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Research Article

Active magnetic bearings used as exciters for rolling element bearing outer race defect diagnosis

Yuanping Xu [a], Long Di [b], Jin Zhou [a,*], Chaowu Jin [a], Qintao Guo [a]

[a] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] Rotating Machinery and Control Laboratory (ROMAC), University of Virginia, Charlottesville, VA 22904-4743, USA

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ABSTRACT

The active health monitoring of rotordynamic systems in the presence of bearing outer race defect is considered in this paper. The shaft is assumed to be supported by conventional mechanical bearings and an active magnetic bearing (AMB) is used in the mid of the shaft location as an exciter to apply electromagnetic force to the system. We investigate a nonlinear bearing-pedestal system model with the outer race defect under the electromagnetic force. The nonlinear differential equations are integrated using the fourth-order Runge–Kutta algorithm. The simulation and experimental results show that the characteristic signal of outer race incipient defect is significantly amplified under the electromagnetic force through the AMBs, which is helpful to improve the diagnosis accuracy of rolling element bearing's incipient outer race defect.

1. Introduction

Rolling element bearing is one of the most common components in the rotating machinery. Its health condition directly determines the performance of the rotating machinery. Defects in bearings may arise during operation or during the manufacturing process, which will cause vibration, noise, and even system failure. Therefore, it is important to detect the defects in bearings at their incipient stage to prevent the catastrophic damage or failures to the rotating machine.

Different monitoring methods are used in industry to prevent machinery failures caused by the rolling element bearing defect. These methods can be classified as vibration measurement, acoustic measurement, temperature measurement and wear analysis [1]. Vibration based condition monitoring has been the most widely used method in the monitoring application since a local defect produces successive impulses at every contact of defect and the rolling element, and the housing structure is forced to vibrate at its natural modes. The vibration pattern of a damaged bearing includes the low-frequency components related to the impacts of the defect and the high-frequency components excited by the impacts when a rolling element passes over defected area [2].

A lot of researches have been accomplished and many methods have been created to model the vibration response of a bearing. McFadden and Smith [3,4] analyzed a theoretical model of the rolling element bearing with single and multiple point defects, where the vibration induced by bearing defects were modeled as a series of impulses when the rolling elements pass the point defect area. The frequency of the impulse is related to the rotating speed and the defect location. Wang and Harrap [5] presented the envelope autocorrelation analysis for diagnosing multiple element defects of rolling element bearings. Tandon and Choudhury [6] presented an analytical model and obtained the dynamic response of the rings due to localized defects on the outer race, the inner race and one rolling element under an axial load. A mathematical two degrees of freedom (DOF) bearing dynamic model for the orthogonal inner race was proposed by Sunnersjo [7], who applied Hertz contact theory to calculate the deflection. Feng [8] developed a 4 DOF bearing-pedestal dynamic model, including 2 DOF pedestal model. The model considered the slippage in the rolling elements, the effect of the rotor unbalance and the possibility of introducing a localized fault in the inner and outer races. Tadina [9] developed an improved bearing model in order to investigate the vibrations of a rolling element bearing during run-up. The numerical bearing model was developed with the assumptions that the inner race had 2 DOF and the outer race was deformable

* Corresponding author. Tel.: +86 25 84892905.
E-mail addresses: ypxu@nuaa.edu.cn (Y. Xu), ld4vv@virginia.edu (L. Di), zhj@nuaa.edu.cn (J. Zhou), jinchaowu@nuaa.edu.cn (C. Jin), guo_qintao@nuaa.edu.cn (Q. Guo).

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in the radial direction, and was modeled with finite elements. The simulated vibration response of rolling element bearings with different local faults was realized using this model.

Although several literatures tried to model the vibration response under defected bearing condition during the bearing incipient faulty stage, it is difficult to extract the defect characteristic signal because the defect itself is not significant and the weak fault signal is interfered with random noise and vibration caused by other moving components. More importantly, even a perfect bearing generates varying compliance (VC) vibrations due to the time-varying distribution of the rolling elements relative to the inner and outer races, which is equivalent to the outer race defect frequency Ball Pass Frequency Outer (BPFO, which is the frequency created when all the rolling elements roll across a defect in the outer race) for a rolling element bearing with zero contact angle and it becomes more difficult to detect the incipient outer race defect [9].

