A Probabilistically-based Damage Tolerance Analysis Computer Program for Hard Alpha Defects in Titanium Rotors

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DARWIN™ - Design Assessment of Reliability With INSpection

- Motivation - what's the need, what problem does it address.
- Elements - what is the technical content.
- Availability - who's using it.
- Future Developments - where's it going.
- Summary
- Acknowledgments
Need for DARWIN

- Modern engines have excellent reliability and safety records.
- Nevertheless, uncontained disk failures do occasionally occur.
- Engine manufacturers recognize the need to address the potential for unanticipated anomalies and to adopt a damage tolerance philosophy - and are actively working to implement it.
1989: United Airlines plane crashes in Sioux City Iowa. Cause was a rotor disk fracture - cracks initiated from a "hard alpha" particle produced during melting.

1990: FAA post-crash report recommends a probabilistic damage tolerance approach to reduce the risk of failure due to hard alpha in future designs.

- AIA Rotor Integrity Sub-Committee (RISC) established.

1995: FAA establishes a grant to SwRI with submembers AlliedSignal, General Electric, Pratt & Whitney, and Rolls-Royce Allison to develop probabilistically-based, damage tolerance design code to augment current safe-life approach for life management of commercial aircraft gas turbine rotors and disks.
DARWIN part of TRMD

- Turbine Rotor Material Design - grant awarded by FAA to team from Southwest Research Institute, AlliedSignal, General Electric, Pratt & Whitney, Rolls-Royce Allison
  - Hard alpha defect distribution modeling
  - Hard alpha deformation during forging
  - Crack nucleation and growth specimen tests
  - *Software development* -&gt; DARWIN
  - Technology transfer: reports, meeting, workshop
DARWIN Overview

Design Assessment of Reliability With INspection

- Anomaly Distribution
- NDE Inspection Schedule
- Probability of Detection
- Finite Element Stress Analysis
- Probabilistic Fracture Mechanics
- Pf vs. Cycles
- Material Crack Growth Data
- Risk Contribution Factors
**Design Assessment of Reliability With Inspection**

### Graphical User Interface
- Plot finite element stress results, defect distribution, inspection time, POD curves, & material properties
- Define zones graphically by selecting elements & defect location

### Random Variables
- Anomaly occurrence
- Anomaly distribution
  - Size
  - Built in library, user-definable
- Stress
- Life Scatter
- Shop visit time

### Probabilistic Methods
- System reliability approach
  - Define approx. iso-risk zones
  - Sum risks from all zones
- Monte Carlo simulation
- Importance Sampling method
  - Simulate large defects only, very efficient

### Stress and Fracture Mechanics Analysis
- Finite Element Model
- Random Defect

### Risk & Sensitivity Analysis
- Zone 13
- Without Inspection
- Flight Cycles
- With Inspection

### Crack Growth
- Built-in code or user supplied code or tabular a vs. N input
- Surface, subsurface, and corner 3D cracks
- Univariate Stress gradient effects

### Stress Analysis
- Axisymmetric models
- Interface with finite element results
- ANSYS interface
- Neutral file for other FE codes

### Inspection Features
- Different POD's for different regions
- Different POD's for initial and field inspection
- POD library built in, user-definable
- Random time of inspection

### Computer Operation
- Graphical user interface
- Text input file interface
- HP & Sun, SGI Unix-based workstations

### Failure Modes
- Life prediction of low-cycle fatigue of hard alpha defects in titanium
Probabilistic Methodology: Zone-based Risk Assessment

Procedure:

- Define zones based on similar stresses, inspections, defect distribution, fracture mechanics
- Probability of having a defect determined by defect distribution and volume of zone
- Probability of failure assuming a defect computed using Monte Carlo sampling
- Total probability of failure for zone computed by multiplying probability of having a defect times the probability of failure given a defect
- Probability of failure for disk obtained by summing zone probabilities

\[ P_i = P_i[A] \cdot P[B|A] \]
Retrieve stresses along line

Fracture Mechanics Model of Zone

Finite Element Model

Fracture Mechanics Model

(Not to Scale)

Defect

m

h_x

h_y

Y

x

Gradient direction
Fracture Mechanics Model

- GUI developed to graphically define plate & crack location for each zone
Stress Processing

FE Stresses and zone definition

Stress gradient extraction

Rainflow stress pairing

Residual stress analysis
**Flight_life Overview**

- FCG analysis of a crack in a plate
- Variety of appropriate K solutions
- Full crack transitioning capabilities
- Variety of commonly-used FCG equations
- Variety of commonly-used stress ratio methods
Anomaly Distribution

- Defines the number of anomalies per volume of material and probability distribution of size of defects
Probability of Detection Curves

