Probabilistic Methodology For Life Prediction of Aircraft Turbine Rotors

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Abstract

The presence of rare metallurgical or manufacturing anomalies in aircraft turbine rotors/disks may contribute to uncontained engine failures. A probabilistic methodology has been developed to quantify the risk of fracture and the influence of periodic inspection on overall risk, supplementing the current safe life approach. This paper summarizes the methodology and computational implementation, including a brief description of a new method for defining surface damage-related crack growth using 3D finite element results. The results can be applied to risk assessment of aerospace structures where uncertainties associated with fatigue crack growth must be quantitatively addressed.

Introduction

Nearly a decade ago, the Federal Aviation Administration (FAA) and the Rotor Integrity Subcommittee (RISC) of the Aerospace Industries Association (AIA) proposed a probabilistic damage tolerance approach to account for the presence of metallurgical (inherent) and manufacturing (surface damage) anomalies that can occur during the manufacturing process (Leverant *et al.* 1997, 2003). This recommendation, based on the results of a National Transportation Safety Board report (NTSB 1990) linking metallurgical anomalies to uncontained engine events, led to the development of an advisory circular (FAA 2001) and the Turbine Rotor Material Design (TRMD) research program (Leverant *et al.* 2000) and associated DARWIN[®] (Design Assessment of Reliability with INspection) computer software (Southwest Research Institute 2003).

DARWIN is a simulation-based program used to predict the probability of fracture of rotors and disks in commercial aircraft gas turbine engines. Six primary random

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variables are used to model crack growth behavior and associated risk:

- defect size and occurrence rate
- stress scatter
- life scatter (i.e., crack growth rate variability)
- inspection quality (probability of detecting a defect)
- inspection time

Deterministic crack growth computations are performed using Flight_Life, an internal fracture mechanics module that includes a number of advanced capabilities such as crack transitioning and stress intensity factor solutions for multidimensional stress fields. A simulation-based framework is used for probabilistic life prediction including a capability to quantify the influence of periodic inspections on the risk of fracture.

General Probabilistic Approach

A probabilistic methodology has been developed to predict the risk of fracture associated with both inherent and surface damage-based defects (Figures 1a and 1b, respectively). A comparison of the primary differences in the current methodology for these two defect types is given in Table 1. It is assumed that inherent defects can occur anywhere within a component, so the probability of occurrence of a defect is directly proportional to the volume of the component. In contrast, surface damage-related defects are assumed to occur only at specific features, so the probability of occurrence of a defect is based on the number of features and the surface area associated with each feature. A defect distribution has been developed for hard alpha

Figure 1. A probabilistic methodology has been developed to predict the risk of fracture associated with (a) inherent material defects, and (b) surface damage-based defects.

Table 1. Summary of the primary differences in the damage tolerance approach for inherent and surface-damage-based defects in DARWIN

Defect Type	Risk basis	Stress Gradient & Temperature Data
Inherent	Component Volume	2D Finite Element Model
Surface Damage	Surface Feature Area	3D Finite Element Model

inherent defects (Aerospace Industries Association 1997). Another distribution is under development for surface damage at machined bolt holes.

Strategy for Inherent Material Defects

For analysis of components containing inherent defects, a zone-based approach is used in which a component is subdivided into volumes of approximately equal risk. Component risk is approximately equal to the sum of the risks of the individual zones (Millwater 2000). Currently, this is accomplished using the results from a 2-D axisymmetric finite element model, in which finite elements are assigned to specific zones (Figure 2). Each zone can have a number of unique characteristics associated with it (e.g., stress gradient, crack growth rate model and associated variability, stress intensity factor solution type, number and quality of inspections, among others). The zone represents a volume of material in which an inherent defect may be present. A capability is provided for iteratively improving zone discretization based on the contribution of each zone to overall risk (Millwater *et al.* 2002). Additional details

Figure 2. A zone-based approach is used for inherent (material) defects in which the component is subdivided into regions of approximately equal risk.

regarding the strategy for inherent defects can be found in Leverant *et al.* 2000 and Wu *et al.* 2002.

Strategy for Surface Damage-Based Defects

In contrast with inherent defects that may be present anywhere in a component, surface damage-based defects are assumed to be concentrated in specific regions (e.g., bolt holes, surfaces subjected to abusive machining). A feature-based approach is used in which component risk is approximately equal to the sum of the risks of the individual features. Similar to a zone, each feature can have a number of unique characteristics associated with it. For a typical gas turbine engine disk, the number of features associated with a surface damage assessment is relatively small compared to the number of zones associated with an inherent defect-based assessment. Stress and temperature data, typically defined only at key features, can be defined directly by the analyst (i.e., no finite element results are required, Enright *et al.* 2003).

