The Status Quo of Aerospace Engine Vibration Fatigue

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Abstract. In the working environment of aero engine blades, it is necessary to withstand the influence of factors such as aerodynamic stress, vibration stress, centrifugal stress, thermal stress, high temperature oxidation, thermal corrosion, etc. The blades often exhibit vibration fatigue fracture, foreign object damage, corrosion, material defects, and sports damage. This article summarizes the fatigue fracture problems of aero-engine blades, provides a systematic basic theory for the design, innovation and development of aero-engine blades, and has certain reference value.

Keywords: Engine Blades, Stress, Fatigue Fracture

1. Introduction
Engine blade failures mainly include: vibration fatigue fracture, foreign object damage, corrosion, material defects, micro-transport damage, etc. The main manifestations of fatigue conclude blade fracture, blade shedding, casing containment problems, blade drop corners [1], As shown in Figure 1.
At present, most of the blade fatigue experiments are carried out at room temperature, and the research is based on the theoretical basis of a cantilever beam with equal rectangular cross section. The specific method removes or cuts a single blade from the wheel, design an experimental fixture to install the blade in the actual connection mode of the blade and the wheel, and uses the excitation device to excite the blade to study the fatigue characteristics of the blade [2].

This paper analyzes the causes of fatigue fractures at this stage by sorting out engine fatigue fractures, and explores the three aspects of engine blade resonance fatigue fractures, high temperature fatigue vibrations, and blade fracture dynamics. The design, innovation and Development provide the basic theory of the system.

2. Research Status

2.1 Resonance Fatigue Fracture
Resonance fatigue can lead to crack initiation, propagation and fracture. Resonance fatigue will change the original vibration characteristics of the vibrating component. Accompanied by the coupled vibration with frequency steering and mode conversion as the main features, the initial crack length and position will affect the frequency, mode shape and various modes of the vibrating component. Make an impact. Scholars at home and abroad have carried out research on resonance fatigue through vibration fatigue test.

Shih et al. [3] analyzed the crack propagation law of a unilateral cracked plate and the influence of vibration factors on the crack propagation through the generalized Forman model.

Lau et al. [4] analyzed the vibration behavior of blades caused by aerodynamic vortex, and discussed the influence of blade pitch, chord length, wake frequency and other parameters on blade vibration.

Fan Bonan et al. [5] conducted a systematic study on the low-order bending vibration characteristics of blades caused by crack parameters.

Cheng Li [6] et al. proposed a high-order bending and torsion composite resonance test using a blade simulation specimen (rectangular specimen) for fatigue mechanism testing. The feasibility of the specimen to simulate the failure of blade angle drop was studied. It was proposed to use analog parts to carry out high-order bending-torsion resonance fatigue mechanism test research. The finite element was used to design the simulated specimen and analyze the nonlinear vibration characteristics of the specimen. A high-order bending torsional resonance fatigue test was performed on the strengthened...
specimen. The resonance test of the simulated test piece under the "double-torsion-bending compound" mode can simulate the "high-order bending-torsion compound".

2.2 High Temperature Fatigue Vibration
Aero-engine blades are used in high-temperature environments and can withstand temperatures up to 600°C. The first-order frequency at high temperatures is between 2200-2350Hz. The traditional blade fatigue experiment under a single mechanical environment cannot meet the test requirements. It is necessary to perform high temperature vibration fatigue experiments on the blade to study its fatigue characteristics. The blade vibration fatigue experiment conducted at high temperature is a key issue that needs to be addressed.

Li Quantong et al. [7] proposed "af value" (blade tip amplitude a and first-order frequency f) as a scalar of blade vibration intensity, which was used to characterize the magnitude of blade vibration stress, and used the constant cross-section cantilever beam theory to calculate the feasibility of this characterization method. This method requires the determination of the relationship between the "af value" and the vibration stress before the experiment, and the process of determination can be called "calibration". For the blade with the first-order frequency f determined, this "calibration" is equivalent to "amplitude-stress calibration". After the "calibration" is completed, the blade fatigue stress can be controlled or monitored by controlling the blade amplitude.

Zhang Busheng [8] proposed the "amplitude-strain" calibration at room temperature to characterize the high-temperature vibration fatigue stress of a certain type of titanium-aluminum aero-engine blade, and proved the feasibility of this method through theory and experiment. The test device is shown in Figure 2. Through theoretical deduction and experimental verification, it is proved that the "amplitude-strain" calibration relationship of engine blades is independent of temperature, and the linear relationship between amplitude and deformation (strain) still exists, has nothing to do with elastic modulus, and does not change with temperature. The "amplitude-strain" calibration at room temperature can be used for subsequent high-temperature fatigue experiments. The closed-loop control method based on phase-based resonance search and dwell is used for blade vibration stress control (the resonance frequency will fluctuate in a small range to achieve the concentration of fatigue data), which can achieve high precision of blade vibration fatigue stress (better than ± 2%) Control reduces the dispersion of fatigue test data.

