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Research Paper

Study on the influence of thermal characteristics of rolling bearings and spindle resulted in condition of improper assembly

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HIGHLIGHTS

- The effect of tilting outer ring induced by improper installation on bearing thermal feature was investigated.
- Systematic experimental analysis of spindle thermal characteristics resulted from tilting outer ring was conducted.
- Simulation was verified by experimental tests and thermal displacements of spindle front-end was discussed.

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ABSTRACT

Thermal analysis of spindle-bearing system with improper assembly is crucial but insufficient. Aimed at this, spindle system of ball bearings with tilting outer ring was proposed. Firstly, based on quasi-static analysis, the bearing friction heat was analyzed and calculated, and the effect of tilting bearing outer ring on bearing's contact angle, contact force and friction heat was investigated. Secondly, steady thermal simulation analysis on spindle in consideration of tilting outer ring was completed. Afterwards, for validation purpose, outer spacers with different non-parallelism were respectively assembled on the spindle to simulate bearing outer ring's different tilt statuses. The results indicated that, bigger tilt angle of bearing outer ring results in greater bearing's heat generation power and higher steady temperature of bearing outer ring. Simultaneously, in comparison with non-tilting outer ring, outer ring tilted to a certain extend will lead to greatly increase in friction heat of the certain rolling element. Experimental results verified the simulation analysis as that increasing non-parallelism of outer spacer leads to decreasing temperature difference between front and rear bearings.

1. Introduction

As an actuator, spindle-bearing system is the key component of a machine tool, and it is fairly crucial for machine tool's machining accuracy, reliability and service lifespan [1]. During the manufacturing process of a spindle, the assembly condition is one of the critical elements to determine its performance [2]. Since increasingly high demands on spindle service performances, such as accuracy and rotating speed, were raised by numerical control machine tools, strict requirements on spindle assembly were also proposed at the same time. Currently, although a growing number of instruments and methods on precision measurement for spindle assembly were used, dependence on skilled assembly workers was still heavy during the assembly process. Nowadays, key parts with high quality and precision like rolling bearing, electric motor and lubrication system were applied on the spindle manufacturing process in many spindle production corporations, but spindles with excellent performance were just produced by few several enterprises. Obviously, assembly process is the main reason which profoundly influenced the spindle performance. Given this, it is extremely indispensable to study the impact on spindle performance caused by assembly quality. In the future, less reliance on skilled assembly workers by studying spindle assembly technology will become an effective way to ensure the assembly quality of spindles.

Since spindle assembly seriously affects the spindle performance, many scholars and research institutions have deeply studied this subject. Jang [3] summarized that misaligned journal bearing may be resulted from an individual or combination of the following factors: asymmetric bearing loading, elastic deflection and thermal distortion of the shaft; distortions caused by bearing housing supports; manufacturing tolerances and errors

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Nomenclature

A	distance between inner and outer ring raceway curvature center/mm
A_1	introduced variable/mm
A_2	introduced variable/mm
a	semi-major axis of Hertz contact ellipse on contact zone/mm
b	semi-minor axis of Hertz contact ellipse on contact zone/mm
D_b	ball diameter/mm
d_m	bearing pitch diameter/mm
F_a	axial load/N
F_c	centrifugal force/N
F_r	radial load/N
f	curvature coefficient of bearing race
H	heat generation power/W
J	moment of inertia/kg mm^2
K	load-displacement coefficient along normal direction/ N·mm$^{-1.5}$
M_g	gyroscopic moment/N·mm
n	spindle speed/r·min^{-1}
Q	normal load/N
R	trajectory radius of raceway curvature center/mm
t_{front}	average temperature of outer ring of front bearings/°C
t_{rear}	average temperature of outer ring of rear bearings/°C
X_1	introduced variable/mm
X_2	introduced variable/mm

