Engine Component CBM using Flexible ET Arrays for Crack Depth Measurement

31 March 2015

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Case Studies

- **Case Study 1**: Commercial aircraft engine knife seal inspection

- **Case Study 2**: US military engine blade dovetail Inspection
  
  (a) Crack detection sensitivity in regions with fretting damage
  
  (b) Crack depth measurement for CBM

- **Case Study 3**: US military automated engine disk slot inspection

- **High-throughput disk inspection feasibility**
High-Throughput Inspection

Goals:

▪ **Reduce Inspection Time**
  - Inspect multiple features simultaneously (need many channels, fully parallel)
  - Inspect wide areas fast
  - Reduced surface preparation requirements enabling practical high-throughput inspection

▪ **Reduce Costs**
  - Lower scanner complexity results from
    - Arrays with many channels
    - Flexible/conformable array construct
    - **Accurate lift-off measurement and defect response rescaling**
  - Provide improved performance without requiring rigidity to control lift-off
  - Reduce false indication rates while maintaining a high probability of detection

▪ **Minimize Burden on Inspector**
  - Automated analysis
  - Automated reporting

*MWM-Array engine inspection is FAA approved on some commercial engines (inspecting thousands of components per year) and has been in use for ten years by the US Navy for engine disk slot inspection*
>10x Higher Array Transit Velocity with Improved Signal-to-Noise

7000 Series Crack response

100 samples per second

8200 Crack Response

1,300 samples per second
Case Study 1: Knife Seal Inspection

- “Technical aspects of the method are FAA approved” (See Service Bulletin)
- Engine OEM implemented this inspection
- Multiple systems in use world-wide since 2011
- AE family engine knife seal Inspection on several stages for cracks
- Thousands of engine stages inspected per year
- Inspection performed with blades in place (minimal disassembly saves substantial dollars)

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Case Study 2: Military Blade Dovetail Inspection

Completed U.S. Military Dovetail Inspection System - Delivered Fall 2006
Case Study 2: Military Blade Dovetail Inspection

MMW-Array Sensors

Precomputed Database (Grid)

C-Scan Image

Sensor Position at Edge of Dovetail

Sensor Coverage

Lift-Off Imaging

Individual Sensing Elements

Crack response rescaled based on lift-off

42-mil Crack
Case Study 2a: Blade Dovetail Crack Detection Performance

- Training Set Blade with “Known Cracks”
- Cracks verified using acetate replicas
- On similar blades, MWM-Arrays detected cracks that were not found by the OEM optical method
- These are tight cracks in regions with fretting damage

**Convex Side**

```
42-mil Crack
```

**Concave Side**

```
75-mil Crack Cluster (Maximum Crack Length 50 mils)
```

NOTE: Missing using optical methods is not surprising given length.
Case Study 2a: Blade Dovetail Crack Detection Performance

- Training Set Blade identified as having “No Cracks”
- Cracks found and verified
- These three verified cracks were not found by the OEM optical method
Case Study 2b: Military Engine Crack Depth Measurement

- Engine Blade Dovetail
- Provide crack depth measurement to enable CBM /repair of blade dovetail for life extension
- Technical approach: multiple frequency MWM-Array detection, location and depth sizing for cracks in regions with fretting damage
- Validation method – Detection performance validation included POD study
- Status: Solution validated and system delivered
Case Study 2b: Crack Depth Measurement Results

- **1st Multi-frequency Function**
  - Too Deep
  - Crack Depth from Fractography (mils)

- **2nd Multi-frequency Function**
  - Too Deep
  - Crack Depth from Fractography (mils)

- **Normalized Conductivity Minimum**
  - Too Large
  - Crack Depth from Fractography (mils)

- **Crack Response Width (Mils)**
  - Too Long
  - Crack Depth from Fractography (mils)
Case Study 2b: MWM-Array Conductivity Response

Blade #5

Normalized Conductivity vs. X axis (in.)

- Low Freq
- Medium Freq
- High Freq

Key Measurements:
- 4.6 mils
- 6.5 mils
- 10.5 mils
- 9.8 mils

Edge at X = 2.6
Case Study 2b: User Interface Output

Blade #5

Shallow cracks (Light blue)

Entire image encompasses one complete side of dovetail
Case Study 2b: MWM-Array Conductivity Response

Blade #13

Normalized Conductivity vs. X axis (in.)

- Low Freq
- Medium Freq
- High Freq

6.5 mils, 9.2 mils, 6.1 mils, 10.4 mils, 15.3 mils
Case Study 2b: User Interface Output

Blade #13

Shallow crack (Light blue)

Deep crack (Red)

DETAIL

Entire image encompasses one complete side of dovetail
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  - High-throughput disk inspection feasibility
Case Study 3: Automated Engine Disk Inspection System

Active Sensing Element Coverage

Leading Edge

Concave Side

Trailing Edge

Convex Side

Concave Side

View of Trailing Edge

Convex Side

Concave Side

Convex Side
Case Study 3: Automated Engine Disk Inspection System

- In use at NAVAIR Depot since April 2005, with “no noticeable change in sensitivity”, for a decade
- Nine disks with verified cracks detected, several of these large and small cracks not detected by conventional ET and LPI
- No false indications (over >15000 slots inspected: false indication rate <0.01%)

Winner, FAA-Air Transport Association 2007 “Better Way” Award for “MWM and MWM-Array Engine Component Inspection Technology”

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Case Study 3: Engine Disk Slot Data

Disk #04, Slot #20, Concave Side

Expanded Scale
Case Study 3: Engine Disk Slot Data

Disk #04, Slot #20, Convex Side
Air Calibration and Conductivity/Lift-Off Grids

- Air Calibration
- Point
- Lift-off
- Conductivity
- Full Grid

- Crack (22 Points)
- Blue Background (~1,500 Points)
- Air Calibration Point
- Lift-off
- Conductivity

Lift-Off

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Higher Throughput Inspection Options

- Scan broad surface areas
- Scan multiple features at same time

3x 100 channels

100 0.040” sense elements
Higher Throughput Inspection Options

Current Approach:
Scan 1 blade at a time, 37 channels

Scan up to 6 blades at once

3 Blade Concept

6 Blade Concept
>10x Higher Array Transit Velocity with Improved Signal-to-Noise

7000 Series Crack response

100 samples per second

8200 Crack Response

1,300 samples per second
## High Throughput Case Study: Disk Slot Inspection

### Current Navy System Performance

<table>
<thead>
<tr>
<th></th>
<th>7000 System, 37 channels</th>
<th>8200 System, 119 channels</th>
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<tbody>
<tr>
<td><strong>Scan time</strong></td>
<td>90 seconds per blade</td>
<td>9 seconds</td>
</tr>
<tr>
<td><strong>Rotation time</strong></td>
<td>30 seconds per blade</td>
<td>30 seconds</td>
</tr>
<tr>
<td><strong>Total Time 1 array</strong></td>
<td>1 hour</td>
<td>20 minutes</td>
</tr>
<tr>
<td><strong>Total Time 2 arrays</strong></td>
<td>N/A</td>
<td>10 minutes</td>
</tr>
<tr>
<td><strong>Total Time 3 arrays</strong></td>
<td>N/A</td>
<td>7 minutes</td>
</tr>
</tbody>
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Questions?

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