Application of DARWIN™ to evaluate risk of fracture due to material anomalies in gas turbine engines

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Outline

• Summary of DARWIN™ use at the OEMs
• Evaluation of DARWIN™ at the four TRMD OEMs
  – Capability Analysis
  – Sensitivity Analyses
• Applications of DARWIN™ at the OEMs
  – Hard Alpha Risk Analysis
    • FAA Certification Analysis
  – Surface Damage Tolerance Analysis
• Acknowledgements
Summary of DARWIN™ use at the OEMs

• Four OEM’s have licensed DARWIN™ as a tool for Hard Alpha risk analysis
• FAA certification analyses have been performed on more than 10 components using DARWIN™
• About 20 engineers at OEM companies have been trained in the use of DARWIN™
• Problem Statement: The hard alpha risk analysis process should be robust to the analyst and his or her experience

• Experience with Hard Alpha risk analysis using DARWIN™
  – Variability in analysis due to analyst bias

• Solution
  – Construct a process for use of DARWIN™ that would reduce the analyst bias
  – The process has guidelines for zone definition, plate size, plate orientation, and crack placement

• How was this process arrived at?
  – By several DOE’s using model geometries and stresses based on the Advisory Circular test case
Plan: To determine whether the POF is affected by the use of different seeds

Factors
- Crack Placement
- Plate Orientation
- Plate Size
- Zone Size
- Stress Level
- Stress Gradient
- Seed
- Sample Size
- Material

Result: The choice of seeds does not impact the final POF as long as the sample size is sufficient for the problem.
Capability Analysis: Example of a DOE

Plan: To establish transfer function between inputs (volume, stress) and output (POF)

Factors
- Crack Placement
- Plate Orientation
- Plate Size
- Zone Size
- Stress Level
- Stress Gradient
- Seed
- Sample Size
- Material

Result: Regression equations yielded a relationship between volume and stress and POF that can be used to guide the analyst in choice of zones (POF = 10^C X (stress)^m X Volume)
Evaluated the capability of DARWIN™ as a Measurement System for determining risk of fracture in Titanium Components due to Hard Alpha

- Including guidelines for zone definition, crack orientation, etc.

**Capability Analysis**

- Conducted a Measurement System Analysis (Crossed)
  - Parts selected represent a wide range of geometries, volumes, and stress levels

<table>
<thead>
<tr>
<th>Analyst/Operator</th>
<th>1</th>
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</thead>
<tbody>
<tr>
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<tr>
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</table>
Process Risk*

**Falsely rejecting good parts**
Producer’s Risk
\[ \alpha \] is negligible

**Falsely accepting bad parts**
Consumer’s Risk
\[ \beta \] is negligible

*MSE Results suggest that the process as structured reduces the beta risk to a negligible level*

*based on customer control limits:
AC33.14-1 DTR
Sensitivity Studies

• Sensitivity Studies conducted to support the effort underway for HA distributions update, for example:
  – Impact of vacuum crack growth data
  – Impact of crack growth scatter
  – Impact of crack aspect ratio

• Sensitivity studies also conducted to evaluate new features of the software, for example:
  – Importance Sampling
  – Enhanced modeling of stresses within a zone

• Sensitivity studies conducted on actual components and the Advisory Circular test case
Sensitivity Study I: Impact of Titanium Vacuum Crack Growth Data

• **Objective:** Quantify the impact of vacuum crack growth data on predicted POF for actual components

• **Component probabilistic assessments** were made assuming air data for surface and subsurface FM calculations (AC 33.14-1), and then air for surface and vacuum for subsurface

• **Results show** a systematic reduction in POF of 25 to 50 % for the air + vacuum without inspection, and 15 to 35% reduction in POF with inspection
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Sensitivity Study I: Impact of Titanium Vacuum Crack Growth Data

Air + Vacuum vs Air FCG Data - Sensitivity Study Results (24 zones)

SwRI Vacuum & Air FCG Data

SwRI Air FCG Data

<table>
<thead>
<tr>
<th></th>
<th>Vacuum &amp; Air FCG data</th>
<th>Air FCG data</th>
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<tr>
<td></td>
<td>wo/insp</td>
<td>w/insp</td>
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<tr>
<td>AC Ring Disk</td>
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<td>6.19e-9</td>
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<tr>
<td>Reduction</td>
<td>4.0 X</td>
<td>3.9 X</td>
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<tr>
<td>GE Fan Disk</td>
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<td>0.32</td>
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<tr>
<td>Reduction</td>
<td>1.7 X</td>
<td>1.3 X</td>
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</table>

