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An identification method of orbit responses rooting in vibration analysis of rotor during touchdowns of active magnetic bearings

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Identification of orbit responses can make the active protection operation more easily realize for active magnetic bearings (AMB) in case of touchdowns. This paper presents an identification method of the orbit responses rooting on signal processing of rotor displacements during touchdowns. The recognition method consists of two major steps. Firstly, the combined rub and bouncing is distinguished from the other orbit responses by the mathematical expectation of axis displacements of the rotor. Because when the combined rub and bouncing occurs, the rotor of AMB will not be always close to the touchdown bearings (TDB). Secondly, we recognize the pendulum vibration and the full rub by the Fourier spectrum of displacement in horizontal direction, as the frequency characteristics of the two responses are different. The principle of the whole identification algorithm is illustrated by two sets of signal generated by a dynamic model of the specific rotor-TDB system. The universality of the method is validated by other four sets of signal. Besides, the adaptability of noise is also tested by adding white noises with different strengths, and the result is promising. As the mathematical expectation and Discrete Fourier transform are major calculations of the algorithm, the calculation quantity of the algorithm is low, so it is fast, easily realized and embedded in the AMB controller, which has an important engineering value for the protection of AMBs during touchdowns.

1. Introduction

Active magnetic bearings (AMB) have merits such as low loss, low noise, non-friction and adjustable stiffness and damping. So it has been increasingly used in the rotary machines, especially for high rotating speeds [1,2]. Touchdowns due to AMB components or power failure can result in collisions and friction between rotors of the AMB and the touchdown bearing (TDB) that is one of the vital elements in the AMB systems. The high energy of the rotor can lead to severe damages for both parts [3]. So it is valuable to develop an active protection algorithm for the AMB, when a touchdown happens.

During the touchdown of horizontal AMB rotors, orbit responses include combined rub and bouncing, pendulum vibration and full rub [3], which have different dynamic characteristics, and result in damages in different degrees. Therefore, a number

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of scholars conducted researches about this process. Sun et al. [4] constructed a detailed TDB model to simulate the dynamic and thermal behavior of touchdowns of a vertical rotor-TDB system in the flywheel energy storage system. He remarked that friction coefficients, side loads and support damping were important parameters for the TDB performance. Moreover, the results showed that a high-speed backward whirl and damping were vital factors for its life. Lee and Palazzolo [5] analyzed the influence factors such as the sub/surface shear stress between the rotor, races and balls to estimate the touchdown numbers prior to failure. Sun [6] evaluated the L_{10} fatigue life of the TDB based on the Hertzian contact dynamic loads between the balls and races in the TDB during the touchdowns. Jarroux et al. [7,8] employed both the Kelvin-Voigt model and the generalized Dahl model which considered the stick-slip phenomenon by the dry friction model in the ribbon to simulate the dynamic behavior of the ribbon damper, which made the model more detailed. Precise rotor models supported by the magneto-hydrodynamic bearing were presented in Refs. [9,10], which introduced the Bouc-Wen hysteretic model to reflect the hysteretic property of the rigid magnetic material. A theoretical model considering the elastic deformation and dynamic behavior of a rolling bearing in touchdowns was established by Cole et al. [11]. Kudra et al. [12,13] presented new mathematical models of the contact models, and in Ref. [12], the contact pressure distribution was distorted in a special way, and in Ref. [13], the integral model of friction force and moment were approximated based on Padé approximants and their generalizations. Kärkkäinen et al. [14] simulated touchdowns using a dynamic model coupled a finite element model. The results showed that the misalignment was harmful and could lead to whirling motion of the rotor. Keogh et al. [15] conducted a research about thermal assessment of dynamic rotor/auxiliary bearing contact events during touchdowns. The results showed that significant localized contact temperatures might arise from each contact event, which would accumulate for multiple contact cases. The references mentioned above mainly focused on optimizing parameters the TDB. They can be taken as passive protection methods. A method to re-levitate the magnetic molecular pump in case of touchdowns was proposed in Ref. [16], which conducted a specific active controlling program for the full rub during touchdowns. The operation can effectively reduce the damage for the rotor and the TDB of AMBs. It can be taken as an active protection way. However, the method depends strongly on the particular pump type of the AMB.

The damage can be effectively reduced, if a specific active protection method can run for different orbit responses. Therefore, it is crucial that an identification method of the orbit responses during touchdown of the AMB is developed. Ref. [3] illustrated that the orbit responses could be identified by comparing the dynamic forces and the static loads during touchdowns. However, it is very difficult to measure precisely the dynamic forces on the rotor for most equipment. In contrast, it is very convenient to precisely measure displacements of the rotor of AMB, and the rotor vibration has been a regular parameter that is used to characterize the rotor dynamic of bearings [17–21]. On the basis of the mathematical expectation of axis displacements of the rotor, we present a method to identify whether the response is the combined rub and bouncing. Ref. [22] revealed that the frequency characteristics of the rotor motion showed significant differences between the three orbit responses. Although many time-frequency analysis techniques, for instance, short time Fourier transform [23], wavelet transform [24–27], non-stationary Gabor transform [28,29], Hilbert transform [30,31] and Synchrosqueezing transform [32–34], have been developed, and widely employed. In Ref. [35], an identification algorithm of the orbit response was presented using Hilbert transform. Although the instantaneity of Hilbert transform is better, the accuracy of the calculation is greatly influenced by the smoothness of the signal [36]. Furthermore, discrete wavelet transform (DWT) has been used to characterize and analyze dynamics of AMBs [16,37–39], and Mallat algorithm makes DWT have a fast calculation speed, so it has a good online ability. However, the DWT physical significance of the rotor vibration of the AMB is not clearly clarified. Discrete Fourier transform (DFT) has advantages on low computational cost using Fast Fourier transform (FFT). Besides, frequency, which is used in DFT (in contrast, scale is employed in DWT) to describe the change speed of the signal, has a specific physical significance, and is widely-used in the engineering practice, so employing DFT to realize the identification of the orbit response seems to be more popular in engineering. Therefore, on the basis of DFT of axis displacements of the rotor, we develop a way to distinguish the pendulum vibration and full rub.

2. Thermo-dynamic model of the rotor-TDB system

2.1. Rotor model

The rotor-TDB model is shown in Fig. 1. In the dynamic model, the rotor has been assumed to be rigid as it works under its first bend natural frequency. The rotor motion equations are derived from Lagrange equations to compute the dynamic responses and it is expressed as,

$$\begin{cases} m_r\left[\ddot{x}_r - e\sin(\theta_r)\ddot{\theta}_r - e\cos(\theta_r)\dot{\theta}_r^2\right] = \lambda(-F_{n1}\cos\alpha + F_t\sin\alpha) \\ m_r\left[\ddot{y}_r + e\cos(\theta_r)\ddot{\theta}_r - e\sin(\theta_r)\dot{\theta}_r^2\right] = \lambda(-F_{n1}\sin\alpha - F_t\cos\alpha) - m_r g \\ m_r e[-\sin(\theta_r)\ddot{x}_r + \cos(\theta_r)\ddot{y}_r] + \left(m_r e^2 + J_c\right)\ddot{\theta}_r \\ = \lambda\{F_{n1} e\sin(\alpha-\theta_r) - F_t[r - e\cos(\alpha-\theta_r)]\} - m_r e g\cos(\theta_r) \end{cases} \tag{1}$$

where x_r and y_r are the rotor displacements in X and Y directions, respectively; θ_r is the angular displacement of rotor. F_{n1} and F_{n2} are the contact force and friction applied by the TDB, respectively; m_r and J_r are the mass and moment of inertia of the