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A theoretical study on vibrations of a ball bearing caused by a dent on the races

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ABSTRACT

Dents are commonly localized defects in ball bearings (BABEs), which are also the primary cause of material surface level fatigue failure for the BABEs. A new dynamic model for BABEs with a dent on its race is proposed to investigate the effect of the dent on vibrations of the BABE in this work. The proposed model can consider the effect of the shoulder of the dent on vibrations of a BABE, which cannot be described by the previous dent models without considering the effect of the shoulder in the literature. The time-varying contact force caused by the dent with the shoulder is formulated in the proposed model. Based on the simulation and experimental results in the previous works, the profiles of the dent and its shoulder are considered as a sinusoidal and an exponential function shapes, respectively. The simulation results from the proposed model and previous dent model in the literature are compared. Effects of sizes of the dent on the vibrations of the BABE are discussed. The results show that a dent with the shoulder on the races of a BABE can significantly affect vibration characteristics of the bearing. It seems that the proposed method can provide a new method for dynamic formulation of a BABE considering a dent with the shoulder. Moreover, this study gives a more close to real impulse characteristics caused by a practical dent compared to the previous dent models without the shoulder.

1. Introduction

Dents are commonly localized defects (LOCDs) in BABEs, which usually occur due to spalls and/or material deformation caused by debris [1]. They are also the primary cause of surface level fatigue failure for the BABEs. It is well known that a dent that occurs on the surface of the inner or outer race of the BABE will produce an impulse excitation when the ball passes through the dent. Vibrations of the BABE system will be significantly affected by the impulse excitations caused by the dents. Furthermore, the dents may cause catastrophic failures in the bearing systems. Therefore, the detection and diagnosis methods for a dent in the BABEs are very useful to prevent catastrophic failures of machinery system.

Several methods have been presented to detect and diagnose rolling element bearing (REB) defects, such as use of vibration and acoustic measurements, temperature measurement, and wear debris analysis [1]. One of the most widely used methods is the use of vibration analysis [2–8], which can provide some guidance to defect detection and diagnosis in REBs. For instance, Ashtekar et al. [1,9] used a dry contact elastic model and superposition principle method to study the effects of a dent or bump on the vibrations of a BABE, respectively. Li and Kang [10] presented a three dimensional vibration model of a tapered roller bearing according to an in-house dynamic bearing model to analyze the effect of a LOCD on its vibrations. Tandon and Choudhury [11] studied the vibrations of

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a REB and rotor-bearing system with a LOCD using a triangular, rectangular, and half-sine force excitation models. Kiral and Karagulle [12] presented a finite element model to study the vibrations of a REB with a LOCD using a rectangular force excitation model. Sassi et al. [13] developed a numerical model to analyze the vibrations of a BABE with a LOCD using a sinusoidal and rectangular force excitation models. Behzad et al. [14] proposed a dynamic model to investigate the vibrations of a REB with a LOCD using a stochastic force excitation model.

Sopanen and Mikola [15], Arslan and Aktürk [16], Nakhaeinejad and Bryant [17], Ghafari et al. [18], Kankar et al. [19], and Liu and Shao [20] studied the vibrations of a REB with a LOCD using a rectangular displacement excitation model. Patil et al. [21] proposed a theoretical model to analyze the vibrations of a BABE with a LOCD using a half-sine displacement excitation model. Liu et al. [22,23] proposed a dynamic model to analyze the vibrations a REB with a LOCD using a piecewise function model. Singh et al. [24] developed a finite element model to simulate the contact forces and vibrations of a REB with a LOCD. Niu et al. [25,26] presented a dynamic model to formulate the vibrations of a BABE with a LOCD with a circular shape. Ahmadi et al. [27] established a dynamic model to study the vibrations of a REB with a LOCD. Wang et al. [28] proposed a dynamic model to analyze the vibrations of a cylindrical roller bearing with a LOCD on its races. Khanam et al. [29] proposed a method based on the principles of engineering mechanics to formulate the vibrations of a BABE with a LOCD.

Most of the above research works were focused on modeling of a LOCD such as spalls and pits on the races of the REB. Refs. [1,9,10] formulated the effect of a dent on the vibrations of the REB. However, the effect of the shoulder of the dent was not considered in their dynamic models. In practice, the shoulder of the dent plays a dominant role in causing vibrations of the BABE [10]. To address this gap, a new dynamic model for a BABE with a dent on its race is proposed to investigate the effect of the dent on the vibrations of the BABE in this work. Note that the proposed model can consider the effect of the shoulder of the dent on the vibrations of the BABE, which cannot be described by the previous analytical dent models without considering the effect of the shoulder in the literature. The time-varying contact force produced by the dent with the shoulder is considered in the proposed model. Based on the simulation and experimental results in the previous works [10,30], the profiles of the dent and its shoulder are considered as a sinusoidal and an exponential function shapes, respectively. The time- and frequency-domain of the acceleration responses from the proposed model and previous dent model without considering the effect of the dent in the literature are compared. Sudden changes in the time-domain acceleration response of the BABE caused by the shoulder of the dent are observed, which cannot be captured by the previous dent models in the literature. Effects of sizes of the dent on the vibrations of the BABE are also discussed.

The present paper is organized as follows. The problem description of the dynamic modeling for a dent without and with the shoulder in a BABE is given in Section 2. The description of a theoretical formulation of the dynamic model for a dent with the shoulder in a BABE is described in Section 3. Effects of sizes of a dent on vibrations of a BABE are discussed in Section 4. Finally, concluding remarks are given in Section 5.

2. Problem description

In this work, the effect of the shoulder of the dent on the vibrations of the BABE is considered, which is not formulated in the previous dent models. According to the analysis in Refs. [10,30], the profiles of the dent and its shoulder are considered having a sinusoidal and an exponential function shape and defined by determined by the depth, diameter, shoulder depth, shoulder slope, shoulder location of the dent, as shown in Fig. 1. In Fig. 1, O is the center of the inner race or outer race of the BABE, and O_b is the center of the ball of the BABE. The other parameters of the dent as shown in Fig. 1 will be described as follows.

It is well known that a dent that occurs on the surface of the races of the BABE will produce an impulse excitation when the ball passes through the dent. A practical dent presented by Ref. [10] is shown in Fig. 1a. As shown in Fig. 1, the ball will be in contact with the different positions of the dent when the ball passes through the dent. It can produce different bearing vibration characteristics. As shown in Fig. 1(b) and (d), for the dent with the shoulder, the ball will be in contact with the shoulder when the ball enters and exits the dent, which will also cause impulse excitations. These impulse excitations cannot be formulated by the previous dent models without the shoulder. This work can address this gap. Here, the effect of the shoulder of the dent on the vibrations of the BABE will be formulated in the proposed model.

3. Theoretical formulation description

In this work, the BABE is formulated as a lumped spring-mass system as shown in Fig. 2. The inner race of the bearing is connected rigidly with the shaft. The outer race of the bearing is held in a rigid housing. A fixed radial load and rotational speed are applied on the bearing. The pure rolling contact between the balls and races are assumed. The slipping between the bearing components is ignored. The nonlinear relation load-deformation is considered based on Hertzian contact theory.

3.1. Modeling of the shape function of the dent

According to the calculation results in Ref. [30] and experimental results in Ref. [31], the shape function of the dent on the races of a BABE can be described as