Greek letters

α	contact angle/rad
β	angle between ball velocity vector and pitch circle/rad
δ	displacement or deflection/mm
ε	elliptic integral of the second kind on contact zone
θ	angular displacement/rad
λ	raceway control coefficient
μ	friction coefficient
ν	kinematic viscosity/ mm^2·s^{-1}
φ	balls' angular orientation/rad
ω	rotating speed/rad·s^{-1}

Subscripts

0	original
i	Inner ring
o	outer ring
a	axial direction
r	radial direction
j	the jth ball at angular orientation
s	spinning motion
b	ball
m	cage motion
$roll$	rolling motion

due to installation and assembly defects. To theoretically analyze the effect on system caused by assembly quality, Zhang [4] studied the whole vibration of system resulted from misalignment faults by establishing the dynamic model of rotor-ball bearing system under misalignment situation. Similarly, a model based technique for fault diagnosis of rotor-bearing system was proposed [5]. Besides, through experimental testing and rotor dynamic computer simulations, the radial stiffness of an angular contact ball bearing with inner race static misalignment and outer race dynamic misalignment under various axial loads were investigated by Ertas [6]. Different with the above researches, Yi [7] and Li [8] proposed new methods to reduce the effect of misalignment, namely a proper amount of misalignment which is beneficial for the dynamic characteristics for a misaligned matched rotor-bearing system and non-uniform preloads properly distributed which could decrease the heat generation power of bearing. On the issue about thermal characteristics of rotor-bearing system, Chen [9], Takabi [10] and Yan [11,12] established different thermal models to analyze the thermo-mechanical dynamic behaviors and thermal deformation of spindle by simulations and experiments. Even more important, the impact on bearing performance resulted from outer spacer non-parallelism was numerically analyzed by Zhang [13]. In addition, some bearing enterprises provided many beneficial instructions on spindle assembly process in their handbooks [14]. However, all these were focusing on model of rotor-bearing system or thermal characteristics of bearing. When analyzing the thermal characteristics of spindle, influence on bearing caused by the quality of spindle assembly was not taken into account. What's more, researches on effect of thermal characteristics of bearings and spindle caused by improper assembly of spindle were extremely insufficient.

In fact, during the manufacturing process of a spindle, the case that there exists misalignment between the inner and outer ring of spindle bearing caused by improper assembly occurred frequently [3,13,14]. As the structural schematic diagram of a spindle shown in Fig. 1, parts such as spacers and locknut were in direct contact with the bearing end face, so factors including non-parallelism of contact surface, improper way of screwing up a locknut and torque inequality when tightening end cover bolts even its improper sequence of tightening bolts would result in relative tilt between bearing outer ring and inner ring. Consequently, abnormal bearing rotating would take place, accompanying with spindle's temperature rise and vibration increase. Furthermore, bending deflection would appear on the spindle if the misalignment becomes more serious, which highly influenced the spindle rotating precision.

Therefore, it is essential to research the influence on bearings and spindle performances caused by the spindle assembly quality, particularly the influence on thermal characteristics of bearings and spindle. In this paper, quasi-static analysis on ball bearing with tilting outer ring was carried out firstly. Then the friction heat was analyzed and calculated, and the effect of tilting bearing outer ring on bearing's contact angle, contact force and friction heat was studied. Based on this, steady thermal simulation analysis on spindle with consideration of tilting outer ring was conducted. Afterwards, in order to research the influence on thermal characteristics of bearings and spindle resulted from spindle assembly quality via experiment, outer spacers with different non-parallelism were respectively assembled on the spindle to simulate bearing outer ring's different tilt statuses. Finally, with experiments, temperature changes of front/rear bearings and thermal displacements with the increase of outer spacer's non-parallelism were discussed.

2. Bearing force analysis with tilting outer ring

During the process of assembling a bearing, factors like improper assembly and non-uniform preloads would lead to relative tilt between bearing inner and outer ring. In comparison with a properly assembled bearing, contact parameters like contact angle and contact force between balls and bearing inner/outer ring would change when a bearing was improperly assembled. Generally, the clearance fit was selected between bearing housing and bearing