FRAUCTURE MECHANICS-BASED PROBABLISTIC STRUCTURAL INTEGRITY ASSESSMENT FOR AERO-ENGINE TURBINE DISK

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Abstract

Aero-engine turbine disks are safety-relevant components which are operated under high thermal and mechanical stress conditions. The aim of this work is to present part of a fracture mechanics-based probabilistic assessment procedure under development which aims at calculating the critical rotational speed of the turbine disk based on the numerical-analytical solutions and regulations for the failure probability. In particular, the rim-peeling failure mode is considered as case study. A semi-circular surface crack is modelled at the most stressed region at the diaphragm of a turbine disk. In order to design a lab representative specimen, beside the crack driving force, expressed in terms of J-integral, also the constraint to plastic deformation e.g., stress triaxiality, at the crack-tip must be similar for the same crack in the specimen and in the disk. The analytical solutions to calculate the crack driving force for the lab representative specimen are used for the Monte Carlo simulations, the result of which has been assessed in the form of a Failure Assessment Diagram (FAD). The results of the probabilistic structural integrity assessment show good agreement between Monte Carlo simulations and certification values for the disk in terms of expected failure mode and value of the critical speed.

1. Introduction

The rotor integrity of the aero-engine turbine disks is to be established for the overspeed conditions, during which the rotational speed is increased beyond the normal engine operation envelope. The burst of the turbine disk must be avoided to prevent any catastrophic consequences, for the engine casing is not designed for containment of such failures. Conventionally, the rotor integrity of the turbine disks is established by conducting overspeed spin-test, during which the production-similar component must withstand the most critical operating conditions in combination with a higher-than-normal rotational speed for 5 minutes without failure [1]. Potential defects that can grow into cracks are not considered in such tests, however, their existence cannot be excluded because of the sensitivity of the non-destructive inspection in the quality control. It is therefore important to investigate the worst-case-scenario, or the end-of-life component, in which a surface crack of size 0.381 mm is considered to be present [2]. The presented work is therefore partly based on the theory of damage tolerance, in which the critical load is to be analysed for a given crack size. The correlated critical load corresponds to a critical rotational speed for turbine disks. An overspeed event for the turbine disk is a quasi-static loading condition, which permits the fracture mechanics-based evaluation procedure on fracture mechanics specimen to adequately represent the same loading conditions in turbine disks with crack. These loading conditions consist, apart from mechanical and thermal loadings, the crack-tip loading and the constraint against plastic deformation ahead of the crack-tip. The analytical solutions to calculate these parameters are used for the Monte-Carlo simulations, the result of which has been assessed in the form of a Failure Assessment Diagram (FAD) and the corresponding failure probabilities have been calculated for a spectrum of rotational speeds. Compared with the regulative probability limit for a hazardous engine effect [1], the critical rotational speed has been calculated. One of the advantages of the fracture mechanics-based probabilistic evaluation is that because of its simplicity and cost compared with spin-test, a much more extensive testing campaign, e.g. parameter variation analysis, can be achieved.

2. Results

In order to determine the failure probabilities for the investigated turbine disk under overspeed conditions, a series of Monte Carlo simulations have been conducted. The analytical approaches to calculate the reference yield stress and stress intensity factor for biaxial specimen are used. The load-corresponding L_r of the biaxial specimen is then converted into rotational speed for the turbine disk.

The random variables for the Monte Carlo simulations are K_mat, a, σ_Y, R_m and σ_app. Basically, each Monte Carlo simulation represents a case of the investigated turbine disk with a crack on diaphragm under a specific rotational speed (normalised with N_a), which can be plotted in the FAD as an assessment point based on the analytical calculation of loads and limit curves of biaxial specimen. A group of 10^6 simulations is carried out for each rotational speed, which eventually yields the failure probability, which is the percentage of the assessment points outside of the limit curves. An example of the simulations carried out for $0.913N_\mathrm{a}$ is shown in the FAD (Fig.1a). The Monte Carlo simulations are carried out for totally 18 different rotational speed. With increasing rotational speed in overspeed condition, the corresponding failure probability P_f rises accordingly (Fig.1b).

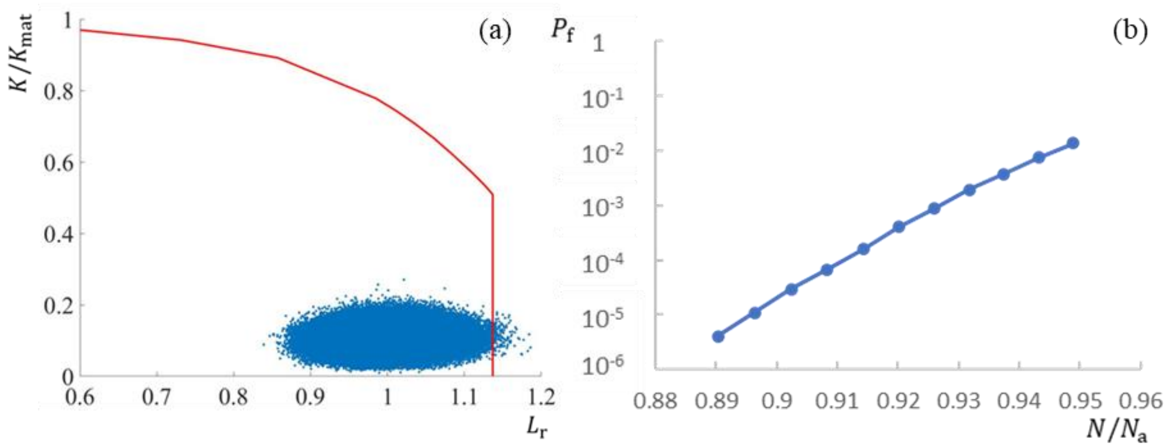

Fig.1 – Probabilistic calculations. a) Monte Carlo simulations based on FAD; b) Failure probabilities for different rotational speeds

According to the certification specifications for engines CS-E 510 [1], the probability of hazardous engine effect should be extremely remote (lower than 10^{-8} per engine flight hour). Combined with a typical service life of 10000 h for the investigated turbine disk, the corresponding failure probability for the investigated turbine disk should be lower than $1 \cdot 10^{-4}$ during the entire service life. Based on the results from Fig.1b, in order to fulfil a failure probability of $1 \cdot 10^{-4}$, the rotational speed must be lower than $0.910N_\mathrm{a}$.

3. Conclusions

A fracture mechanics-based probabilistic structural integrity assessment has been conducted for a turbine disk under overspeed conditions. Based on the failure probabilities calculated based on FAD results, the critical rotational speed has been calculated.

Reference

[1] European Union Aviation Safety Agency (EASA). Certification Specifications and Acceptable Means of Compliance for Engines CS-E Amendment 5, 2018

[2] European Union Aviation Safety Agency (EASA). Certification Memorandum EASA CM – PIFS – 007 Issue: 01: Engine Critical Parts - Damage Tolerance Assessment Manufacturing and Surface Induced Anomalies, 2013