2.3 Dynamic Problems of Engine Blade Fracture
Aero-engine blades work in an environment of high temperature, high intensity and complex vibration throughout its life cycle. Long-term alternating loads are likely to cause plastic deformation and fracture in the stress-concentrated parts, or the impact of large-scale foreign objects can cause partial fracture of the blade. The falling blades continuously hit important parts such as the high-speed rotating blades or the receiver, causing the entire engine to fail, and even causing serious air disasters. Therefore, it is of great significance to analyze the dynamics of the blade after fracture.

After the turbofan blades fall off, the blades will collide and rub against the casing under the action of the sudden imbalance force. It involves highly nonlinear dynamics. Limited by the complexity of
nonlinear dynamics, many scholars simplified the continuum rotor to a spring-concentrated mass model, and then used the model of sudden imbalance force to calculate the transient response and the reaction at the support [9], as well as structural damping, the influence of key parameters such as gyro torque and support stiffness on the law of vibration response [10]. Although this equivalent model can greatly simplify the calculation, it does not reflect the real physical model. Scholars at home and abroad have conducted a lot of research on it.

Plaut et al. [11] analyzed the stability of the simply supported rotor system after considering the axial load and damping. Cohen and Porat [12] studied the phenomenon of combined bending and torsion resonance of an unbalanced rotor. Sinha [13] established a general condition for analyzing the dynamic stability of the rotor under the combined action of torque and longitudinal force. Lee and Yun [14] extended the stability conditions of the bending, torsion, and longitudinal vibration of the elastic shaft. Euler-Bernoulli beam theory analyzes the rubbing process between the rotor system and the casing.

Liu Yang [15] and others innovatively retained the turbofan blades to study the transient dynamics of FBO. Specific research methods are the transient dynamics analysis of the variable cross-section shaft, the transient dynamics analysis of the impact of the blade tip, and the transient dynamics analysis of the joint solution of the shaft and the blade are very strong. The blade finite element analysis model is shown in Figure 3. Through analyzing the vibration characteristics of traditional aero-engine blades.

![Figure 3. Finite element analysis model of blade](image)

Zheng Tong et al. obtained a dynamic model based on the first-order approximate coupling, which introduced a dynamic stiffening term, and the results obtained have certain research value. As shown in Figure 4.

This method simplifies the blade into a flexible thin plate, considers the lateral deformation and the longitudinal deformation, and takes into account the in-plane deformation caused by the out-of-plane deformation, that is the deformation coupling term. The hypothetical modal method is used to describe the deformation of the blade, and the Lagrangian dynamic equation is used to establish the first-order approximate coupled dynamic equation of the flexible blade for large displacement in three-dimensional space. The multi-body system dynamics software MSC.ADAMS was used to study the dynamic behavior of the rotating blade, and the result of the blade dynamics theoretical model was compared with the result of ADAMS, and a conclusion was drawn: the theoretical result of the first approximate coupling model It is consistent with the actual results, but the simulation results of ADAMS and the zero-order approximation coupling model have defects when the blade is high speed. Based on the obtained first-order approximate coupling model of the blade, the problems of "frequency steering" and "mode conversion" of the blade are analyzed, and the feasibility of the proposed method is verified.
3. Conclusion
This paper combs and summarizes the fatigue and fracture problems of aero-engine blades from three aspects: resonance fatigue fracture, high-temperature fatigue vibration, and blade fracture dynamics, and draws the following conclusions:
1. The blade simulation specimen undergoes high-order bending and torsion composite resonance, and the feasibility of the specimen to simulate the blade corner failure of the specimen is studied. The resonance test of the simulated test piece under the "double-torsion-bending compound" mode can simulate the "high-order bending-torsion compound".
2. The "amplitude-strain" calibration at room temperature is used to characterize the high-temperature vibration fatigue stress of a certain type of titanium-aluminum-aluminum aero-engine blade, and the feasibility of this method is proved through theory and experiment.
3. In the process of studying the dynamic response of the blade, the transverse deformation and the longitudinal deformation are considered, and the in-plane deformation caused by the out-of-plane deformation is taken into account, that is, the deformation coupling term. A systematic analysis of the "frequency steering" and "mode conversion" problems of the blades is carried out to verify the feasibility of the method.

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