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Nonlinear coupled dynamics of an asymmetric double-disc rotor-bearing system under rub-impact and oil-film forces

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ABSTRACT

The nonlinear dynamic behavior of an asymmetric double-disc rotor-bearing system with interaction between rub-impact and oil-film forces is addressed in this paper. Using dynamics theory, the mathematical model of an asymmetric double-disc rotor-bearing system is established, considering nonlinear oil-film force and rub-impact force. The nonlinear oil-film force model is presented in Reynolds equation, and the rub-impact is assumed with a Hertz contact and a Coulomb friction. The dynamic equations with coupled rub-impact and oil-film forces are numerically solved using the Runge–Kutta method. Bifurcation diagrams, largest Lyapunov exponent, Poincaré maps, and three-dimension spectral plots are employed to analyze the dynamic behavior of the system. The sub-harmonic, multiple periodic, quasi-periodic and chaotic motions are observed in this study. A special phenomenon is occurring that the motion of system becomes simple and the oil-whirl is restrained or even removed with an increasing imbalance by magnifying the eccentricity. Another special phenomenon is also occurring that the oil-whirl gets diminished or even disappeared with increasing stator stiffness, but the oil-whip is uninfluenced. The discoveries will have a considerable value as diagnostic tools in settling oil-film instability. The numerical results show that the nonlinear dynamic behavior of the system varies with the rotational speed and model parameters.

1. Introduction

Rotating machineries are the key equipments that are used in diverse engineering fields. The stability of bearing-rotor system is a very important issue for design, manufacturing, and operation of rotating machinery. The instability of bearing-rotor system will result in strong vibration and even disastrous accident of machinery. For decades the researches indicate that the 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. The rub-impact is one of the common nonlinear faults in rotor systems, and can bring a serious hazard to machines. Under many circumstances, the rub-impact usually results from excessive vibration caused by other faults in practical rotor systems, such as imbalance, rotor crack, and oil-film instability. The rotor-bearing model takes the nonlinear oil-force into account but the other fault such as rub impact force may be neglected. In modern industry, the machinery is becoming more and more precise with the increasing development of science

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Nomenclature

σ	Somerfield revision number
R	radius of bearing (m)
c	bearing radial clearance (m)
f	friction coefficient
μ	lubricating oil viscosity (Pa · s)
δ.	clearance between rotor and stator
K_c	stator stiffness
L	length of bearing (m)
D	bearing diameter (m)
E	Young's modulus (Pa)
l_1	length of the first axis (m)
l_2	length of the second axis (m)
l_3	length of the third axis (m)
m_1 m_4	mass of bearings (kg)
m_2 m_3	mass of discs (kg)
$[M]$	mass matrix of the system
$[C]$	damping matrix of the system
$[K]$	stiffness matrix of the system
c_i	damping coefficient ($N \cdot s \cdot m^{-1}$)
I_i	section inertia of axis (m^4)
$[F_o]$	plural oil-film force matrix
$[F_p]$	plural rub-impact force matrix
$[F_g]$	plural gravity matrix
b_2 b_2	the mass eccentricity of discs (mm)

and technology. The faults of these machineries are also becoming complicated, and the multiple or coupled faults often occur at the same time. So the dynamic behaviors of the bearing-rotor should be studied considering rub-impact and oil-film forces.

There are a lot of researches in analyzing the nonlinear dynamic of rotor-bearing system. Ehrich [1] studied about the bifurcation of a bearing-rotor system identifying a subharmonic vibration phenomenon in a rotor dynamic system. Diken [2] presented the non-linear vibration analysis and subharmonic whirl frequencies of the Jeffcott rotor mode. Wang et al. [3] analyzed the nonlinear dynamic of a flexible rotor supported by externally pressurized porous gas journal bearings. They demonstrated periodic and quasi-periodic response of journal and rotor center. Whirl and whip instabilities were studied in rotor-bearing system considering a nonlinear force model [4]. The motion equations have been established for symmetrical single-disk flexible rotor-bearing system, and nonlinear oil-film forces of finite journal bearings are calculated [5]. The motion stability of the flexible rotor-bearing system was analyzed with two unbalanced disks [6]. Experiment was observed on fault detection for a direct coupled rotor-bearing system [7]. The non-linear dynamic behaviors of a rotor-bearing coupled system were reported in simulation and experiment [8]. Study of start-up vibration response for oil whirl, oil whip and dry whip was presented in [9]. These researches demonstrated that it is important to study the nonlinear dynamic of rotor-bearing, but the continue work is necessary to be developed, in which the analysis should be made taking into account the dynamic behavior of a rotating system under the oil whirl and oil whip phenomenon, considering the influence of unbalance, model parameters and other fault forces.

The dynamics of rotor to stator contact-dynamics have been studied extensively in the past by many researches. Muszynska [10] presented a comprehensive literary survey on rub-related phenomena. In the 90s a great deal of work treated the nonlinear analysis on rotor to stator contact dynamics. Studies on these rubbing phenomena revealed that the rotating system showed a rich class of nonlinear related dynamics such as sub and super-synchronous responses, quasi-periodic responses and even chaotic motions. Goldman and Muszynska [11] reported that the chaotic motion in a nonlinear study is more likely to occur if a proper impact model is employed. Chu and Zhang [12] investigated the nonlinear vibration characteristics of a rub-impact Jeffcott rotor. They also found that when the rotating speed is increased, the grazing bifurcation, the quasi-periodic motion and chaotic motion occur after the rub-impact. Issam [13] used numerical analysis and evolutionary algorithms to analyze the nonlinear dynamics of a rotor with rub-impact. Chaos and bifurcation of a flexible rub-impact rotor were reported, and the rotor was supported by oil film bearings with nonlinear suspension [14]. Lahriri [15-16] conducted the experimental quantification of contact forces and theoretical analysis of rub-impact rotor-bearing system. The study [17] performed a dynamic analysis of the rub-impact rotor supported by two couple stress fluid film journal bearings, and the strong nonlinear couple stress fluid film force, nonlinear rub-impact force and nonlinear suspension (hard spring) are presented and coupled together.

Of the existing work, some researches [17-19] have thrown light to nonlinear coupled or interaction dynamics considering different forces or different influences, but little research has been carried out on nonlinear coupled dynamics of an asymmetric double-disc rotor-bearing system considering rub-impact and oil-film forces. The studies on interaction of rub-impact and oil-film instability are still not enough either in numerical analysis or in experimental results. Thus, some new attempt will be