-domain signal features such as peak amplitudes do not allow for reliable crack discrimination
- Titanium fasteners further complicate the problem

Probe 9 time domain responses for HLT53DL8-10, acrylic skin thickness = 6.4mm, single coil response
Data Windowing

![Graph 1: Intensity vs. Time for coil 1 and coil 2](image1)

![Graph 2: Intensity vs. Time for coil 2](image2)
Principal Components Analysis

- Statistical technique used to reproduce a set of data using as a linear combination of as few a number as possible of common eigenvectors \( \mathbf{v} \)

\[
\mathbf{X} = z_1 \mathbf{v}_1 + z_2 \mathbf{v}_2 + ... 
\]

Sample signal re-built using 3-5 common (basis) vectors

Principal Components Analysis
Reconstructed Signal

Eigenvector reconstruction of a signal
Principal Components Analysis

Principal Component ($Z$-) Scores

Scatters reveals groupings based on presence of cracks
Discriminant Analysis

- Applying multiple linear regression to PCA scores can quantify in one dimension the presence of a notch.
- Regress PCA scores to zero for no notch present, to one for notch at the bore.

P. Horan, P.R. Underhill and T.W. Krause, IEEE Sensors Journal, ‘Real time pulsed eddy current detection of cracks in F/A-18 inner wing spar using discriminant separation of Modified Principal Component Analysis scores’, Published Sept. 16, 2013, 10.1109/JSEN.2013.2281368
Using CF-188 CFRP skin

At two skin thicknesses: 6.9mm (0.272in) 13.8mm (0.544in)

HLT53DL8-13 (Steel)

HLT313DL8-16 (Ti)
Field Trial

• Pulsed Eddy Current (PEC) technique to detect cracking in Inner Wing spars of F/A-18 Hornet tested at NAS North Island, San Diego, CA on 25-26 Mar 13
Field Trial

- 2 wings fully scanned, portions of 3 additional wings
- 1300+ measurements taken
- 9 cracks, spanning 32 fastener locations

<table>
<thead>
<tr>
<th>Wing</th>
<th>Crack Location (Hole Nos.)</th>
<th>Approx. Length (mm (in.))</th>
<th>Spar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1140RH</td>
<td>464-468</td>
<td>101.6 (4)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>672-664</td>
<td>101.6 (4)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>673-669</td>
<td>50.8 (2)</td>
<td>4</td>
</tr>
<tr>
<td>1140LH</td>
<td>467-469</td>
<td>50.8 (2)</td>
<td>2</td>
</tr>
<tr>
<td>1129LH</td>
<td>467-469</td>
<td>50.8 (2)</td>
<td>2</td>
</tr>
<tr>
<td>1057LH</td>
<td>593-592</td>
<td>25.4 (1)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>570-572</td>
<td>50.8 (2)</td>
<td>3</td>
</tr>
<tr>
<td>516LH</td>
<td>576-571</td>
<td>127 (5)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>687-688</td>
<td>25.4 (1)</td>
<td>4</td>
</tr>
</tbody>
</table>
Sample Results

- Wing 1140RH, 3” crack spanning 4 holes
- Titanium fasteners, skin thickness 0.48”

Actual wing data was required to generate more realistic basis functions.
Sample Results