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Sensitivity Study II: Importance Sampling versus Monte Carlo

• Objective: Evaluate the Importance Sampling method for probabilistic risk analysis

• Importance Sampling used on three components at one OEM
  – Three analysts, three components, nine measurements per component

• Importance Sampling shows gains in efficiency along with much tighter confidence bounds compared to Monte Carlo
Sensitivity Study II: IS vs MC: Results

<table>
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<tr>
<th>Seed 1</th>
<th>Rand 1</th>
<th>Rand 2</th>
<th>Seed 1</th>
<th>Rand 1</th>
<th>Rand 2</th>
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<th>Rand 1</th>
<th>Rand 2</th>
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</thead>
<tbody>
<tr>
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<td>MC (Million)</td>
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<td>IS (10K)</td>
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<tr>
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<td>Mean</td>
<td>UB</td>
<td>LB</td>
<td>Mean</td>
<td>UB</td>
<td>LB</td>
<td>Mean</td>
<td>UB</td>
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</tbody>
</table>

Normalized POF

Time (seconds)
Applications of DARWIN™: HA Risk Analysis for engine certification by the FAA

Methodology

• 2D axisymmetric FE stress models used for analysis

• Basic elements of HA risk analysis using DARWIN™
  – Industry standard (Aerospace Industries Association of America, Inc. [AIA] Rotor Integrity Sub-Committee [RISC] default) HA inclusion distributions
  – The crack growth rate data for titanium in air and the associated stress-strain curve data from the OEM’s materials design database
  – Crack growth analysis (Flight_Life is internal to DARWIN™)
  – A probability method (MonteCarlo) for random sampling
  – Appropriate NDT inspections, and associated probability of detection (POD) curves
A Fan-Disk DARWIN™ Model

13 Zone Model

42 Zone Model

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A Radial Compressor Disk DARWIN™ Model

15 Zone Model

60 Zone Model
Fan/Radial Compressor Results

Fan and Radial Compressor
HA Risk Convergence With Zone Refinement

Fan and Radial Compressor Disk

Events/Flight-Cycle vs. Number of Zones

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Applications of DARWIN™: Surface Damage Risk Analysis

• Part Selected: A highly stressed critical bolt hole on a commercial application

• Material: IN-718 with an OEM’s proprietary processing
Surface Damage Risk Analysis: Stress

- Full 3-D Finite Element Model was developed
- Stress Gradient is presented as Normalized Stress versus Normalized Distance (to the distance between the bolt holes)

![Stress Gradient at the Bolt Hole](image-url)

Normalized Stress

Normalized Distance
Surface Damage Risk Analysis: CCGL

- Three cases were run using an OEM’s code and DARWIN™
  - Initial crack: 0.001 X 0.001 with a stress gradient
  - Initial Crack: 0.002 X 0.002 with a stress gradient
  - Initial Crack: 0.001 X 0.001 with a constant stress of 134 KSI

<table>
<thead>
<tr>
<th>Initial Crack</th>
<th>L/D</th>
<th>Gradient</th>
<th>Material</th>
<th>CCGL Honeywell/DARWIN</th>
<th>Stress</th>
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<td>IN-718</td>
<td>1.02</td>
<td>Gradient</td>
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<tr>
<td>0.001 X 0.001</td>
<td>0.94</td>
<td>NO</td>
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<td>Constant</td>
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<tr>
<td>0.002 X 0.002</td>
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<td>YES</td>
<td>IN-718</td>
<td>1.05</td>
<td>Gradient</td>
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</table>

- DARWIN™ and OEM CCGL analyses agree well
- Surface Crack in a plate solution used for compatibility with OEM’s code
- OEM’s material design database properties were used
• DARWIN™ was used with the RISC EIFS distribution to compute POF
Surface Damage Risk Analysis: POF

- POF is calculated
- Comparison of DARWIN™ calculated POF with POF calculated using OEM’s probabilistic techniques is ongoing
Acknowledgements

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