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Research paper

Vibration response characteristics of a dual-rotor with unbalance-misalignment coupling faults: Theoretical analysis and experimental study

Nanfei Wang, Dongxiang Jiang*

State Key Laboratory of Control and Simulation of Power System and Generation Equipment, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

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A B S T R A C T

In order to improve energy efficiency and compact structure, the dual-rotor structure, with low-pressure rotor and high-pressure rotor, has been widely used in aero-engines. In severe operation conditions, the high rotating speed dual-rotor structure is vulnerable to some faults, such as misalignment, which may cause strong vibration and even catastrophic accidents. Perfect balance of the dual-rotor system cannot be obtained in practice, and some amount of unbalance is almost always present. The rotors' centrelines are not co-linear in the couplings and the rotors run in improper axial positions in a dual-rotor system. The differential equations of rotor system is derived by using modern nonlinear dynamics and dual-rotor dynamics principles. The governing equations of the dual-rotor system with unbalance-misalignment coupling faults are solved numerically by the Runge–Kutta method. The complicated vibration responses influenced by different rotational angular speeds, mass eccentricity, misalignment angle and parallel misalignment are analyzed by the cascade plot, time waveform and frequency spectrum. Second harmonic frequency and rotational frequency components of dual rotors are observed. To verify the validity of the dual-rotor system dynamic model, the unbalance-misalignment coupling faults are carried out on a dual-rotor test rig by adjusting the height and quantity of gaskets and installing a screw on the disk of the inner rotor. The simulation results are found to agree with the experimental results. These results provide important theoretical and engineering references for the safe operation of dual-rotor system and the exact identification of coupling faults.

1. Introduction

Rotating machinery has been widely used in many fields, such as energy development, transportation and defense. However, the rotating equipment is often malfunctions due to faults during the running process because of assembly error or the damage to some critical components, and rotor system misalignment is one of the most common and severe faults encountered in operation. Statistics show that more than 60% of the total number of modern rotating machinery faults are caused by rotor system misalignment [1]. Misalignment results in radial and axial vibrations and is usually caused by primary faults

* Corresponding author.
E-mail addresses: wnf14@mails.tsinghua.edu.cn, nanfei.wang@mail.utoronto.ca (N. Wang), jiangdx@tsinghua.edu.cn (D. Jiang).

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that include looseness, inertial unbalance [2], which may cause strong vibration and reduce the performance of the overall unit.

The misalignment dynamics and diagnosis of single-rotor have attracted many scholars' attention in the past few decades. Xu and Marangoni [3,4] formulated the generalized equations of rotor system with misalignment to obtain the misalignment exciting force, and found that the excitation frequency is twice the rotational frequency, and the result is proved through experiments. Al-Hussain [5] confirmed the relationship between the frequency and transient response of the dimensionless stability criteria under misalignment condition by using the numerical method to solve nonlinear equations. Patel [6] obtained the relevant diagnosis features of parallel misalignment and angles misalignment by investigating vibration response of the dual-disk rotor system with misalignment fault. Sekhar and Prabhu [7] revealed the effects of coupling misalignment on the rotor vibration by using numerical method, which demonstrated that an increase in misalignment resulted in changes in the second and third harmonics of the dynamic responses. Li et al. [8] investigated the dynamic mechanism of the rotor system connected by the gear coupling and physical properties of faults. Han et al. [9] conducted a study on the misalignment mechanism of rotor system connected by gear coupling from the prospective of kinematics. Wang [10] discussed the shaft misalignment dynamics and characteristics of vibration malfunction in detail. Bouaziz et al. [11] presented the effect of angular misalignment on the dynamic behavior of a rotor supported by two hydrodynamic journal bearings by means of analytical and numerical methods. Saavedra and Ramirez [12] carried out experimental research on misaligned rotor system, and revealed frequency spectrum with series of harmonics of rotational speed under misalignment condition. Tejas [13] developed the rotor model with misalignment fault by using Timoshenko beam elements, and the effects of misalignment are simulated by utilizing nodal force vector. Wang et al. [14] utilized an interval analysis method to obtain transient responses by means of interval mathematics and Taylor expansion method. Qin et al. [15,16] developed the FE models for rotating bolted disk–drum type rotors to predict dynamic characteristics. Yi et al. [17] derived the nonlinear restoring force and built a matched bearing-rotor system model. It was revealed that calculated misalignment may be useful for the matched bearings-rotor system to optimize dynamic characteristics. Ma et al. [18] investigated the oil-film instability laws of an overhung rotor system with parallel and angular misalignment in the run-up and run-down processes. Li et al. [19] presented the quantification of uncertainty influences under shaft misalignment and the mass unbalance condition. Florian and Jan-Olov [20] studied the nonlinear dynamic responses induced by numerous contacts with an outer ring as well as deformation of massless blades in a misaligned bladed Jeffcott rotor by utilizing numerical and experiment methods.

