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Casing vibration response prediction of dual-rotor-blade-casing system with blade-casing rubbing

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ABSTRACT

This paper focuses on the dynamic responses of whole aero-engine with blade-casing rubbing. The vibration response of casing is simulated and the dynamic behaviors of casing acceleration under blade-casing rubbing are investigated to diagnose the blade-casing rubbing fault effectively. Firstly, the finite element model of a dual-rotor-blade-casing (DRBC) system with inter-shaft bearing is proposed. The shear deformations and inertias of the rotor and casing are taken into account. The gyroscopic moments of the rotors are evaluated. Secondly, the effects of the blade-casing clearance and the number of blades on the vibration responses of DRBC system with blade-casing rubbing are considered. Finally, the casing acceleration responses of the DRBC system with blade-casing faults are solved numerically, and the influences of some variables, such as the rotating speed ratio, eccentricity of disk and rubbing stiffness, on the dynamic behaviors have been investigated by time waveform of acceleration, frequency spectrum and waterfall. The results indicate that (1) blade-casing rubbing can cause impulsive load to the casing and rotor, and lead to abrupt increase of the vibration amplitude; (2) the obvious periodic impact characteristics are contained in the casing vibration acceleration signals, and the impact frequency equals the product of the rotational frequency and the numbers of blades; (3) the fraction frequency component of rotating speed difference of dual rotors is excited on both sides of impact frequency and its multiple frequency components.

1. Introduction

The dual-rotor structure has been widely used in aero-engine, which consists of many rotary and stationary accessories. To improve the performance of aero-engine, reducing the blade-casing clearance is one of most widely used methods [1]. However, minimizing clearances increases the possibility of blade-casing rubbing, which has long been identified as the main cause of engine malfunction. The blade-casing rubbing fault may result in excessive vibration of the whole machine, high maintenance cost and even catastrophic accidents [2,3]. Hence, in order to detect fault effectively, it's necessary to develop the whole aero-engine model and analyse the vibration characteristics of blade-casing rubbing.

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Due to the complexity of the rubbing fault, the blade-casing interaction have attracted increasing attention of scholars. Considering the influences of different parameters, Padovan and Choy [4] analyzed the dynamic behaviours under single- and multiple-blade rubbings. Sinha [5–7] investigated the vibration behaviours of a rotating Timoshenko beam exposed to a periodic pulse because of local rubbing between rigid casing and radial blade. Ma et al. [8,9] introduced an improved blade-casing rubbing model and evaluated the correctness of the new model by using experiments, and adopted the pulse loading model to study the dynamic behaviours of the single rotor system under blade-casing rubbing. Batailly et al. [10] investigated the blade-casing rubbing characteristics by utilizing the reduced models to detect the modal interaction. Legrand et al. [11–13] analyzed the modal interaction phenomenon and the effects of blade-casing interaction on the dynamic behaviours. Ma et al. [14] analyzed the effects of different variables on the dynamic responses of the shaft-disk-blade system with blade-tip rubbing. Petrov [15] developed a method for frequency domain analysis in gas turbine engines with rubbing between bladed disk and casing. Based on a revised rotor-blade dynamic model, Ma et al. [16] simplified the casing as a lumped mass point and revealed the vibration characteristics of the single- and four-blade rubbing faults. Thiery et al. [17] proposed the finite element model of a Kaplan turbine and evaluated the dynamics of the initially misaligned rotor with blade-casing rubbing. Cao et al. [18] introduced a novel rubbing force model to describe the blade-casing rubbing fault in aero-engine. Thiery et al. [19] adopted numerical and experimental methods to investigate the nonlinear vibration of a bladed Jeffcott rotor. Wang et al. [20,21] adopted finite element method, envelop demodulation and empirical mode decomposition to investigate the dynamic behaviours of a single rotor system with rub-impact and extract fault features. Chen et al. [22,23] investigated the dynamic responses of the casing under blade-casing rubbing, and the numerical results are verified by experiments. Qin et al. [24,25] verified the correctness of finite element models to predict dynamic characteristics of rotating bolted disk-drum type rotors. Ma et al. [26] investigated the vibration response resulting from blade-casing rubbing during the run-up process and steady-state process.