- Corrected results
- Regression re-analyzed
# Results

<table>
<thead>
<tr>
<th>Wing</th>
<th>Crack Description</th>
<th>Spar No.</th>
<th>Lab-calibrated (On-Site) Indications</th>
<th>Calibrated (Post-Analysis) Indications</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hole Nos.</td>
<td>Detect. Rate (%)</td>
<td>Hole Nos.</td>
</tr>
<tr>
<td>1140RH</td>
<td>464-468</td>
<td>4</td>
<td>2</td>
<td>465-467</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>672-664</td>
<td>5</td>
<td>4</td>
<td>672-666</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>673-669</td>
<td>2</td>
<td>4</td>
<td>Nil/Nil</td>
<td>0%</td>
</tr>
<tr>
<td>1140LH</td>
<td>467-469</td>
<td>2</td>
<td>2</td>
<td>465-469</td>
<td>100%*</td>
</tr>
<tr>
<td></td>
<td>1129LH</td>
<td>467-469</td>
<td>2</td>
<td>2</td>
<td>467-469</td>
</tr>
<tr>
<td>1057LH</td>
<td>593-592</td>
<td>1</td>
<td>3</td>
<td>593</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>570-572</td>
<td>2</td>
<td>3</td>
<td>572</td>
<td>33%</td>
</tr>
<tr>
<td>516LH</td>
<td>576-571</td>
<td>5</td>
<td>3</td>
<td>576-573, 571</td>
<td>83%</td>
</tr>
<tr>
<td></td>
<td>687-688</td>
<td>1</td>
<td>4</td>
<td>687</td>
<td>40%</td>
</tr>
</tbody>
</table>

| Totals | By Crack** | 8 of 9 | 89% | 9 of 9 | 100% | **At least one fastener indication for a given crack location |
|        | By Fastener | 21 of 32 | 66% | 29 of 31 | 94% | **At least one fastener indication for a given crack location |

Crack extends to ferrous HLT265 fastener at 464
Thickest skin in these locations (0.84”), at inboard pylon station.
*2 on-site unconfirmed indications at 465-466, estimated crack length 2” longer than indicated by radiography
1 unconfirmed indication at 578 on this spar. No neighboring indications – possible partial crack or anomalous ferrous fastener response
Titanium bushing repair in area of interest
Wing Skin Thickness Variation

Increasing wing skin thickness

![Graph showing wing skin thickness variation](image1)

![Graph showing discriminant score](image2)
Issues

• Cracks that span individual ferrous fasteners among numerous titanium ones
• Ex: able to detect cracking at Ti fasteners by comparing discriminant scores from adjacent unflawed sites
  – But single ferrous fasteners among Ti can’t be compared
• On-site a 4” crack was identified as 3” due to a single ferrous fastener on the end of it
Issues

• Fasteners of “wrong” material show up where CFTO’s call for opposite material
  – Possibly as the result of repairs or parts substitution, ferrous HLT53 fastener will be installed where CFTO’s call for titanium HLT313
  – Clearly obvious due to magnitude of PEC response
• Different fastener part numbers than those listed in CFTO’s as well
• Analysis algorithm must be able to account for this
  – Preferably without operator input
• Technique must be able to detect cracking in the presence of various repairs
  – Titanium busing repair scheme seen on wing 516LH
Comparison with Radiography

- 45 shots per wing → 90 total shots/aircraft

- Conventional Film (wing off)*
  - Each shot:
    - 2 min exposure time
    - 15 min developing time
    - 20 min for setup
  - 37 min/shot
- 3330 min total
- 55.5 hrs per aircraft (with 2 people) + analysis time

- Computed Radiography (CR) (wing off)*
  - Each shot:
    - 1 min exposure time
    - 1 min scan time
    - 20 min for setup
  - 22 min/shot
- 1980 min total
- 33 hrs per aircraft (with 2 people) + analysis time

- PEC System
  - Each wing:
    - 30 min setup time
    - 30 mins per spar × 4 spars
    - 2.5 hrs per wing
  - 5.0 hrs per aircraft (includes analysis time)

*Figures from ATESS NDT Trg O
Summary

- 2 full wings, and portions of 3 additional wings (1300+ total fasteners) were completed over 10 hours of work.
- 89% on-site crack detection, 100% in post-analysis.
- 66% of flawed fastener locations identified on-site, 94% in post-analysis.
- Identified gradual thickness transitions.
- Identified unexpected fastener types and repairs.
- Pulsed Eddy Current works well on ferrous fasteners.
Acknowledgements

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Questions?