In the above literature, the researchers pay more attention to the single-rotor system, which has significant differences from actual aero-engine. The arrangement of dual rotors is a regular configuration utilized in practice to obtain a higher thrust-weight ratio [21]. The key distinction between dual-rotor structure and single-rotor structure is the involvement of inter-shaft bearing, which completes the coupling between high-pressure rotor and low-pressure rotor. Wang et al. [22] investigated the dynamic responses of a dual-rotor-bearing system via 1D beam-type model, 3D solid model and experimental test. Guskov et al. [23] investigated the natural characteristics of a dual-rotor system by means of simulations and experiments. Ferraris et al. [24] analyzed the dynamic behavior of a non-symmetric dual-rotor system without misalignment, involving the Campbell diagram and the mass unbalance response. Childs [25] presented the transient response of a dual-rotor system without misalignment. Yang et al. [26, 27] analyzed the vibration characteristics of a dual-rotor system with fixed point rubbing faults by theoretical and experimental study. Wang et al. [28] presented a finite element model of dual-rotor system with pedestal looseness and investigated the fault features by simulation and experiment. Sun et al. [29] described the steady-state vibration characteristics and corresponding stability of a dual-rotor system under rub-impact condition by means of numerical calculation, lacking the assessment of experiments. Xu et al. [30] further developed the rub-impact fault model of dual-rotor system, in which rubbing board is considered as elastic sheet. Wang et al. [31] performed the study on the vibration responses of a dual-rotor sys-tem with rubbing faults by using numerical and experimental methods. Lu et al. [32] theoretically presented the nonlinear vibration characteristics of a dual-rotor system with a breathing transverse crack in the hollow shaft of the outer rotor without experiments. Until now, the effects of misalignment on the vibration responses of the dual-rotor system have not been systematically investigated. Meanwhile, perfect balance of the rotor system cannot be obtained in practice, and some amount of unbalance always exists. Hence, it is of crucial importance to investigate the dual-rotor system of unbalance-misalignment coupling faults mechanism for safe and steady running of aero-engines.

Considering the coupling effect of inter-shaft bearing, a dual-rotor system dynamic model with unbalance-misalignment coupling faults is set up in the study. The coupling misalignment model is utilized to describe the misalignment excitation force. The vibration equations of dual-rotor system are computed by numerical method and the results are investigated by the 3D waterfall plot, time waveform and frequency spectrum. Finally, the experiments with unbalance-misalignment is carried out on a dual-rotor test rig and the vibration displacement signals of the low-pressure rotor are collected to analyze in detail.

2. Mathematical formulation

2.1. Dual-rotor system model

The dual-rotor system with misalignment fault is shown in Fig. 1, which consists of a low-pressure rotor (rotor 1, lumped mass point 1 to 5) with a lower rotating speed and a high-pressure rotor (rotor 2, lumped mass point 6 to 9) with a high rotating speed. There are four bearings included in the model, in which bearing 3 denotes the inter-shaft bearing. The disks