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Analysis of varying contact angles and load distributions in defective angular contact ball bearing

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ABSTRACT

Angular contact ball bearing (ACBB) is widely used in rotating machinery for its great external load capacity. The operating condition of ACBB is easily affected by surrounding mechanical components. The variations of contact angles and load distributions can sufficiently reflect the operating condition of ACBB. A localized defect on the raceway will lead to the dramatic change of contact angle and load distribution of ACBB. In this paper, a mechanical model of ACBB with a localized defect on outer raceway is established, in which the effects of centrifugal force and gyroscopic moment on the force equilibrium relation of balls in high speed operating condition are considered. The proposed model is verified by comparing with the existing model in literature. On the basis of the proposed bearing model, the effects of some parameters on the variations of contact angles and load distributions are investigated. The results show that as the operating speed increases, the centrifugal forces of balls increase and the balls are gradually moving towards outer raceway, which results in that the load distributions between balls and outer raceway are much larger than those between balls and inner raceway. In view of the combined external forces and moments acted on the bearing, the variations of contact angles and load distributions become more complicated than those under the single force or moment applied condition. With the increase of the circumferential extent of localized defect, abrupt changes of contact angles and load distributions in defect area increase obviously.

1. Introduction

Ball bearings are widely adopted in rotating machines such as the reduction gearbox of rolling mill drivetrains [1–3], and they are the most critical but vulnerable supporting components. The operating state of bearing is of vital importance on precise, reliability and life of the whole mechanical system [4,5]. Angular contact ball bearings (ACBBs) are widely used among all types of ball bearing, since it could bear the enormous external load in both axial and radial directions. A bearing failure can lead to significant changes in contact angles and load distributions of ACBB. Therefore, analysis of varying contact angles and load distributions of defective ACBB are essential to reflect the failure mechanism of bearing and prevent the deterioration of bearing failure.

Failure modes in ball bearings can be mainly classified into two broad categories, which are distributed defect and localized defect, respectively [6,7]. The distributed defects in bearings are caused by the error of bearing manufacturing process and the misalignment of bearing installation process, which are typically manifested as the surface roughness, waviness and off-size balls

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[8–10], etc. The localized defects in bearings are inevitably related to the occurrence of corrosion and wear in bearing operation process, which are generally characterized as sub-surface cracks, dent, pitting and spalling [11–14], etc. Generally, when a localized defect occurred on bearing raceway, the stiffness and contact characteristics will change rapidly [15]. In combination with balls striking the localized defect area, periodic impulses will appear in the vibration response of defective bearing [16]. In recent years, researches on dynamic modelling of defective bearing have gained more and more attentions [17–20]. Yuan et al. [18] established a dynamic model of a bearing-rotor system to discuss the effects of single and compound multi-defects on vibration response. Patil et al. [19] proposed an analytical model of bearing by modelling the localized defect in raceway as a part of sinusoidal wave. A piecewise function related to the ratio of ball size to defect size was adopted by Liu et al. [20] to accurately reflect the morphology of localized defect area. The localized defect areas in above mentioned literatures are commonly viewed as a displacement excitation, which is invariant with the change of operating speed, pre-load, etc. However, the defect edge shapes are greatly influenced by the variations of operating speeds and pre-load conditions. The contact deformation at the defect edge cannot be neglected in reality. To address this issue, Ahmadi et al. [21] made an improvement on the nonlinear dynamic modelling proposed by Harsha et al. [22] with considering the time-varying plastic deformation when balls were passing over the rectangular shape defect area. Liu et al. [23–25] presented a series of dynamic modelling methods for defective roller bearing and angle contact ball bearing with considering the contact deformations at different defect edges.

