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™
Capability Analysis: Background

• 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
Capability Analysis: Example of a DOE

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)

<table>
<thead>
<tr>
<th>Factors</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
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<tr>
<td>Crack Placement</td>
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<td>Plate Orientation</td>
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<td>Material</td>
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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)
Capability Analysis: Evaluation of DARWIN™

- 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

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<tr>
<th>Analyst/Operator</th>
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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
Sensitivity Study I: Impact of Titanium Vacuum Crack Growth Data

SwRI Vacuum & Air FCG Data

SwRI Air FCG Data

POF/cycle | Vacuum & Air FCG data | Air FCG data
---|---|---
wo/insp | w/insp | wo/insp | w/insp
AC Ring Disk | 7.44e-9 | 6.19e-9 | 2.99e-8 | 2.44e-8
Reduction | **4.0 X** | **3.9 X** | 
GE Fan Disk | 0.60 | 0.32 | 1.00 | 0.41
Reduction | **1.7 X** | **1.3 X** | 

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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

Normalized POF

MC (100K)  MC (Million)  IS (10K)

Seed 1  Rand 1  Rand 2  Seed 1  Rand 1  Rand 2  Seed 1  Rand 1  Rand 2

LB  Mean  UB  Time

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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

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Fan/Radial Compressor Results

Fan and Radial Compressor
HA Risk Convergence With Zone Refinement

Number of Zones

Events/Flight-Cycle

Radial Compressor Disk

Fan
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

Crack Plane

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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

![Stress Gradient Graph](image_url)
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

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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