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Nonlinear dynamics near resonances of a rotor-active magnetic bearings system with 16-pole legs and time varying stiffness

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ABSTRACT

In this paper, we analyze the complicated nonlinear dynamics of rotor-active magnetic bearings (rotor-AMB) with 16-pole legs and the time varying stiffness. The magnetic force with 16-pole legs is obtained by applying the electromagnetic theory. The governing equation of motion for rotor-active magnetic bearings is derived by using the Newton's second law. The resulting dimensionless equation of motion for the rotor-AMB system is expressed as a two-degree-of-freedom nonlinear system including the parametric excitation, quadratic and cubic nonlinearities. The averaged equation of the rotor-AMB system is obtained by using the method of multiple scales when the primary parametric resonance and 1/2 subharmonic resonance are taken into account. From the frequency-response curves, it is found that there exist the phenomena of the soft-spring type nonlinearity and the hardening-spring type nonlinearity in the rotor-AMB system. The effects of different parameters on the nonlinear dynamic behaviors of the rotor-AMB system are investigated. The numerical results indicate that the periodic, quasi-periodic and chaotic motions occur alternately in the rotor-AMB system.

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1. Introduction

Without physical contact with rotors, the active magnetic bearings (AMBs) have several distinct advantages, for example, much lesser friction, absent lubrication, high rotating speed and performance under the extreme conditions. The rotor-AMBs are being used in growing number of engineering fields, such as the aeronautic and astronautic engineering and mechanical engineering. However, most of the components in the AMB system are characterized by the nonlinearities and the dynamics of the whole system is comparatively complicated. The inherent nonlinear properties of the rotor-AMB system may cause unpredictable oscillations of the rotor in the certain parameter regions. Hence, it is essential to take nonlinearities into account in the rotor-AMB systems.

Nowadays, many researchers have focused their attention on the dynamics of the rotor-AMB systems for many years. However, few of them contributed on the nonlinear dynamics of a rotor-AMB system with 16-pole legs. The number of poles in a rotor-AMB system, which plays an important role in the bearing force and heat dissipation, results in different parameters in the governing equations of motion. The rotor-AMB system with 16-pole legs has many advantages compared to the system with 4-pole or 8-pole legs, which include better bearing capacity, better heat dissipation ability, higher efficiency and lower energy consumption. With the development of the manufacture technology, the rotor-AMB system with 16-pole legs

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will be becoming more and more popular in the industrial application. In the industrial application, a suitable poles number should be chosen according to the different operating requirements and working conditions.

Over the past three decades, a number of literatures have been conducted to study the nonlinear dynamic behaviors of the rotor-AMBs. Ji [1,2] presented the theoretical and experimental researches for the nonlinear dynamics of a Jeffcott rotor-magnetic bearing system with time delays. In addition, Ji and Leung [3] also studied the nonlinear oscillations of a rotor-magnetic bearing system subjected to a super-harmonic resonance. Later, Ji and Hansen [4] constructed an approximate analytical solution of a periodically excited nonlinear oscillator under primary resonance conditions. Zhang and Zhan [5] studied the periodic and chaotic motions of a rotor-AMB system with 8-pole legs using the asymptotic perturbation method. Zhang et al. [6] discussed the Shilnikov type multi-pulse chaotic dynamics for a rotor-active magnetic bearing system with the quadratic and cubic terms and time-varying stiffness. Eissa et al. [7,8] analyzed the nonlinear behaviors of a rotor-AMB system with the time-varying stiffness under combined excitations. Awrejcewicz and Dzyubak [9] investigated the chaos and saturation phenomenon in vibrations of a rotor supported by the magneto-hydrodynamic bearings. Messaoud et al. [10] surveyed the nonlinear dynamic behaviors of a misaligned rotor in the AMB. Besides, Bouaziz et al. [11,12] investigated the influence of angular misalignment on the dynamic behaviors of a misaligned rotor supported by active magnetic bearings.