Most of the above researches were focused on dynamic modelling for defective bearing and analyzing the vibration response of defective bearing in comparison with that of healthy bearing. However, the effects of localized defect on contact characteristics, i.e., contact angles and contact forces between balls and inner/outer raceways, were not mentioned. Petersen et al. [26] presented an analytical formulation method to investigate the effect of defect size on load distribution of defective ACBB. Following this research work, they [15] also proposed a dynamic modelling to analyze the static contact forces of double row bearings with a raceway localized defect of varying depth, length, and surface roughness. Cui et al. [27] proposed an analytical method to realize the quantitative and localization diagnosis of a ball bearing outer raceway defect, in which the static load distributions of faulty bearing were analyzed. Liu et al. [28] proposed a dynamic modelling of cylindrical roller bearing with considering the time-varying deflection excitation and time-varying contact stiffness excitation caused by localized defect, in which the effects of defect sizes and locations on the contact forces were analyzed. Above researches for dynamic simulation of rolling bearings are helpful to understand the contact characteristic of defective bearing. However, what the drawback lies in those researches was that the effects of some parameters, i.e., rotational speed, centrifugal force, gyroscopic moment, external force and moment, on the operation condition of bearing were not considered.

Jones developed a complete mechanics model of ACBB in 1960 [29]. As one of the most famous and reprehensive quasi-static models, the inner race owns five degrees of freedom, including three translational displacements and two rotational deflections. Correspondingly, there also existed three external forces and two external moments in Jones' model. The centrifugal force and gyroscopic moment at high operating speed are also considered. Based on Jones' bearing model, a large number of researches have been conducted [30–32]. Wang et al. [30] developed a mechanics model of ACBB without raceway control hypothesis, in which the gyroscopic moments of balls were assumed to be entirely resisted by frictional forces between balls and inner/outer raceways. Zhang et al. [31] proposed a dynamic modelling of bearing rotor system to investigate the variations of the bearing contact angles in bearing rotor system thoroughly. In his study, the contact angle of the bearing was represented by the simplified Jones' bearing model. Sheng et al. [32] proposed an analytical method to study the variation rules of bearing stiffness under varying operating speed condition. In his calculation method, the differentiation of implicit function was used to deal with the mathematical relations between the input of displacement vector and the output of external load vector in Jones' model.

Though the researches mentioned above are helpful to understand the kinematics characteristic of ACBB, the mechanics models adopted by them are built for healthy ACBB. Some researches considered the effect of localized defect on contact characteristics. However, the effects of centrifugal force and gyroscopic moment were not considered in their dynamic models. To address those problems, a new mechanics model of ACBB with considering the localized defect on outer raceway is proposed in this study. The proposed mechanics model is an improvement of Jones' model and the effects of some parameters, i.e., rotational speed, centrifugal force, gyroscopic moment, external force and moment, circumferential extent of localized defect on the operating condition of bearing are adequately considered.

The rest of the paper is organized as follows: Section 2 elaborates the mechanics model of ACBB with a localized defect occurred on the outer raceway. Section 3 verifies the proposed model and depicts the effects of some influence factors, i.e., operating speed, external axial load, combined external load and circumferential extents of localized defect on varying contact angles and load distributions of defective bearing. Section 4 summarizes the main outcomes and findings from this study.

2. Mechanics model of defective ACBB

Jones' model mainly consists of three parts, i.e., the geometrical constraint equations of balls, the force equilibrium equations of balls and the force equilibrium equation of inner raceway. In his model, it is able to consider the varying contact angles and load distributions between balls and inner/outer raceways, especially at high operating speed [29]. However, when a localized defect occurred on the raceway, the contact angles and the load distributions between balls and raceways will change obviously. Analysis of varying contact angles and load distributions of bearing is helpful to draft relevant scheme and prevent the further deterioration of bearing failure. Thus, a mechanics model of defective ACBB is presented by introducing the depth profile function of localized defect into Jones' model. Firstly, the kinematics equations of bearing and the depth profile function at localized defect area are presented in Section 2.1. Then, the depth profile function of localized defect is introduced into the geometrical constraint equations of balls in