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Probabilistic failure risk assessment for aeroengine disks considering a transient process

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ABSTRACT

One of the key processes for safety design of aeroengines is to accurately predict the failure risk of aeroengine disks. Current risk assessment methods mostly based on a constant stress are suitable for steady-state analysis but inappropriate for dangerous transient process. This work proposes a method of probabilistic failure risk assessment for aeroengine disks considering a transient process, and the core procedure is zone definition through refinement and further partition of a constant pre-zone based on the time-varying stress in a flight cycle. An aeroengine compressor disk is analyzed, and the failure risks of the disk considering a transient process and based on a steady-state design point are compared to examine the influence of the transient process on the failure risk of the disk. Results show that the failure risk considering the transient process is approximately 3.7 times of that based on the steady-state design point because the peak stress of the disk during the transient process exceeds the steady-state stress. The proposed method obtains more accurate predictions of failure risk, and is thus valuable for the safety design of aeroengines.

1. Introduction

As a key aeroengine part [1], disks play an important role in the safety of aeroengines. Disk fracture directly induces non-containment of high-energy debris, which results in catastrophic events, such as loss of aircraft and death [1,2]. Aeroengines generally operate with high failure rates during a transient process [3] possibly because transient and complex environments can induce stresses different from those in a steady state [2,4]. A typical example of the thermal and stress responses of a turbine disk for a transport engine over a full flight is shown in Fig. 1 [5]. A large temperature difference exists between the hub and rim of the disk during take-off and climb periods, and the resulting transient thermal stress is approximately 10% larger than that in the cruise period. This example implies that a peak stress that is larger than steady-state stress exists in a disk during a transient process and seriously affects the safety of aeroengines. Thus, the effect of the transient process must be considered in research on the safety of aeroengines disks.

Various safety analysis methods have been proposed involving key structural components like engine cylinder heads [6,7], aeroengine disks [8,9] and aircraft spars [10–12]. Variable amplitude loads [12,13] were considered to simulate the actual complex working conditions of aircrafts during the service period. All these methods provide effective tool for the safety design of aircraft, and are thus valuable. Specifically for aeroengine disks, the most widely used method is the conventional rotor life management methodology, which was established based on the assumption that no anomaly exists in disks prior to flight service [8]. Industrial gas turbine experience has shown that the occurrence of material and manufacturing anomalies, although rare, can potentially degrade the structural integrity of high-energy rotors [14]. The conventional methodology does not explicitly consider the occurrence of anomalies and may thus be insufficient for safety analysis.

A probabilistic damage tolerance design method, namely, probabilistic failure risk assessment, was established to augment the conventional life management approach for aeroengine disks. The framework of this method is presented in Fig. 2. The fundamental philosophy behind this method is to predict the failure risk of a disk (i.e. the probability of fracture) as a function of flight cycle in consideration of the existence of an initial anomaly. The assessment process involves a zone-based probabilistic fracture analysis [9] (Fig. 3), which consists of the following three steps:

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Nomenclature

a	crack length	m
C	Paris constant	
E	Young's modulus	MPa
F	event of failure	
G	geometrical correction coefficient	
K	stress intensity factor	MPa m$^{1/2}$
K_c	fracture toughness	MPa m$^{1/2}$
m	total number of zones	
n	Paris index	
N	flight cycle; rotation speed	r/min
p	pressure	Pa
p_d	conditional failure probability of zone	
P_f	probability of fracture of disk	
r	radius	mm
T	temperature	K
α	thermal expansion coefficient	K^{-1}
ΔK	range of stress intensity factor during flight cycle	MPa m$^{1/2}$
γ	anomaly occurrence rate	
λ	thermal conductivity	W/(m K)
ν	Poisson's ratio	
ρ	density	kg/m^3
σ	circumferential stress	MPa
τ	time	s

Subscripts

DP	based on steady-state design point
i	index of zone
in	inlet of disk cavity; initial crack
out	outlet of disk cavity
TR	considering transient process

