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Modeling and analysis of fit clearance between rolling bearing outer ring and housing

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A R T I C L E I N F O

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A B S T R A C T

In the assembly and using the process of the rolling bearings in high-speed rotating machines, including aero-engines. Because the change of the bearing temperature and pre-stressing force of installation, there will inevitably appear fit clearance between the bearing outer ring and the bearing housing. The fit clearance fault may lead to the impact and friction between bearing and bearing housing, a strong non-linear vibration be caused, the rolling bearing and the entire rotor system vibrate strongly, which leads to the service life of the bearing and rotor system reliability reduces greatly. In this study, the rotor-rolling bearing tester is considered to be the research object, and a rotor-rolling bearing dynamic model with the bearing fit clearance fault is established. The time-domain numerical integration method is used to study the influence of factors such as fit clearance, rotor unbalance, and bearing outer ring tightening torque on the vibration response. Finally, the bearing fit clearance fault test is performed to verify the simulation results. The research work in this study is of great significance for understanding, diagnosing and preventing the bearing fit clearance fault between rolling bearing outer ring and housing.
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1. Introduction

Rotating mechanical loose fault can usually be divided into bolt looseness fault and bearing fit clearance fault. A lot of researches on bolt looseness fault have been carried out. Segmented nonlinear stiffness model has been applied to study the synchronous and non-synchronous vibration caused by bolt looseness fault.

Goldman and Muszynska [1] performed experimental, analytical and numerical investigations on the unbalance response of a rotating machine with one loose pedestal. The model was simplified as a vibrating system with bi-linear form. Synchronous and subsynchronous fractional components of the response were found. In a subsequent paper [2], they discussed the chaotic behavior of the system based on the bi-linear model. Z. Ji and J. W. Zu [3] developed a method of multiple scales to analyze the free and forced vibration of non-linear bearing pedestal systems. The rotating shaft is described by the Timoshenko beam theory which considers the effect of the rotary inertia and shear deformation. A non-linear bearing pedestal model is assumed which has a non-linear spring and linear damping characteristics. Numerical simulations are carried out to illustrate the non-linear effect on the free and forced vibrations of the system. It is shown that for free vibrations; the amplitude has a one-to-one relationship with the non-linear natural frequency. For steady-state response, however, multi-valued displacements occur, indicating the existence of bifurcation points in the system. Chu [4] considered a non-linear

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mathematical model containing stiffness and damping forces with tri-linear forms. The shooting method is used to obtain the periodic solutions of the system. Stability of these periodic solutions is analyzed by using the Floquet theory. Period-doubling bifurcation and Naimark-Sacker bifurcation are found. Finally, the governing equations are integrated using the fourth order Runge-Kutta method. Different forms of periodic, quasi-periodic and chaotic vibrations are observed by taking the rotating speed and imbalance as the control parameter. Three kinds of routes to or out of chaos, that is, period-to-chaos, quasi-periodic route and intermittence, are found. Ma [5] presented a finite element model of a rotor system with pedestal looseness stemming from a loosened bolt and analyzes the effects of the looseness parameters on its dynamic characteristics. When the displacement of the pedestal is less than or equal to the looseness clearance, the motion of the rotor varies from period-one through period-two and period-three to period-five with the decreasing of stiffness of the non-loosened bolts. The similar bifurcation phenomenon can be also observed during the increasing process of the rotational speed. But the rotor motion is from period-six through period-three to period-four with the decreasing of the foundation stiffness. When the stiffness of the foundation is small and the displacement of pedestal is greater than the looseness clearance, the response of the rotor exhibits period-one and high order harmonic components with the decreasing of looseness clearance, such as 2X, 3X etc. However, when the stiffness of the foundation is great, the spectrum of the response of the rotor will be from combined frequency components to the continuous spectrum with the decreasing of the looseness clearance. Wang and Chen [6] used the modeling method in Ref. [11] to establish a rotor-support-casing whole model for a certain type turbofan aero-engine based on certain type turbofan engine structural features. The rotor and casing systems are modeled by means of the finite element beam method; the support systems are modeled by a lumped-mass model; the support looseness fault model is also introduced. The coupled system response is obtained by numerical integral method. In this paper, based on the casing acceleration signals, the impact characteristics of symmetrical stiffness and asymmetric stiffness models are analyzed, finding that the looseness fault would lead to the longitudinal asymmetrical characteristics of acceleration time domain wave and the multiple frequency characteristics, which is consistent with the real trial running vibration signals. Asymmetric stiffness looseness model is verified to be fit for aero-engine looseness fault model. In a subsequent paper [7], they established a single degree of freedom lumped mass model, and a looseness fault model was introduced. The response of the system was obtained by numerical integration methods and the asynchronous response characteristics were analyzed. The experiments were conducted on the connectors with looseness clearance. It is found that the acceleration response of the mass block after noise reduction has up-down asymmetrical impact characteristics in the waveform, also the pseudo-critical subharmonic resonance and the pseudo-critical ultra-harmonic resonance appear in frequency spectrum. These characteristics are in agreement with the results of the numerical simulation, which can be identified as the characteristics of the looseness fault.