The resonant responses are becoming popular in the researches of the rotor-AMB systems. Amer and Hegazy [13] investigated the nonlinear dynamics of an AMB system subjected to a periodically time-varying stiffness and the primary resonance, simultaneously. Hegazy et al. [14] numerically studied the stability and the steady-state responses of a time-varying stiffness rotor-AMB system under the combined resonance effects. Chen and Hegazy [15] researched the nonlinear dynamic behaviors of a rigid disc-rotor suspended by the AMBs under both primary and internal resonances. Kamel and Bauomy [16] employed the method of multiple scales to analyze the nonlinear behaviors of a rotor-AMB system with the multi-parametric excitations and time-varying stiffness under the case of the simultaneous primary and internal resonances. Bauomy [17] considered the stability of a rotor-AMB system under the external excitation. Saeed et al. [18] applied the method of multiple scales to construct an approximate analytical solution of a rotor-AMB system subjected to the primary resonance and 1:1 internal resonance. Yang et al. [19] investigated the nonlinear dynamics of the rotor-AMB system with 8-pole pairs and found there are three types of motions in two degree-of-freedom nonlinear systems.

Furthermore, several papers are devoted to discuss the bifurcation phenomena in the AMB systems. Chinta and Palazzolo [20] used the collocation method to analyze the stability and bifurcations of the AMB rotor motion. Ji et al. [21] utilized normal form method to investigate the nonlinear vibrations and bifurcations of an AMB rotor. Ji and Hansen [22] indicated that the steady state solutions lose their stability by either saddle-node bifurcation or Hopf bifurcation in the rotor-AMB system. Zhang et al. [23,24] discussed the global bifurcations and chaotic dynamics in a rotor-AMB system with time-varying stiffness. Li et al. [25,26] analyzed the bifurcations of the multiple limit cycles for a rotor-AMB system and found that the selection of the singular points has significant impact on the number of the limit cycles. Inayat-Hussain [27,28] considered the geometric coupling effect on the responses and bifurcations of a rotor AMB system.

The active magnetic bearing is a new kind of support device that can realize active control. Therefore, some researches are devoted to the controlling problems of the rotor-AMB systems. Chang and Tung [29] improved the traditional identification technique in accordance with the principle of harmonic balance and the curve fitting method to identity the nonlinear electromagnetic system. Flowers et al. [30] designed an integrally augmented state feedback controller to eliminate static offsets in a rotor-AMB system. Maslen and Montie [31] studied the sliding mode control problem of the magnetic bearings in the case of rotor flexibility and finite amplifier voltages. Na et al. [32] proposed a new algorithm for implementing fault-tolerant operation of a flexible rotor-magnetic bearing. Fang et al. [33] presented an active vibration control method to solve the undesirable synchronous vibrations problem in an active magnetic bearing system. Chen et al. [34] used a new recurrent wavelet fuzzy-neural network approach to control the rotor position on the axial direction in a magnetic-bearing mechanism.

Since only few of nonlinear differential equations can be solved accurately, many asymptotic perturbation techniques, such as the averaging method, the harmonic balance method and the method of multiple scales, have been widely used to construct the approximate solutions for weakly nonlinear systems. The correctness of these mentioned approximate methods are validated by many researchers. As shown in Refs. [35–38], great consistency between the solutions of the original equations and the approximate equations is presented using the method of multiple scales, which is also used in this paper to investigate the complicated nonlinear dynamics near resonances of a rotor-AMB system with 16-pole legs and the time varying stiffness. The rotor-AMB system with 16-pole legs is modeled by a set of two-degree-of-freedom ordinary differential equations with the quadratic and cubic nonlinearities and parametric excitations. The method of multiple scales is utilized to obtain the averaged equation under the case of the primary parametric resonance and the 1:2 internal resonance. The numerical results demonstrate that there are both soft-spring and hardening-spring types in the frequency-response curves of the rotor-AMB system. The effects of various parameters on the nonlinear dynamic behaviors are investigated in detail, which indicate that there exist the periodic, quasi-periodic and chaotic motions in the rotor-AMB system.

2. Equation of motion and energy equation

The rotor-AMB system studied in this paper is a uniform, symmetric rigid rotor suspended by two radial AMBs at its both ends. It is assumed that each AMB has a stator of 16-pole legs and identical structure. A cross-section diagram of the rotor-

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