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A new nonlinear dynamic analysis method of rotor system supported by oil-film journal bearings

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ABSTRACT

The strong nonlinear behavior usually exists in rotor systems supported by oil-film journal bearings. In this paper, the partial derivative method is extended to the second-order approximate extent to predict the nonlinear dynamic stiffness and damping coefficients of finite-long journal bearings. And the nonlinear oil-film forces approximately represented by dynamic coefficients are used to analyze nonlinear dynamic performance of a symmetrical flexible rotor-bearing system via the journal orbit, phase portrait and Poincaré map. The effects of mass eccentricity on dynamic behaviors of rotor system are mainly investigated. Moreover, the computational method of nonlinear dynamic coefficients of infinite-short bearing is presented. The nonlinear oil-film forces model of finite-long bearing is validated by comparing the numerical results with those obtained by an infinite-short bearing-rotor system model. The results show that the representation method of nonlinear oil-film forces by dynamic coefficients has universal applicability and allows one easily to conduct the nonlinear dynamic analysis of rotor systems.

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1. Introduction

The stability of bearing-rotor system is a very important problem for design, manufacturing, and operation of rotating machinery. The unstability of rotor system will result in the strong vibration and even disastrous accident of machinery. In 1920's, the air blower manufactured by American General Electric Company (GE) showed severe sub-harmonic vibration when it was working in the super-critical state. So the air blower could not normally operate when the working speed was close to the twice of its first natural frequency [1]. In 1925, Newkirk pointed out that this phenomenon was resulted from the self-exciting vibration of bearing oil-film forces [2]. The researches for decades indicate that the strong-nonlinear exciting sources such as oil-film forces, sealing forces and nonuniform steam forces et al. are main reasons which can make unstable accidents in rotating machineries. The oil-film forces are the leading nonlinear exciting source which makes the bearing-rotor system to be a self-exciting vibration system and results in fatal accidents. So solution of nonlinear oil-film forces in sliding bearings is always very important for dynamic analysis of rotor-bearing systems.

Since Lund [3] produced the model of linear oil-film forces represented by using eight linear dynamic coefficients, the researches on dynamics of rotor-bearing systems have made large progress. Nicoletti and Santos [4] applied the model of linear oil-film forces to study the dynamic responses of rotor system supported by oil-lubricated tilting-pad bearings and

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also used the proportional controller to effectively depress the system vibration. Rao and Sawicki [5] calculated the linear stiffness and damping coefficients of cylindrical bearings in two states of complete oil lubrication and cavity. Then they analyzed the stability of rotor system in these two lubrication states. The model of linear fluid-film forces also can be suitable for gas-lubricated bearing-rotor systems. San Andres et al. [6–8] figured out the linear dynamic coefficients of flexure pivot tilting-pad gas bearings and brush seals by using the finite element method with the assumption of small perturbation and conducted dynamic analysis of rotor systems. Lee et al. [9] studied the vibration responses of rotor systems supported by viscoelasticity foil bearings by using the bearing linear stiffness and damping coefficients. Yang et al. [10–11] computed the linear dynamic stiffness and damping coefficients of self-acting tilting-pad gas bearings, respectively by using the partial derivative method and equivalent coefficients method. Then they carried out stability analysis of this kind of rotor–bearing system by adopting the model of linear gas-film forces [12].

For the rotating machineries such as gas turbine etc., they will develop in the directions of high speed and large power, so the perturbations of the journal in the fluid-film forces are not small perturbation any more. Furthermore, because of the errors of manufacture, installation and operation in actual rotors, the complex nonlinear dynamic behaviors such as nonsynchronous, period-doubling and chaotic motion et al. will happen in the rotor systems. Therefore, the design and analysis methods based on the classical linear theories cannot accurately reflect the actual motion laws of machine sets and also cannot satisfy the needs of engineering design. Consequently, the computational methods of bearing nonlinear fluid-film forces must be studied to carry out the nonlinear dynamic analysis of rotor systems and widely reveal the operation laws of large-scale rotating machineries. It has very important theoretical significance for advancing the stability, safety and reliability of rotating machineries.

