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Thermal performances on angular contact ball bearing of high-speed spindle considering structural constraints under oil-air lubrication

Dexing Zheng[a,b,*], Weifang Chen[a]

[a] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, 210016 Nanjing, PR China
[b] School of UG, Yancheng Institute of Technology, 224051 Yancheng, PR China

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ABSTRACT

To predict thermal behaviors of high-speed angular contact ball bearings is essential for operating precision. Particularly, the characteristics of high-speed angular contact ball bearings depend on their thermal performances. However, most researchers only considered the convection effect between housings and ambient air, whereas the coolant/lubricant and specific structural constraints effect were not integrated. In this investigation, the load equilibrium model of angular contact ball bearings with thermal expansion was first established to calculate bearing loads. The coolant/lubricant, radial and axial structural constraints and assembly constraints were fully taken into account to study the heat generation and transfer of bearings, and then a novel muti-node thermal network model for angular contact ball bearings was proposed. Applying this muti-node model, an integrated comprehensive thermal grid model for the front bearing of high-speed spindle and its surroundings was established to forecast the bearing temperature. Next Euler's method was employed to solve the equations by *Matlab* and the node temperature was calculated. Finally, the bearing temperature rise was tested and the comparative analysis was made with the numerical results. The results indicate that both series of results agree well. So, the thermal grid model established is verified.

1. Introduction

High-speed machining is one of advanced manufacturing technologieswhich is characterized by high-speed and high precision. High-speed CNC machine tools are the basis of high-speed machining, whose behaviors first depend on spindles and other key functional components.

Angular contact ball bearings bearing radial and axial loads are widely used as supporting components of high-speed spindle units for the advantages of simple structure, high rotational speed, low friction torque, high operation precision, etc. [1–3]. The operating temperature affected by many critical parameters such as the structural constraints, assembly relation among parts, oil-air operation parameters and power loss, plays a key role in the overall performance of a bearing system. Unfortunately, due to their inherent geometric and dynamic complexity, the thermal analysis of ball bearings has not been addressed thoroughly. Hence, understanding heat generation and transfer mechanisms is a major issue for high-speed angular contact ball bearings. However, in contrast to journal bearings investigated by many researchers, only a few experimental and theoretical investigations so far are available to improve the design of angular contact ball bearings. These literatures can broadly be categorized in two groups. The first category focuses on the mechanism of bearing thermal characteristics, including heat generation and heat dissipation. The second category aims at developing a model to estimate the bearing temperature field.

One of the pioneering works on the mechanism of the bearing temperature is presented by Palmgren [4]. By conducting a series of experiments on various bearings Palmgren fitted an empirical formula to calculate the friction torque; the quasi- dynamics of rolling bearings was investigated by Harris and Kotzalas [5], and next the research findings were employed by Bossmanns and Tu [6] to analyze the thermal performances of machine tool spindle. In their researches, the friction heating power between balls and rolling contact, the friction heat caused by lubricating oil viscosity, the friction heat between the cage and the ring and the friction heat between the roller end and the inner ring side were calculated based on friction torque to explain the power loss of bearings. Later, the heat expansion of trap and rolling bodies was considered by Lin and Tu [7] to study the thermal-mechanical coupling of bearings; with the contact thermal resistance between rollers and rings considered, Kim and Lee [8] established an analysis model, yet the friction heat induced by the gyroscopic motion of balls was ignored; with the bearing material thermal expansion considered, Yang et al. [9] investigated the automatic adjustment of preload. However, they also neglected the gyroscopic motion of balls;

* Corresponding author at: College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, 210016 Nanjing, PR China.

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based on the total frictional torque equation modified by Stein and Tu [10], Takabi and Khonsari [11] developed a mathematical model to comprehensively analyze the ball bearing temperature with provision for frictional heat generation, heat transfer processes and thermal expansion of bearing components; considering the thermal response and preload, Liu and Chen [12] built a thermal-mechanical coupling dynamic model of angular contact ball bearing. By this model, the friction loss and dynamic bearing stiffness of shaft bearing were fully analyzed; Brecher et al. [13] experimentally proposed a new, simple calculation model to estimate the cage-induced frictional losses in high-speed spindle bearings with minimal lubrication; Yan et al. [14] investigated the effects of the oil–air flow pattern inside bearing cavity and the cage parameters such as the pockets shape, methods of guiding, clearance, on bearing cage heat dissipation performance, and the results indicate that cage significantly impacts the air–oil flow and thermal dissipation inside bearing cavity; Mišković et al. [15] established a new equation to express the statistically significant correlation between ball bearings temperatures, their working time, and concentration of contaminant particles in their grease, and then analyzed the effect of grease contamination on the internal radial clearance of ball bearings by thermographic inspection; based on a quasi-static model and finite different method, Than and Huang [16] presented a unified method to predict nonlinear thermal characteristics of a high-speed spindle bearing subjected to a preload.