- Defines the probability of detecting a flaw as a function of flaw size

![Graph showing Probability of Detection Curves](image-url)
Material Properties

- da/dN
  - fcg format, stress ratio model, temperature interpolation format
- Stress-Strain
  - format (Ramberg-Osgood, tabular), temperature interpolation

Independent inputs for Air and Vacuum
Pre-defined Library of Inputs

- POD curves, defect distributions, and material properties files distributed with DARWIN
  - AIA RISC defect distribution curves
  - ETC POD curves
  - TRMD Ti fatigue crack growth properties
- User selects file
- Engine companies can develop own databases
Random Inspection Time

- Inspection time modeled with Normal distribution (mean, st. dev.)
Random Inspection Time

- Inspection time modeled with tabular input format

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Stress Random Variable

Stress Multiplying Factor

- Account for variations in stress
- Multiply finite element stresses by a random variable, $S$

$$\sigma = \sigma(\text{FE}) \times S$$

- $S$ defined by median and Coefficient of Variation (COV)
- Lognormal distribution assumed
- $S$ same for all zones
Life Scatter Random Variable

Life Scatter Factor

- Account for material scatter, fracture mechanics modeling error
- Multiply computed cycles to failure by a random variable, B

\[ N = N(\text{Flight\_life}) \times B \]

- B defined by median and COV. Lognormal distribution assumed.

- B is zone dependent, i.e., different for different zones
Risk Assessment
Solution Methods

- Monte Carlo Sampling
  - Standard - call FM module each sample
  - Fast - set up table, sample from table
- Importance
  - Selectively chose defect sizes, e.g., large flaws
- Each zone computed independently then integrated
- Inspections simulated during analysis
Advisory Circular Test Case

Material Properties
Paris Crack Growth Law
C = 5.248E-11
n = 3.87

Defects located in center of zone
Effects of stress gradients included
Post 1995 #3/#3 FBH Defect Dist.
1-1 #3 FBH POD Curve
Inspection at 10,000 Flight Cycles

DARWIN Results:
Prob. Fracture/Cycle
w/o Inspection 1.18E-9
w Inspection 7.30E-10
Disk Risk Assessment vs. Flight Cycles

Disk Risk Assessment vs. Flight Cycles (volume effect included)

Without Inspection With Inspection

(Inspection at 10,000 cycles)
Risk Assessment/Cycle vs. Cycles

Disk Assessment vs Cycle (volume effect included)

With Inspection
Without Inspection

(Inspection at 10,000 cycles)
Risk Assessment vs. Cycles per Zone
Risk Contribution Factors

Identify regions of disk with highest risk
Availability

- DARWIN delivered to TRMD steering committee members since 1997.
- DARWIN beta version 2.2 delivered to all RISC members in Jan. 1999
- DARWIN 3.2 released to RISC and others in July 1999

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Advisory Circular 33.14

- Damage tolerance aspect - requires fracture mechanics-based risk assessment of threat due to hard alpha

- Establishment of Design Target Risk (DTR) for rotors

![Diagram showing risk reduction required for components A, B, and C. DARWIN - acceptable means to assess compliance.]

RISK

Maximum Allowable Risk

Components

A  B  C

Risk Reduction Required

DARWIN - acceptable means to assess compliance
TRMD Phase II awarded April 1999 - 5 year duration.

- Finish work on Hard Alpha.
- Extend to cast and wrought nickel.
- Extend to surface defects: induced defects (as opposed to inherent) by machining, maintenance, etc.
- Extend to powder nickel.
Southwest Research Institute and industry team under FAA sponsorship has developed a probabilistically-based damage tolerance code DARWIN to assess the risk of hard alpha in titanium rotors.

DARWIN one means to assess rotors for compliance with Design Target Risk.

DARWIN under evaluation/use buy engine manufacturers.

SwRI/industry team under contract to extend DARWIN to:
  - nickel (cast/wrought),
  - induced surface defects due to machining and maintenance,
  - powder nickel
Acknowledgements

- Outstanding cooperation from all team members
  - FAA - Joe Wilson, Bruce Fenton, Tim Mouzakis
  - Industry representatives:
    - AlliedSignal, General Electric, Pratt & Whitney, Rolls-Royce Allison
      - supply data, technical advice, establish priorities, debug software, ...
    - Others: MTU, Williams
More Information

- ASIP SwRI booth: demo, brochures
  - hmillwater@swri.org

- DARWIN web site
  - TRMD Program overview,
  - DARWIN overview
  - Previous publications,
  - Upcoming conferences
  - Mailing list - (upcoming)

www.darwin.swri.org