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Effect of race conformities in angular contact ball bearing

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ABSTRACT

The determination of race conformity of ball bearing is mainly based on the classical fatigue life theory; however, besides the fatigue life, skidding may also become the main concern due to high frictional heating in high-speed application; therefore the strategy of race conformity determination should be changed accordingly. This paper investigates the influences of race conformity on the contact characteristics and motion of ball based on the developed dynamic model for angular contact ball bearings. The results show that the race conformity has a significant influence not only on the contact pressure between ball and raceways, but also on skidding of ball on raceway, which implies that the race conformity should be optimally determined according to the different applications.

1. Introduction

Angular contact ball bearing is extensively used in high-speed rotors, aero-engines, and other rotary machines to support the axial load and radial load. Skidding in rolling bearing contributes to the micro-spalling and thermal characteristics of rolling bearings, and may lead to smearing damage, all of which are the tribological issues. Elastohydrodynamic lubrication (EHL), as the main lubrication mechanism of rolling bearing, is extensively studied in the past decades, and often separated from the bearing system; however, EHL performance and bearing dynamics are affected mutually in real bearing. Therefore, the combination of lubrication analysis and bearing dynamic modeling is much desirable for both the lubrication community and bearing design.

The race conformity is one of the most important structural parameters of ball bearing, which is defined as the ratio of the race-groove curvature radius to the ball diameter in a plane passing through the bearing axis and transverse to the raceway. The race conformities significantly influence the size of contact area and therefore the resultant contact pressure between ball and raceways. The effect of race conformity on bearing life is usually considered by incorporating into the bearing geometry and material coefficient f_{cm} appeared in the formulae for the basic load capacity for ball bearings [1]. Recently, Zaretsky et al. [2] reassessed the effect of ball-race conformities on ball bearing life with considering the life of ball set, and found that for the radial loaded bearing with constant outer-race conformity of 0.52, the calculated life decreased by 81% when the inner-race conformity was varied from 52% to 57%; for constant inner-race conformity of 0.52, the calculated life decreased by 55% when the outer-race conformity was changed from 52% to 57%, and similar results were obtained for the thrust-loaded bearing; the results imply that the tight race conformities for both inner and outer race should be preferred from the aspect of fatigue life. However, the tight race conformities are prone to cause sliding velocities in contact zone that will result in severe power loss and high temperature in high-speed conditions. Gloeckner [3] experimentally investigated the influence of the race conformities on power loss and temperature of a high-speed ball bearing used in jet engine, he considered three different conformity designs: tight race conformities on both inner and outer races, tight inner race conformity but open outer conformity, and open conformities on both inner and outer races, and found that the introduction of more open conformities on both inner and outer races can significantly reduce the bearing power loss and temperature for a broad range of operating conditions, which implies that high-speed ball bearings can use more open race conformities to prevent classical subsurface fatigue and high temperature rise. It can be found that the race conformities affect the bearing performance through two ways: one is to change the size of contact zone and the value of contact pressure and therefore bearing fatigue life; the other is to change the sliding velocities and therefore bearing power loss and temperatures. Thus, the race conformities should be determined based on the consideration of not only the bearing fatigue life but also the effect of sliding on power loss and temperature in the design stage of high-speed ball bearings. To this end, the powerful dynamic model of rolling bearing should be developed to obtain the characteristics of bearing from aspects of force and kinematics.

