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Effect of preload on ball-raceway contact state and fatigue life of angular contact ball bearing

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ABSTRACT

The performance of angular contact ball bearing is greatly affected by the preload. In the present research, by analyzing the state of ball-raceway contact, a quasi-dynamic model is proposed to study the load distribution of ball bearing under arbitrary preloads. The new model is then used to study the influences of external loads, rotating speed and preload on ball-raceway contact state. Based on this, the fatigue life of ball bearing under running condition is calculated. The results show that a proper preload improves the load distribution and extends the fatigue life of ball bearings. For any given load and rotating speed, an optimum preload, estimated through the bearing life, can be obtained.

1. Introduction

Angular contact ball bearing is widely used in rotating machinery systems for its high reliability and low power consumption. With the ever-increasing demands on bearing performance, accurate models of the rolling bearing are becoming more and more important, especially for bearing at high running speed for which the centrifugal force and gyroscopic moment of balls cannot be neglected. With the influence of the inertial loads, the position of the ball center and ball-raceway contact state (contact or separation) change remarkably, influencing the service characteristics of bearing, such as load distribution, stiffness, life, and so on.

Over the past decades, many researchers have conducted numerous studies on the bearing dynamic performance when it is subjected to a combined loads (axial, radial or moment). Based on the Hertz contact theory and the Raceway Control Hypothesis, Jones [1] and Harris [2] proposed a classical analysis model of ball bearing, which is still widely used in bearing simulation. Liao [3] proposed a new method for the analysis of displacement and load in a ball bearing with variable contact angle. Wang [4] developed a new model for ball bearing calculation, and this model discarded the Raceway Control Hypothesis.

Ball bearing often requires a small internal clearance to accommodate interference fits and thermal strain. And the internal clearance has a great impact on the fatigue life, vibration, noise and temperature rise of ball bearing. A great number of studies about the nonlinear vibrations of ball bearing with internal clearance have been reported. For instance, Yamamoto [5] proposed an analytical model to study the vibrations of a vertical rotor supported by ball bearings with radial clearance. Tiwari [6] et al. studied theoretically and experimentally the dynamic nonlinear response of a balanced and an unbalanced rotor supported on ball bearings due to the effect of internal clearance. Harsha [7] presented a model for investigating structural vibrations in bearings due to internal clearance. Lioulios and Antoniadis [8] proposed a dynamic model for a horizontal rotor by considering the effect of varying compliance and the internal clearance.

The above-mentioned researches mainly focus on deep groove ball bearing, therefore no axial load is considered. But for angular contact ball bearing, in order to improve the bearing performance, an initial preload is always needed and a negative clearance is generated by the contact deformation between ball and raceway. However, when the external loads are large or the preload is small, some balls are separated from the raceway and clearance turns to be positive. The phenomenon of ball-raceway separation of angular contact ball bearing has been neglected in previous researches. Stribeck [9] first investigated the load distribution for the radially loaded ball bearing with different clearances. Based on the Stribeck research, Sjov äll [10] studied the load distribution and ball-raceway contact state of ball bearing under given external radial and axial preload. These researches are based on the static analysis and the centrifugal force and gyroscopic moment of balls are neglected.

Proper preload of angular contact ball bearing is notably important for the stiffness, rotating accuracy, temperature rise and fatigue life of bearing-rotor system [11–14], and many researches on the determination of the optimum preload of rolling bearing have been reported.

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Nomenclature

α^o	Bearing initial contact angel, rad
P_d	Bearing internal radial clearance, mm
B	$B=f_i+f_o$-1
F_p	Bearing initial preload, N
δ_a,δ_r,θ	The relative displacement of the inner and outer rings, mm
δ_i,δ_o	Ball-inner raceway and ball-outer raceway contact deformations, mm
δ_n	$\delta_n = \delta_i + \delta_o$, mm
ψ	Ball angular position, rad
$\Re_i$	$\Re_i = d_m/2 + (r_i - 0.5D)cos\alpha^o$, mm
F_r, M	Externally applied radial load and moment load, N (N.mm)
d_m	Bearing pitch diameter, mm
K_n	Normal deflection constant
f_i, f_o	$f_i = r_i/D$, $f_o = r_o/D$
r_i, r_o	Bearing inner and outer raceway groove curvature radius, mm
D	Ball diameter
Z	Ball number
A_1, A_2	The distances between the inner and outer raceway groove curvature centers, mm
X_1, X_2	Auxiliary variables, mm
Q_i, Q_o	Ball-inner raceway and ball-outer raceway contact forces, N
T_i, T_o	Ball-inner raceway and ball-outer raceway friction forces, N
F_c, M_g	Ball centrifugal force and gyroscopic moment, N (N.mm)
α_i,α_o	Ball-inner raceway and ball-outer raceway contact angles, rad
m, J	Ball mass and mass moment of inertia
ω_i,ω_m,ω_b	Bearing inner ring, cage revolution and ball spin angular speed, rad/s
β	Ball pitch angle, rad
γ	D/d_m
C	Basic dynamic load rating
L_{10}	Bearing fatigue life
i, o	Subscripts: i refer to inner contact and o refer to outer contact
k	Subscripts: k refer to the kth ball
$\overline{O_oO_i'}$	The distance between points O_o and O'_i, mm
$\overline{O_oO_i}$	The distance between points O_o and O_i, mm
$\overline{O_oO_d'}$	The distance between points O_o and O'_d, mm
$\overline{PO_d'}$	The distance between points P and O'_d, mm
$\overline{PO_i'}$	The distance between points P and O'_i, mm