In additions, a large number of experimental researches have been carried out. Muszynska and Goldman [2] presented experimental vibration characteristics of rotors with looseness or rubs, obtained from rotor rigs. The results exhibited regular periodic vibrations of synchronous ($1\times$) and sub-synchronous ($1/2\times, 1/3\times, \ldots$) orders, as well as chaotic vibration patterns of the rotor, all accompanied by higher harmonics. Lee and Choi [8] developed a newly time-frequency analysis method, HHT (Hilbert-Huang Transform), is applied to the signals of partial rub and looseness from the experiment using RK-4 rotor kit. Conventional signal processing methods such as FFT, STFT and CWT were compared to verify the effectiveness of fault diagnosis using HHT. The results showed that the impact signals were generated regularly when partial rub occurred, but the intermittent impact and friction signals were generated irregularly when looseness occurred. The time and frequency information was represented exactly by using HHT in both cases, which makes clear fault diagnosis between partial rub and looseness. Lu and Chu [9] established an experimental setup of rotor-bearing system, and investigated vibration characteristics of the system with pedestal looseness. The pretightening bolt between the bearing house and pedestal is adjusted to simulate the pedestal looseness fault. The vibration waveforms, spectra and orbits are used to analyze the nonlinear response of the system with pedestal looseness. Different parameters, including speed, looseness gap, imbalance mass and disk position are changed to observe the nonlinear vibration characteristics. The experiments show that the system motion generally contains the 1/2X fractional harmonic component and multiple harmonic components such as 2X, 3X, etc. Under some special conditions, the pedestal looseness occurs intermittently, that is, occurs in some periods and does not in other periods. Nembhard and Sinha [10] presented an experimental study on the shaft orbit response for different rotor related faults including pedestal looseness. Experiments are done on a small laboratory ball bearing rig on which vibration displacement data are acquired for a baseline condition as well as six different fault conditions that are introduced separately at different subcritical steady state speeds. For each condition tested, orbit plots are generated and critically analyzed. These orbits are also compared to those observed on a similarly configured rig with different dynamic characteristics on which the same experiments are done in order to assess any changes in the shaft orbit. The present work provides useful results for practical rotor fault diagnosis as well as worthwhile qualitative information to analytical studies related to the rotor faults observed here.

The existing research results show that the rotor nonlinear vibration law caused by the system looseness nonlinear factors (variable stiffness, impact and friction). However, there are little research on vibration caused by fit clearance between the bearing outer ring and the bearing housing; in addition, existing researches mainly focus on the synchronous and non-synchronous vibrations caused by looseness fault, and the looseness fault features aiming at the practical rotor-bearing system were rarely studied. In fault diagnosis, it is often classified as a friction fault model. However, compared with the classical stator-rotor rubbing model, the fit clearance between the bearing outer ring and the bearing housing has its particularity, for example, the bearing outer ring and the bearing housing do not rotate, the direction of the friction force needs to be judged; and with the fit clearance, the bearing outer ring will have a friction effect respect to the tightening torque and so

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