Jones [4,5] proposed the first quasi-static model for ball

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Nomenclature

a	semi-major axis of ball-raceway contact ellipse, m
b	semi-minor axis of ball-raceway contact ellipse, m
d_m	bearing pitch diameter, m
E'	equivalent Young's modulus, Pa
D	ball diameter, m
F_a	externally applied axial load, N
N	ball number in bearing
F_{ac}	the critical applied axial load to effectively prevent skidding in bearing, N
F_r	externally applied radial load, N
F_c	ball centrifugal force, N
F_{cage}	contact force between ball and cage pillar, N
F_d	viscous drag force, N
$F^{x''}$	traction forces between ball and raceways in x'' direction, N
$F^{y''}$	traction forces between ball and raceways in y'' direction, N
f_i	the inner race conformity
f_o	the outer race conformity
h	lubricant film thickness, m
K_o	load-deformation coefficient for ball and outer raceway contact, $N/m^{1.5}$
K_i	load-deformation coefficient for ball and inner raceway contact, $N/m^{1.5}$
m	ball mass, kg
M	inner ring and shaft mass, kg
$M_{i/o}$	traction moments between ball and raceways, N m
I	rotational inertia, kg m^2
Q_i	contact force between ball and inner raceway, N
Q_o	contact force between ball and outer raceway, N
r_o	outer raceway groove curvature radius, m
r_i	inner raceway groove curvature radius, m
α_0	free contact angle, rad
α_o	ball-outer raceway contact angle, rad
α_i	ball-inner raceway contact angle, rad
ω_i	inner ring revolution speed, rad/s
ω_c	ball orbital revolution speed, rad/s
ω_m	cage orbital revolution speed, rad/s
ω_b	ball rotation speed around the axis passing its center, rad/s
$\omega_{x'}$	ball rotating angular velocity around x' axis, rad/s
$\omega_{y'}$	ball rotating angular velocity around y' axis, rad/s
$\omega_{z'}$	ball rotating angular velocity around z' axis, rad/s
ω_s	ball spinning speed on the contact path, rad/s
ΔV	speed difference between two contacting surfaces, m/s
u	mean velocity, m/s
Δ_x	displacement of the inner ring center in x direction, m
Δ_y	displacement of the inner ring center in y direction, m
Δ_z	displacement of the inner ring center in z direction, m
Δ'_{jy}	displacement of the ball center in y' direction, m
Δ'_{jz}	displacement of the ball center in z' direction, m
SRR	Slide–roll ratio, $=2(u_1-u_2)/(u_1+u_2)$
G	dimensionless viscosity parameter, $=\alpha E'$
U	dimensionless speed parameter, $=2\eta_0 u/E'R_x$
W	dimensionless load parameter, $=Q/E'R_x^2$
L	Thermal loading parameter
$\delta_{ij/oj}$	deformation between jth ball and raceways, m
η_0	lubricant viscosity at atmospheric pressure and temperature, Pa s
γ	viscosity-pressure coefficient, Pa^{-1}
ζ	viscosity-temperature coefficient, $°C^{-1}$
K_c	the lubricant thermal conductivity, J/(kg K)

bearings, but it depends on raceway control hypothesis to achieve a solution. Later Harris [6,7] developed an improved quasi-static model to predict the motions of balls in thrust-loaded angular contact ball bearings without raceway control hypothesis, and got a good agreement with the experiment data reported by Poplawski et al. [8]. The quasi-static model developed by Wang et al. [9] without the raceway control assumption can deal with the condition of combined action of radial, axial loads and the shaft tilting moment along with the consideration of the effects of centrifugal force and gyroscopic moments. Boness and Gentle [10,11] considered the cage drag, elastohydrodynamic traction forces, elastic deflection, and pocket friction of the bearing elements in detail in their quasi-static model for ball bearings, and reached a good agreement with existing experimental results. The quasi-static models are based on force equilibrium and cannot consider the time-varying transient motions, which needs a dynamic model that can consider inertial effects. Walters [12] firstly attempted to develop a dynamic analysis model of ball bearings, in which the ball motion is constrained and the ball-race contact is considered in a simplified model. Gupta [13,14] developed a dynamic model for ball bearings, which considered three-dimensional and time-varying motions of every bearing component to simulate the dynamic performance; but in his model, the variations of the slip speed along the minor axis of the contact ellipse between balls and raceways are neglected. Meeks [15,16] adopt a quasi-static model to determine the internal load distribution in ball bearings, and a dynamic formulation to analyze cage transient motion in ball bearings. Meeks' model is more suitable to simulate cage motion than to predict ball dynamics. Based on a simplified quasi-static model to determine the internal load distribution, Jain [17] established a dynamic model to analyze the ball motions for investigating the skidding phenomenon in angular contact ball bearings. Shao et al. [18] studied the skidding phenomenon when balls enter into the loaded zone of ball bearing and later extended it to include the lubricant influence [19]. Tu et al. [20] studied the skidding behavior during the acceleration process of deep-groove ball bearings by using a dynamic model; however, this model can only be applicable for deep-groove ball bearings. Recently, Wang et al. [21] proposed a dynamic model to investigate skidding in angular contact ball bearings with considering the interaction between balls and raceways, cage and lubricant, and found that the skidding in angular contact ball bearing is greatly influenced by different factors. Yan et al. [22] investigated the heat dissipation characteristic of ball bearing cage and inside cavity by numerical model based on the motions and heat generation obtained via the quasi-dynamic model of ball bearing, and found that cage parameters are significant to air–oil flow and thermal dissipation inside bearing cavity at ultra high rotation speed.

In this paper, the influence of race conformities on the internal contact characteristics and ball motions in angular contact ball bearings is investigated based on the developed dynamic model [21], which is coupled with the EHD theory at each contact spot, the strategy for optimally determining the race conformities of ball bearing is further proposed.

2. Theoretical model

Fig. 1 shows the coordinate systems used in this study and velocities of a ball. The assumptions of the mathematical model