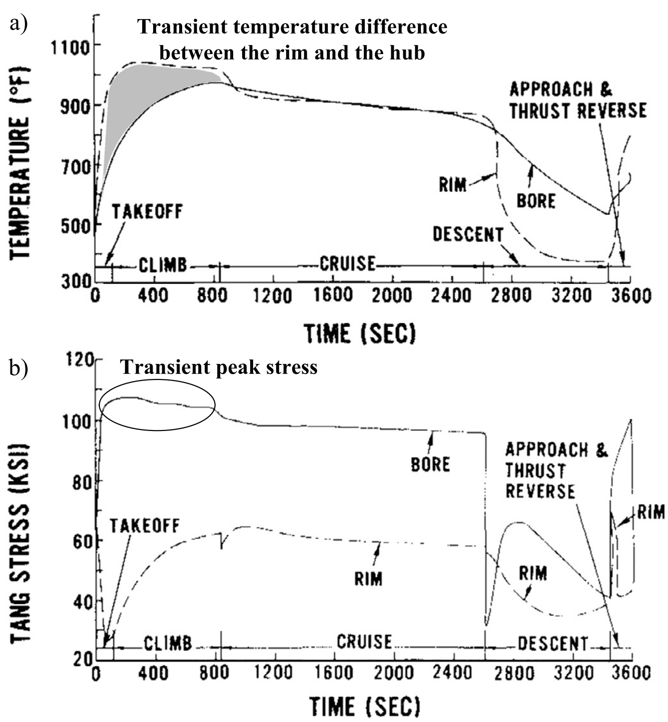

Fig. 1. Typical thermal and stress responses of a turbine disk [5].

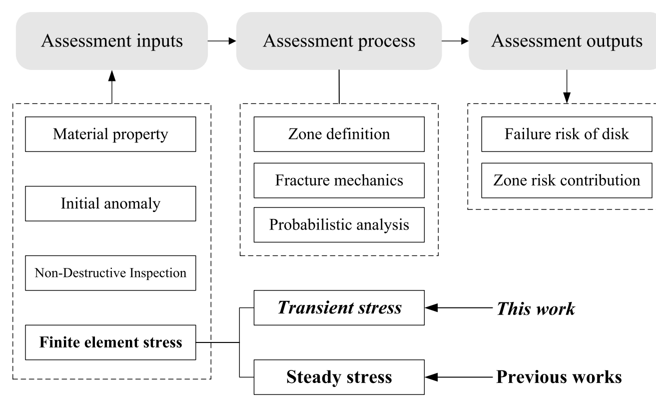

Fig. 2. Framework of probabilistic failure risk assessment for disks.

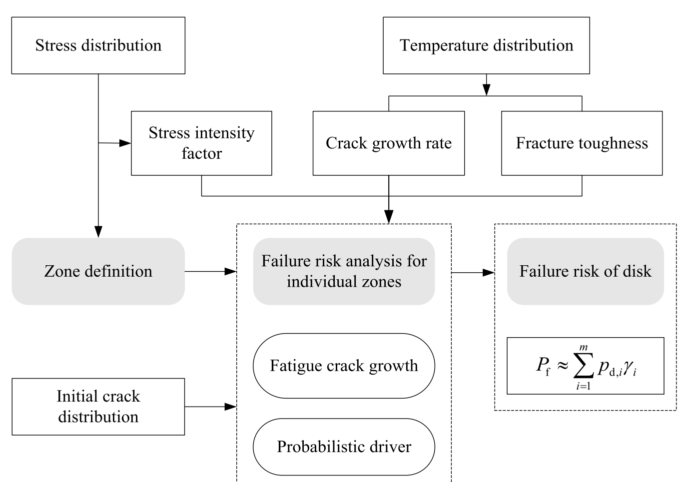

Fig. 3. Process of probabilistic failure risk assessment.

1) Zone definition. A disk is subdivided into a finite number of zones.
2) Failure risk analysis for individual zones. The probability of fracture of each zone is calculated independently.
3) Failure risk analysis for the disk. The results of the zones are summed statistically to obtain the failure risk of the disk.

The basic idea of the three steps is as follows. An anomaly, if it exists, could be in any location on a disk, and the stress of the disk is generally non-uniform. The risk caused by the anomaly can vary with different locations. Thus, the disk structure is divided into a number of zones on the basis of a finite element mesh and the stress results. The stresses of all sub-regions in each zone are similar, such that each zone is an approximately uniform stress field, and the risk computed for an anomaly occurring in any sub-region can be regarded as similar. The failure risk of the disk is the combination of the risks for all zones, that is,

$$P_f = P[F_1 \cup F_2 \cup \cdots \cup F_m] \tag{1}$$

where P_f is the probability of fracture of the disk, F_i represents the failure of zone i and m is the total number of zones. Notably, the probability that the disk contains an anomaly is generally low. Therefore, assuming that only one anomaly exists in the disk is