From above literatures, emphasis is put on the dynamic behaviours of single rotor with blade-casing rubbing and the actual dual-rotor structure of aero-engine is not fully considered. Wang et al. [27] revealed the dynamic characteristics of dual-rotor system by using finite element models and experiments. Yang et al. [28,29] adopted numerical and experimental methods to analyse the vibration responses of a dual-rotor system under fixed point rubbing condition. Wang et al. [30] proposed the dynamic model of dual-rotor and investigate the dynamic characteristics of the system under pedestal looseness fault. Lu et al. [31] investigated the complicated vibration response of a dual-rotor system with cracked high-pressure rotor. Xu et al. [32] developed rub-impact fault model and the finite element model of a dual-rotor system, and obtained the vibration responses under faulty condition by using theoretical and experimental methods. Hou et al. [33] carried out the resonance analysis of a dual-rotor system with two rotor unbalance excitation by using HB-AFT method. Wang et al. [34,35] performed the investigation on the dynamic behaviours of a dual-rotor system with rub-impact and misalignment faults. Sun et al. [36] adopted theoretical model to predict the steady-state responses and stability of a dual-rotor system under rub-impact condition. Yu et al. [37] investigated the vibration response of the dual-rotor system at instantaneous and windmilling statuses when fan blade out event occurs. However, the elastic casing and blades are not considered in these dual-rotor models, and the dynamic characteristics are investigated by means of the displacement responses of rotors.

Considering the complex structure of actual aero-engine, some characteristics are rarely taken into account in the existing experiment and theoretical studies at the same time, such as dual-rotor structure and thin-walled casing, and thus the current results don't truly reflect the vibration fault features of whole aero-engine. In addition, various rubbing types are not fully taken into account in the models. Besides, for aero-engine, only the casing acceleration signal can be obtained to diagnose rubbing fault. Therefore, it is of great importance to reveal the dynamic behaviours and laws of casing acceleration response for the precise blade-casing rubbing fault diagnosis and stability of aero-engine.

The paper is organized as follows. Based on the actual structure of aero-engine, a simplified dual-rotor-blade-casing (DRBC) system is introduced in Section 2.1. The blade-casing rubbing model, the rotor-casing clearance simulation and the finite element model of the DRBC system are proposed in Section 2.2, Section 2.3 and Section 2.4, respectively. In Section 3, the dynamic characteristics and the effects of rotating speed ratio, eccentricity of disk and rubbing stiffness on the dynamic behaviours of DRBC system are investigated in detail. Finally, the conclusions are drawn in Section 4.

2. Mathematical formulation

2.1. DRBC system model with blade-casing rubbing

CFM56 is one of most widely used aero-engines, and its rotor-support structure is shown in Fig. 1(a). Fig. 1(b) illustrates the structural coupling relationship of low-pressure rotor, high-pressure rotor and casing in CFM56. Based on the basic structure of CFM56, a dual-rotor-blade-casing (DRBC) system consisting of a high-pressure rotor (outer rotor), a low-pressure rotor (inner rotor), blades, casing and elastic support is developed, as shown in Fig. 1(c), where Bearing 1 and Bearing 2 (Fig. 1(a)) are simplified as one bearing. Each of the rotors consists of elastic shaft and two disks representing compressor and turbine, respectively. The inter-shaft bearing is employed to connect low-pressure rotor and high-pressure rotor. Two engine mounts are used to support the whole system. The attention is paid to the rubbing between disk 1 and casing. ω_1 and ω_2 are the rotating speeds of inner and outer rotors, respectively. Perfect balance can't be achieved, and assuming that