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Fixed-point rubbing characteristic analysis of a dual-rotor system based on the Lankarani-Nikravesh model

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ABSTRACT

A dual-rotor system dynamics model is established for simulating the aero-engine vibration with unbalance-partial rubbing coupled faults. The main characteristics of the dual-rotor model are as follows: (1) the compressor disc and turbine disc are considered in both low pressure rotor and high pressure rotor; (2) two eccentricities exist in the LP and HP turbine discs, respectively; (3) two convex points exist in the casing and then fixed-point rubbing may occur in the LP and HP turbine discs, respectively; (4) coatings are painted on the surfaces of all the discs and casing. Taking into account the soften characteristics of coatings, the Lankarani-Nikravesh model is used to describe the impact forces between two convex points and two turbine discs. Then, the case of two fixed-point rubbings is simulated by the Runge-Kutta method. At different rotational speeds, the responses of the dual-rotor system are analyzed by spectrum cascades and waveforms. Meanwhile, the effects of rotational speed ratio, initial clearance and curvature radius of convex point on the dynamic characteristics and impact force are discussed. Finally, the experiment performed on a dual-rotor test rig proves the validity of the dynamics model.

1. Introduction

Reducing rotor-stator clearance can provide dramatic reductions in specific fuel consumption (SFC), time-on-wing, compressor stall margin and engine efficiency as well as increased payload and mission range capabilities [1]. Unfortunately, tighter clearances increase susceptibility to rub-impact. Rub-impact results in decreased machine life via increased wear, heightened susceptibility to fatigue and adverse thermal effects [2]. Therefore, understanding the characteristics of rub-impact is essential for engineers to diagnose fault. Usually, rub-impact belongs to a secondary fault with apparent coupled fault characteristic. It may result from imbalance, misalignment, pedestal looseness, thermal failure and oil whirl [3]. According to contact components, rub-impact is divided into two classes: blade-to-shroud [4,5] and rotor-to-stator [6,7]. According to contact area, rub-impact is recognized by two motion types: full annular rubbing [8,9] and partial rubbing [10–12]. Full annular rubbing denotes that the rotor maintains contact with the stator during the whole process of whirling. Partial rubbing denotes that the rotor occasionally makes contact with the stator, and the contact zone may be a single point, multi points, local area, etc.

Over the last few decades, dynamic characteristics of a single rotor system with unfixed-point rub-impact have been investigated. Taking a Jeffcott rotor system with rub-impact as the object, Chu et al. [13] investigated the law of periodic motion going into and out of chaotic region by numerical simulation. Ren et al. [14] studied the stability and Hopf instability of a rotor-bearing

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system with coupled faults of rub-impact and crack. Lu et al. [15] solved the existence problem of rubbing periodic motions to find the grazing circle motions and the single-impact periodic motions. Choi [16] explained the onset and disappearance of the backward whirling by experiment and simulation. Muszynska [17] developed a polar co-ordinates model for rub system, in which the impact is considered as a variable stiffness with associated damping effects. Due to thermal deformation and external suspension, convex points may exist in casing. Therefore, it is of practical significance to investigate the dynamic characteristics of rotating machinery with fixed-point rubbing. Ma et al. [18] adopted the finite element method to establish a rotor system with two types of fixed limiters, i.e., four pin shape stators and three pin shape stators. Han et al. [19] analyzed the stability and bifurcation of a dual-disc rotor system via the Floquet theory. For the case of dry and lubricated inner surface of the guide, Lahriri et al. [20] studied the impact motion of a rotor impacting a conventional backup annular guide. On this basis, a new unconventional backup bearing was proposed to reduce the rub related severity [20].

For actual rotor system in engineering, the arrangement of two spools is a common configuration adopted in practice to achieve higher thrust-weight ratio [21]. Therefore, much attention has been paid to dynamic characteristics of linear dual-rotor system. Ferraris et al. [22] predicted the dynamic behaviors of the non-symmetric coaxial rotor system, including the Campbell diagram, the mass unbalance response, etc. Aiming at dual-rotor system, Childs [23] developed a complete dynamics model, which is composed of elastically coupled rotors and casing structures.