Thermal network method is an analytical method of thermoelectric analogy. Based on the thermal resistance theory, the subjects are subdivided into several cell nodes, and then the heat transfer equations are established based on KCL law and KVL law. Because the boundary conditions are more easily determined than finite element method (FEM) [17,18], it is widely employed to analyze the heat transfer of complex systems. With this method, Parker and Signer [19] introduced the oil scaling factor to investigate the thermodynamic performances of bearings; Ma et al. [20] developed the transient thermal grid model for a grease-lubricated SRB-shaft-bearing housing system; Neurouth et al. [21] proposed a simplified thermal network model for grease-lubricated thrust ball bearings; based on Neurouth's research, Ai et al. [22] created a thermal network model for double-row tapered roller bearings lubricated with grease to study the bearing temperature at different speeds, filling grease ratios and roller large end radius; Pouly et al. [23] integrated the rolling friction and sliding friction between balls and rings, the resistance between balls and oil and the sliding friction between balls and cage in a thermal network model of angular contact ball bearing under oil-air lubrication, but unfortunately the model is inapplicable to high-speed angular contact ball bearings; in consideration of the radial and axial deformation of spindle system during assembling process, deformation by thermal extension and centrifugal effect, Yan et al. [24] developed a novel network model for thermal-structure interaction.

Overall, various heat sources of angular contact ball bearings, as mentioned above, have been investigated by researchers successively. However, the effect of heat convection on the thermal performances is not yet thorough. So far, few scholars considered the heat convection between housing and atmosphere, but the effects of cooling and lubrication systems have not been fully considered. Also, the structures outside bearings influencing heat convection and conduction have not been discussed in depth, and thus the structural constraints outside bearing are rarely factored into the available thermal models as well as the fit states among components. The effect of cooling and lubrication medium on heat transfer by convection, meanwhile, has not been integrated into the thermal models proposed by the pioneers. Consequently, to accurately predict the thermal behaviors of bearings, especially angle contact ball bearings with oil-air lubrication is still a hot topic so far.

In this paper, the bearing is investigated under oil-air lubrication. And the structural constraints, radial and axial assembly relation among parts and cooling/lubrication operation parameters are well considered to develop an integrated thermal network model to investigate the thermal performances of angular contact ball bearing of high-speed spindle.

2. Ball and force equilibrium of angular contact ball bearing with thermal expansion

Bearing force in operation, for an angular contact ball bearing, is normally considered as a combination than simple accumulation of external loads and operation-induced additional force. The external loads are composed of the working loads and external preloads, and the initial preloads play a key role to reach an appropriate stiffness for the bearing assembly. The thermal-induced preload is one of operation-induced additional forces, which is associated with uneven expansion of the bearing components. During the operation as the temperature of the bearing assembly increases, components of the bearing experience different expansion rates due to differences in their temperature and geometry. As a result, the initial interference at the bearing installation is affected, which leads to changes of the contact loads between parts, namely the real working loads are changed. Next in this section is the ball and force equilibrium of angular contact ball bearing with thermal expansion.

As shown in Fig. 1, F_c is the centrifugal force, α_i and α_e are contact angles, and Q_i and Q_e are contact loads at the inner and outer ring respectively. Using the notation in Fig. 1, the local force vector can be obtained from the contact load and contact angle at inner ring of the bearing, and written as

$$\begin{cases} Q_r = -Q_i \cos\alpha_i \\ Q_z = -Q_i \sin\alpha_i \, . \\ M = 0 \end{cases} \tag{1}$$

The load equilibrium at the ball is determined by the following formula

$$\begin{Bmatrix} F_r \\ F_z \end{Bmatrix} = \begin{Bmatrix} Q_i \cos\alpha_i - Q_e \cos\alpha_e + F_c \\ Q_i \sin\alpha_i - Q_e \sin\alpha_e \end{Bmatrix} = 0. \tag{2}$$

Here, F_r and F_z are the radial and axial loads of bearing respectively, and the contact loads Q_i and Q_e are calculated by Hertzian theory for spherical contact,

$$\begin{cases} Q_i = K_i \delta_i^{3/2} \\ Q_e = K_e \delta_e^{3/2}, \end{cases} \tag{3}$$

where K_i and K_e are the load-deflection parameters, δ_i is the contact deformation between ball and inner ring, and δ_e is the contact deformation between ball and outer ring.

$$\begin{cases} \delta_i = l_i - l_{oi} \\ \delta_e = l_e - l_{oe}, \end{cases} \tag{4}$$

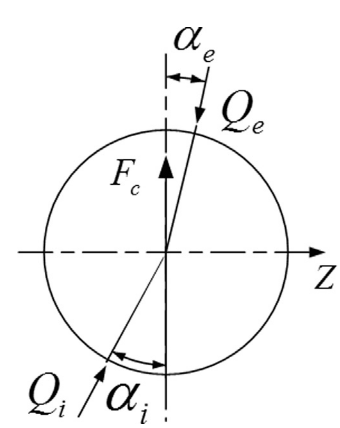

Fig. 1. Contact angle and load of a ball.