Active magnetic bearings are mainly used to provide supporting forces, but they can be used as exciters and sensors [10]. As exciters, the amplitude and frequency can be easily altered. Knopf [12] used the AMBs to identify the rotor-dynamic coefficients of a turbulent journal bearing. Humphris [13] utilized AMBs as both support and perturbation for the shaft, for the purpose of monitoring and diagnosing machine health condition. Kasarda [14] proposed a method using AMBs for the non-destructive evaluation of manufacturing process. Lyu et al. [11] used AMBs as exciters to emulate the gyroscopic effect of an energy storage flywheel. Zhu et al. [15] studied the dynamics characteristics of a rotor with crack supporting by AMBs and found that crack could significantly change the vibration characteristics of the system and make the control design and analysis more complex. Mani et al. [16,18] and Quinn et al. [17] applied excitation from the AMB to a cracked rotor bearing system and used multiple scale method to diagnose the rotor crack. Similarly, Sawicki [19] applied harmonic balance method based on sinusoidal excitation generated from AMBs for analyzing, which was validated by simulated and experimental results. Chasalevris [20] investigated the response of an experimental system consisting of a simple elastic rotor supported by two fluid-film bearings, while one of the bearings was worn under the AMB transient excitation.

Although many researchers have investigated the vibration characteristics and bearing fault identification of rolling element bearings due to local defects and AMBs have been used to detect faults, few studies have been reported on analyzing vibration due to local defects under the electromagnetic force. Based on the model in [8], this paper develops a bearing-pedestal model with outer race defect. Taking SKF 61901 bearing as an example, we analyze the characteristics of outer race defect frequency BPFO signal under the electromagnetic force using AMBs and obtain the simulation and experimental result, which shows that the vibration characteristics BPFO signal will be amplified dramatically under the electromagnetic force.

The remainder of the paper is organized as follows. Section 2 presents the model of rolling element bearing with outer race defect and the equation of motion under AMB force. Section 3 describes the simulation results. Section 4 presents the experimental results. Conclusions are drawn in Section 5.

2. Rolling element bearing modeling

2.1. Contact force

For a rolling element bearing, the main components include the outer race, the inner race, the cage and the rolling elements. The important geometrical parameters are the number of rolling elements N, the element diameter d_b, the pitch diameter D, the radial clearance r_0 between rolling elements and bearing races and the contact angle α. Fig. 1 represents the rolling element bearing schematic under vertical load distribution.

The bearing was modeled with two DOF and the two orthogonal DOF are related to the inner race of the rotor. The outer race is fixed in the pedestal and the slippage of rolling elements, the mass and the inertia of the rolling elements are ignored. The displacement of the shaft can be divided into x and y directions and the contact deformation for the ith rolling element δ_i is given by

$$\delta_i = x\cos\theta_i + y\sin\theta_i - r_0. \tag{1}$$

The angle of the rolling element θ_i shown in Fig. 1 is given as

$$\theta_i = \omega_c t + \frac{2\pi}{N}(i-1), \tag{2}$$

$$\omega_c = \frac{\omega_s r}{(R+r)}, \tag{3}$$

where ω_s is the shaft rotating speed in rad/s, equivalent to the inner race speed; ω_c is the cage speed and it can be calculated from bearing geometry and the shaft speed ω_s assuming there is

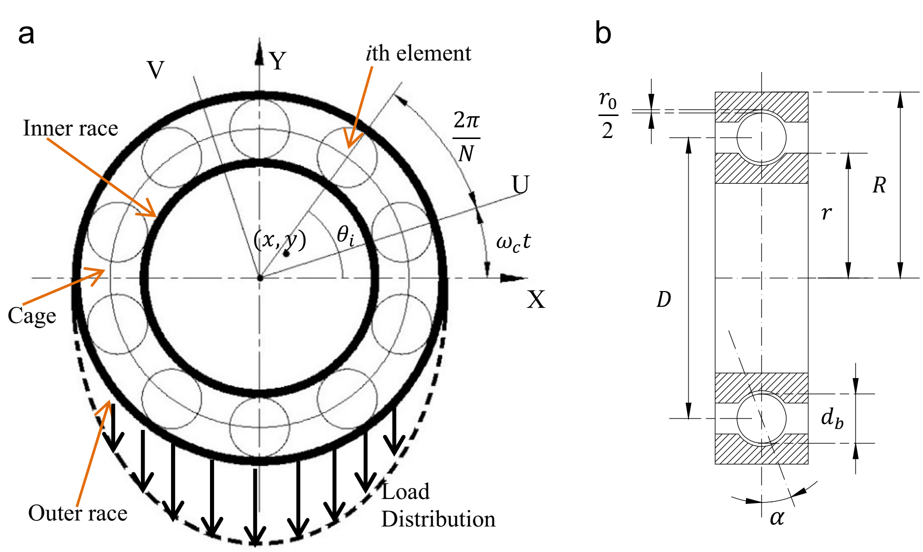

Fig. 1. Schematic of a rolling element bearing.