A Probabilistic Damage Tolerance Analysis
Computer Program for Engine Rotor Integrity

Special Session on Engine Life Management:
Addressing Fleet Risk with Innovative Approaches
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H. R. Millwater, M. P. Enright,
R. C. McClung, and G. R. Leverant

Southwest Research Institute
San Antonio, Texas, USA
Background

- Undetected material/manufacturing anomalies can reduce rotor reliability
  - Very rare occurrences
  - Some famous accidents
  - Not addressed by safe life design practices

- Engine industry developing an enhanced life management process
  - Requested by FAA following Sioux City accident
  - AIA Rotor Integrity Sub-Committee (RISC) leadership
  - Probabilistic damage tolerance methods and opportunity inspections
  - Process now documented as FAA Advisory Circular 33.14

- SwRI and engine industry jointly conducting an FAA R&D program
  - Develop enhanced predictive tool capability
  - Develop enhanced material/anomaly characterization and modeling
Hard Alpha Defects in Titanium Components

- Initial focus on “hard alpha” defects in titanium
  - Small brittle zone in microstructure
  - Alpha phase stabilized by N accidentally introduced during melting
- HA cracking led to loss of DC-10 at Sioux City (1989)
  - In-flight separation of Stage 1 fan disk
  - Failure at 15,503 cycles (life limit 18,000 cycles)
Overview of TRMD Program

- “Turbine Rotor Material Design” research program
- Southwest Research Institute is program manager
- Engine companies are steering committee, subcontractors
  - General Electric, Honeywell, Pratt & Whitney, Rolls-Royce Inc.
- Total program is ~9 years, ~$14M (now in Year 6)
- Wide range of technical tasks
  - Defect distribution modeling
  - Modeling of hard alpha deformation during forging
  - Crack nucleation and growth data and modeling
  - Development of DARWIN™ software tool for reliability assessment
  - Technology transfer to FAA and industry
DARWIN™ Overview

Design Assessment of Reliability With INspection

- Anomaly Distribution
- Finite Element Stress Analysis
- Probabilistic Fracture Mechanics
- Material Crack Growth Data
- NDE Inspection Schedule
- Probability of Detection
- Pf vs. Cycles
- 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
- 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**

**Risk & Sensitivity Analysis**
- Probability of Fracture
- Life prediction of low-cycle fatigue of hard alpha defects in titanium

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

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

**Failure Modes**
- Life prediction of low-cycle fatigue of hard alpha defects in titanium

**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

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DARWIN™ Code Structure

Pre/Post Processing

Finite Element Result

Input Text File

Output Text File

User Input

Analysis

Probabilistic Analysis Driver

Stress Processing

Fracture Mechanics Flight Life
Zone-Based Risk Assessment

- Define zones based on similar stresses, inspections, defect distributions, lifetimes
- Defect probability determined by defect distribution, zone volume
- Probability of failure assuming a defect computed using Monte Carlo sampling or advanced methods
- 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
Zoned Impeller Model
Fracture Mechanics Model of Zone

Finite Element Model

Retrieve stresses along line

Fracture Mechanics Model

(Not to Scale)

Defect

hx

hy

Not to Scale
Stress Processing

FE Stresses and zone definition

Rainflow stress pairing

Stress gradient extraction

Residual stress analysis

Stress gradient extraction

Shakedown module

Computed relaxed stress

σ_{relax} = σ_{elastic} - σ_{residual}
Fracture Mechanics Module

- **Flight_Life**: default FM module
  - Tailored for rotor problems
  - Relatively fast
- FCG analysis of crack in plate
- K solutions for embedded, surface, corner, and through cracks
- Full crack transitioning
- Variety of common FCG eqns
- Variety of common stress ratio methods
- Tabular da/dN vs. ΔK

- Alternatively, link DARWIN™ with user-supplied FM
  - User-supplied module
  - User-supplied a vs. N results
Anomaly Distribution

- # of anomalies per volume of material, distribution of defect sizes
- Library of default anomaly distributions for HA (developed by RISC)

CDF = 1 - \( \frac{N_d(a) - N_d(a_{\text{max}})}{N_d(a_{\text{min}}) - N_d(a_{\text{max}})} \)
Probability of Detection Curves

- Defines probability of flaw detection as function of flaw size
- Can specify different PODs for different zones, schedules
- Built-in POD library or user-defined POD
Random Inspection Time

- Inspection time modeled with Normal distribution
- Can also input table to define CDF of inspection time
Output: Risk vs. Flight Cycles

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

- Without Inspection
- With Inspection
Output: Risk Contribution Factors

Identify regions of component with highest risk
Output: Fracture Mechanics Results

![Fracture Mechanics Results](c:/data/TRMD2/charts/AHS57.ppt)
Use of DARWIN by Industry

- FAA Advisory Circular 33.14 requests risk assessment be performed for all new titanium rotor designs
- Designs must pass design target risk for rotors

Maximum Allowable Risk

Risk Reduction Required

10^{-9}

Components

A: DARWIN – Acceptable Means To Assess Compliance
B: Acceptable
C: Acceptable
Current TRMD program addressing additional threats
- Surface damage from abusive manufacturing or maintenance
  ⇒ Current focus on bolt hole problems
- Metallurgical anomalies in cast/wrought nickel materials
- Inclusions in powder nickel materials

Each of these problems is being worked in close coordination with engine industry (RISC)

DARWIN is suitable for other applications
- Currently limited to 2-D [axisymmetric] geometries
- Expansion to general 3-D geometries in TRMD plan
- Possible aircraft structure and rotorcraft uses
DARWIN™ Release History and Industrialization

- Current release version is 3.4
  - HP, Sun, SGI versions (GUI is platform-independent)
- 350-page user manual available
- DARWIN™ is being used or evaluated by numerous organizations
  - 11 gas turbine engine companies
  - 10 other organizations
- Engine companies asked SwRI to industrialize DARWIN
  - Licensing and user support
  - FAA funded development of basic support structure
  - Formal code licensing begun in 2001