When rub-impact (fixed-point or unfixed-point) appears in the rotor system, it may lead to various nonlinear characteristics. In the previous researches, impact force was mainly described by the piecewise linear model [24]. In the piecewise linear model, the impact stiffness is usually considered as the structural stiffness of stator. For actual aero-engine components, various coatings (hard and soft coatings) are painted on the surfaces of compressor, combustion chamber and turbine sections for longer service lives [25]. Generally speaking, soft coatings are applied in the work environment of lower temperature, and hard coatings are used in the work environment of higher temperature. The reference [26] presents that with the increase of environment temperature, the surface coatings soften obviously, and the local contact stiffness of surface coatings may be far less than the structural stiffness of stator. Therefore, the piecewise linear model is difficult to describe the rub-impact force in the different conditions of coatings. Moreover, the researches on the nonlinear dynamic characteristics of a dual-rotor system with rub-impact are not sufficient. Actually, it is of crucial importance to carry out this kind of work for safe running of rotating machine.

In this paper, a dual-rotor system capable of describing the mechanical vibration resulting from unbalance-partial rubbing coupled fault is established, in which the compressor disc and turbine disc are considered in both low pressure rotor and high pressure rotor. Due to the eccentricities of LP and HP turbine discs, fixed-point rubbing may occur in the LP and HP turbine discs, respectively. For contact analysis, taking into account the soften characteristics of coatings, the Lankarani-Nikravesh model [27] and the Coulomb friction model [28] are used to describe the impact force and frictional force, respectively. Then the dynamic equations of the dual-rotor system are solved by the Runge–Kutta method, where the impact instant is predicted by a linear interpolation method [29]. At different rotational speed, the dynamic responses of the dual-rotor system are analyzed in terms of waveforms, spectrum cascades, etc. Moreover, the effects of model parameters, such as rotational speed ratio, initial clearance and curvature radius of convex point, on the dynamic characteristics of the dual-rotor system are discussed. Eventually, the validity of the dual-rotor system dynamics model is verified by comparing with the actual experimental results and the models available in the existing literature.

2. Mathematical formulation

All three main modes of rotor vibrations – lateral, torsional, and axial modes – may be present during rotor operation. Among these modes, the lateral modes of the rotor are of the greatest concern. For the dual-rotor system developed in this paper, both LP

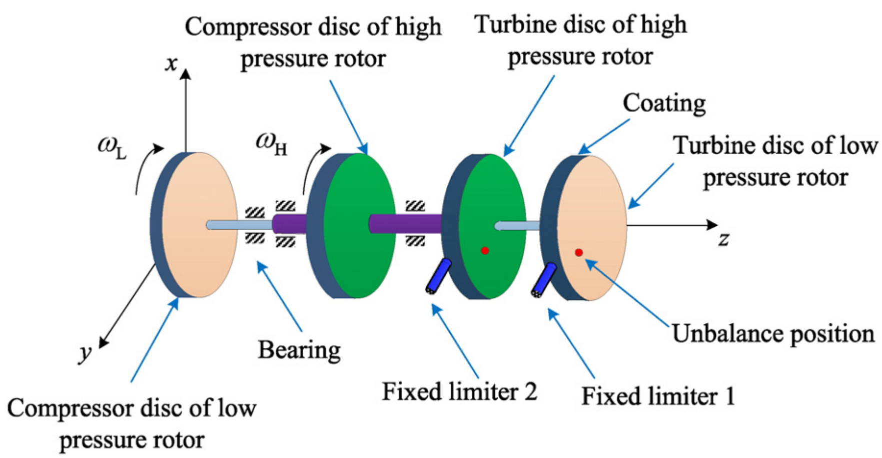

Fig. 1. Schematic diagram of a dual-rotor system.