A new method has recently been developed for modeling surface damage-related crack growth using results from 3D finite element analysis (McClung *et al.* 2004, Waldhart *et al.* 2004). It is based on the assumption that a Mode I crack propagates in the plane normal to the maximum principal stress (for the dominant stress pair in a given mission profile) in a region that is idealized as a rectangular plate. The method can be summarized as follows:

- Specify an initial crack location at a node on the surface of a 3D finite element model
- Extract the six stress components at the initial crack location, and compute the magnitude and orientation of the maximum principal stress (MPS)
- Identify the orientation of a “slice plane” - a plane normal to the orientation of the MPS at the crack location
- Identify the location of points of intersection between the slice plane and the 3D finite elements, and compute stresses at the intersection points
- Create a new 2D finite element mesh on the crack plane consisting of triangular elements based on the intersection points using a Delaunay triangularization algorithm
- Define a rectangular region within the new 2D mesh that includes the initial crack location and orientation of a stress gradient vector
- Extract stresses along the stress gradient vector for use in 2D fracture mechanics computations

The method, recently implemented in DARWIN, is illustrated for an offset surface crack at a hole in a typical gas turbine engine component (Figure 3). As shown in Figure 3a, the analyst can import and manipulate a 3D finite element model directly in the GUI to specify the location of an initial crack. The GUI automatically computes the magnitude and orientation of the maximum principal stress and associated plane. Stresses on this plane are extracted to reveal a 2D cross section of

the crack propagation plane (Figure 3b). The 2D cross section can then be used to specify the location and dimensions of a rectangular plate for fracture mechanics computations. This illustrates the applicability of the method to nonaxisymmetric geometries for probabilistic life prediction of general aerospace components. See Enright *et al.* 2003 for additional details regarding the probabilistic surface damage tolerance strategy.

Computational Efficiency

The target failure probability for gas turbine engine components subjected to inherent or surface damage-related defects is on the order of 10^{-9} on a per flight cycle basis (FAA 2001), or 10^{-5} on a cumulative basis. To achieve sufficient computational accuracy, a large number of Monte Carlo samples may be required. Since the computation time associated with predicting the crack propagation life associated with each Monte Carlo sample is nontrivial, a number of techniques have been developed/implemented in DARWIN over the past several years to improve computational efficiency. A summary of these techniques is indicated in Table 2 (see also Leverant *et al.* 2000).

Figure 3. Illustration of a new method for definition of surface damage-related cracks using 3D finite element results: (a) import 3D finite element model, reorient to display and select initial surface crack location (GUI automatically identifies principal stress plane), and (b) slice model along principal stress plane to reveal crack propagation plane and associated rectangular plate for fracture mechanics assessment (McClung *et al.* 2004, Waldhart *et al.* 2004).

Table 2. Techniques developed in DARWIN to address computational efficiency associated with probabilistic life prediction

Technique	Classification	Description	Reference
Life Approximation Function	Tailored response surface	Create tables of crack area and cycles to failure for use during Monte Carlo simulation	Wu <i>et al.</i> 2002, Southwest Research Institute 2003
Importance Sampling	Zone-based variance reduction	Combined technique of numerical integration and failure region-based Monte Carlo simulation	Wu <i>et al.</i> 2002, Huyse and Enright 2003
Zone Refinement	Defect location uncertainty	Focused discretization of zones based on relative contribution to component risk	Millwater <i>et al.</i> 2002
Optimal Sampling	Component-based variance reduction	Allocate Monte Carlo samples to each zone based on its relative contribution to component risk	Enright and Millwater 2002, Enright <i>et al.</i> 2004
Distributed Processing	Parallel processing	Provide computational framework for distributing computational tasks to multiple computers	Millwater and Guduru 2004

Summary

A probabilistic methodology has been developed to quantify the risk of fracture associated with rare metallurgical/manufacturing defects in aircraft gas turbine engine components. This paper summarizes the methodology, and provides a brief overview of the specific strategies developed for inherent and surface damage-related defects. A new method for defining surface damage-related crack growth using 3D finite element results is illustrated that is applicable to the probabilistic life prediction of general aerospace components.

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