Hagiu [15] has studied the optimum preload for a spindle supported by a pair of ball bearings, and the relation between the preload and service life was studied by means of a static model. Jiang [16] presented a method to determine the variable preload of machine tool spindle at the entire speed range, and a variable preload spindle has been developed using hydraulic pressure. Xu [17] proposed a preload analytical method that accurately determines the optimum preload for different speed ranges.

By summarizing of the above-mentioned studies, the fatigue life of rolling bearing is of great important for determining the optimal preload. According to the fatigue life theory proposed by Lundberg and Palmgren [18], the load size and distribution on bearing play an important role in bearing life. The preload can modify the load size and distribution on bearing which are initially determined by means of the external loads and rotating speed. In order to ensure higher fatigue life for rolling bearing, it is needed to analyze the relationship between the preload and fatigue life of the bearing under the running condition, especially for the ball bearing at high speed, since the load distribution and internal contact change drastically due to the effect of the inertial loads.

Therefore, this study proposes a quasi-dynamic model to analysis the load distribution and ball-raceway contact state of ball bearing under the running condition. The influence of external loads, rotating speed and preload on internal contact state of ball bearing are studied in detail, and the results from the static and quasi-dynamic models are analyzed and compared. On this basis, the fatigue life of ball bearing under different operation condition is calculated. From the results, the optimum preload can be obtained.

2. Theoretical analyses

2.1. Static model

As shown in Fig. 1, for an angular contact ball bearing at static state, the initial contact angle α^o is defined by:

$$\cos\alpha^o = 1 - \frac{P_d}{2BD} \tag{1}$$

where P_d denotes the radial clearance and BD is the distance between the centers of inner and outer raceway groove curvature, and $B=f_i+f_o$-1.

As shown in Fig. 1(b), assuming that the outer ring is fix, the internal clearance of ball bearing is eliminated by applying an initial preload F_p. When a radial load and a moment are simultaneously acting on the preloaded bearing as shown in Fig. 1(c), the inner is relatively displaced by a radial displacement δ_r and an angular rotation θ. The balls are not equally loaded as shown in Fig. 1(c). In addition, when the

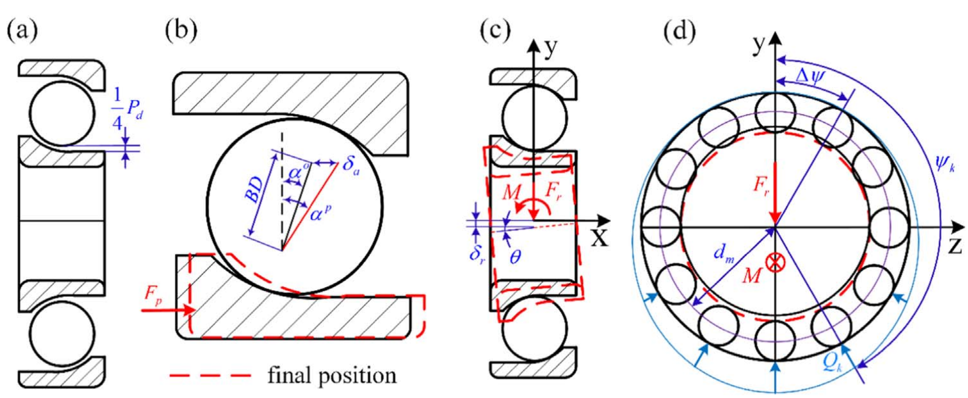

Fig. 1. Bearing load schematic: (a) free state; (b) under preload; (c) under a combined load; (d) internal load distribution.