At present, two main computational methods are used to obtain the nonlinear fluid-film forces. One is the numerical integration method which directly solves the Reynolds equation by the finite difference method or finite element method and has higher computational accuracy, but slower computational speed. The other one is the analytical method which applies the infinite-short or infinite-long bearing model to obtain the nonlinear fluid-film forces and has quicker computational speed, but lower computational accuracy. Refs. [13–14] obtained bearing nonlinear oil-film forces by the numerical integration method to analyze the nonlinear behaviors of symmetrical rotor systems. In order to improve the computational efficiency, the approximate models of fluid-film forces are widely used. Castro et al. [15–16] studied the bifurcation and chaotic motions of rotor systems in different working conditions by applying the infinite-short bearing model of nonlinear oil-film forces. Adiletta et al. [17] applied the correctional approximation theory of infinite-short bearing to analyze the nonlinear behaviors of a rigid rotor-bearing system in the wide range of parameters. Because the bearing axial pressure flow is completely neglected in the infinite-short bearing model of nonlinear fluid-film forces and the end leakage is ignored in the infinite-long bearing model, the computational results by these approximate models often depart from those of the actual bearing with length-diameter ratio 0.8 to 1.0. Moreover, whether the numerical integration method or the approximate analytical method, they have not universal applicability as the linear fluid-film forces model.

Inspired by the linear fluid-film forces model based on eight linear dynamic coefficients, some researchers presented the solving methods of bearing nonlinear dynamic stiffness and damping coefficients to represent the bearing nonlinear fluid-film forces and have obtained some research achievements. Czolczynski [18] firstly obtained the journal moving orbit by solving the equation of motion of rotor system, and employed the orbit method to calculate the nonlinear dynamic stiffness and damping coefficients of hydrostatic gas bearing. Choy et al. [19] expanded the nonlinear oil-film forces as the odd power functions of journal perturbation displacements to compute bearing nonlinear stiffness coefficients by the finite perturbation method. They draw the conclusion that for large amplitude perturbation, the higher power of stiffness coefficients can obtain more accurate representation of nonlinear oil-film forces. Chu et al. [20] calculated bearing linear and nonlinear dynamic coefficients by using the quasi-static nonlinear dynamic model and also estimated the applicable range of higher-order dynamic coefficients by examples. They pointed out that the nonlinear model of oil-film forces can more precisely reflect the dynamic behaviors of rotor systems than linear model when the vibration amplitude of journal exceeds ±6% of the minimum oil-film thickness. Meruane and Pascual [21] defined the dynamic oil-film forces as the three-order Taylor functions of journal perturbation displacements and velocities. The bearing nonlinear dynamic coefficients are calculated by means of a least mean square method according to the moving orbit of journal under a known external excitation force. The all research results indicate that the nonlinear oil-film forces represented by higher-order nonlinear dynamic coefficients are more close to the actual values. However, the above solving methods of bearing nonlinear dynamic coefficients are closely related with the perturbation displacements and velocities of journal and also have not universal applicability.

In Ref. [22], with assumption of small perturbation, authors presented a computational method of bearing nonlinear dynamic coefficients by extending the partial derivative method [23] to the second-order approximate extent. Firstly, in order to verify the reliability of the method, the linear dynamic coefficients of a two-axial-groove bearing are calculated and compared with the results of published paper. Then, the effects of eccentricity ratios and length-to-diameter ratios on the dynamic coefficients of a simple oil-lubricated 360° journal bearing model are mainly discussed. Finally, the representation forms of nonlinear oil-film forces are given and used to analyze dynamic behaviors of a symmetrical flexible rotor system.

Firstly, this paper briefly describes the computational methods of linear and second-order nonlinear dynamic coefficients of finite-long and infinite-short bearing. Secondly, by using the nonlinear approximate oil-film forces to analyze the nonlinear dynamic performances of rotor system supported by plain journal bearings, the effects of mass eccentricity are mainly investigated. Furthermore, the numerical method is validated by comparing the numerical results with those obtained by using the infinite-short bearing model. This paper provides a more universal approximation method of bearing nonlinear dynamic fluid-film forces to perfect the nonlinear dynamic analysis of rotor system.

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