Qualitative research on the relationship between spindle vibration characteristics and bearing thermal load

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Abstract. The dynamic performance of machine tool is one of the most important factors affecting the machining accuracy. As the core part of machine tool, the dynamic performance of spindle directly determines the performance of machine tool. In this paper, the spindle of machine tool is taken as the research object, and the change of fit clearance between bearing inner and outer rings, rotating shaft and bearing seat caused by spindle bearing heat, and its influence on the stiffness of spindle system are analyzed. Based on Timoshenko beam theory and finite element method, this paper qualitatively analyzes the variation characteristics of spindle stiffness caused by bearing overheating and grease lubrication failure during high-speed machining.

1. Introduction

With the improvement of living standards, people have been inseparable from mobile phones, computers, automobiles and other mechanical products, and put forward higher and higher requirements for their quality. Machine tool as the "mother of industry", in order to meet the growing demand of people, it is imperative to improve its machining accuracy. As the core component of Computerized Numerical Controlled (CNC) machine tool, whether the spindle has good dynamic and static performance is of decisive significance to the machining accuracy of the machine tool, and directly determines the quality of the processed products. Therefore, it is of great significance to clarify the key factors affecting the dynamic and static performance of the spindle to improve the machining accuracy of the machine tool and ensure the product quality [1-3].

Previous studies on the vibration characteristics of shaft parts are mainly focused on large-scale rotor systems such as steam turbines, while there are few studies on small-scale rotor systems such as machine tool spindles [4,5]. As the core component of CNC machine tool, the spindle is used frequently in engineering. Its structure is simple and can be simplified as a rotor system supported by rolling bearing. It is different from the rotor system of steam turbine, which usually bears huge radial load and adopts sliding bearing support. In addition, the ratio of radial dimension to axial dimension of spindle shaft rotor is much larger than that of steam turbine rotor, so the rigidity of spindle shaft rotor system is much higher than that of steam turbine rotor system.

This paper takes FANUC CNC machine tool spindle as the research object, combined with the mechanical vibration theory and finite element method, analyzes the change of the first six natural frequencies of the main shaft rotor under the change of the support stiffness of the spindle bearing under the heating state. This research will help the scholars of CNC machining better understand the
dynamic performance of the machine tool under the thermal state, and improve the machining performance of the machine tool.

2. Heat generation mechanism and matching of machine tool spindle bearing

The research object of this paper is the mechanical spindle. Its structure is shown in Fig. 1. The outermost layer is the mounting seat matched with the machine tool. The rotating shaft is installed on the bearing seat by two diagonal contact ball bearings in the form of DBB. This installation mode has high rigidity, and can resist large overturning moment when the front end is subjected to radial load and has good stability. In order to prevent the bearing inner ring from sliding and reduce the bearing life, the transition fit is usually used between the bearing inner ring and the rotating shaft. The specific method is to use the electromagnetic induction heater to quickly heat the inner ring of the bearing to 80 to 85°C (if the temperature is too high, the grease inside the bearing will fail to lubricate, and if it is too low, it cannot meet the assembly requirements), and then it can be quickly installed on the shaft. The bearing outer ring and the bearing seat adopt clearance fit, which is convenient for bearing assembly and disassembly. Here readers may have such a question: "If the outer ring and the mounting seat adopt clearance fit, will the spindle not slip at high speed, accelerate bearing wear and reduce its service life?". It's normal for readers to have such questions, because when reading some books about bearing assembly, the book usually introduces that "in order to prevent the bearing from slipping in the bearing housing, the bearing outer ring and the bearing housing usually adopt the transitional fit". In fact, there is no problem with this statement. When the bearing is working, the outer ring and the bearing seat cannot have relative sliding. However, this will make it extremely difficult for the bearing to fit into the bearing housing. Therefore, in production practice, clearance fit is usually used between bearing outer ring and bearing seat. Because the clearance fit is adopted, the spindle usually needs to run in for a period of time (running in time usually takes about 1H). After the bearing thermal expansion, the outer ring will form a transition fit with the bearing seat before it can be put into use.

As shown in Fig. 2, the rolling shaft assembled on the spindle shaft bears the action of axial preload
FA. Under the action of FA, the rolling element and the inner and outer rings of the bearing are squeezed. When the bearing works, it needs to overcome the friction torque and resistance from the inner and outer rings and grease to do work, which leads to the temperature rise of the bearing. As shown in Fig. 3, due to the thermal expansion and cold contraction of the bearing outer ring, the curvature center of the raceway moves down $\Delta y$. The inner diameter of bearing inner ring increases and the curvature center of inner ring raceway moves up. As a result, the clearance between the inner and outer raceways of the bearing and the rolling element is reduced, and the bearing support stiffness is increased. Because the spindle shaft is a rotor system with two ends simply supported, the change of bearing support stiffness will inevitably change the vibration characteristics of the rotor system. However, there is no real-time tracking measurement of the bearing stiffness at each moment during the thermal expansion process, but the range can be estimated according to the preload.

![Figure 3. Hot state and cold state of bearing (a) Comparison before and after thermal deformation of bearing outer ring (b) Comparison of bearing inner ring before and after thermal deformation.](image)

3. Vibration characteristics analysis of spindle rotor system

There are two common methods for the dynamic response of the spindle rotor system of computer machine tool: transfer matrix method and finite element method [6]. The finite element method is used in this paper. Compared with the transfer matrix method, the program of the finite element method is more complex and needs more computing resources. However, the finite element method has higher calculation accuracy, the number of elements is less than the transfer matrix method, and the most important thing is to avoid the numerical instability in the transfer matrix method.

The actual spindle rotor system is an elastic system with continuous mass distribution and infinite degrees of freedom. In order to use the finite element method to analyze its dynamics, as shown in Fig. 4, according to its size characteristics, we divide it into 10 Timoshenko beam elements along the axial direction. The rolling bearing can be simplified as a spring damper model, and each element is connected at the node.

![Figure 4. Finite element mesh generation of spindle rotor system.](image)

It is assumed that the support stiffness is the same in all directions, as shown in Fig. 5.
Figure 5. Schematic diagram of shaft support stiffness.

4. Results and discussion

Due to the expansion of the inner and outer rings of the bearing after heating, the support stiffness of the rolling bearing will increase. We analyzed the first six natural frequencies of the main shaft rotor in the range of 1e-3N/m to 1e14N/m. The analysis results are shown in Table 1.

| N/m   | 1e-3 | 1e-2 | 1e-1 | 1e0  | 1e1  | 1e2  |
|-------|------|------|------|------|------|------|
| 1order| 0    | 0    | 0    | 0.01 | 0.06 | 0.53 |
| 2order| 0    | 0    | 0    | 0.14 | 0.43 | 1.37 |
| 3order| 0    | 0.01 | 0.04 | 0.14 | 0.43 | 1.37 |
| 4order| 0    | 0.01 | 0.04 | 3.07 | 3.13 | 3.6  |
| 5order| 3.07 | 3.07 | 3.07 | 1435.01 | 1435.01 | 1435.01 |
| 6order| 1435.01 | 1435.01 | 1435.01 | 1447.23 | 1447.24 | 1447.24 |

When the bearing stiffness is lower than 1e9N/m, the natural frequency of the spindle shaft rotor system increases sharply with the increase of bearing stiffness. When the bearing stiffness is greater than 1e10N/m, the first 6 natural frequency of the spindle shaft no longer changes greatly, until the bearing stiffness of the spindle reaches 1e14N/m, the natural frequency of the spindle shaft rotor system does not increase significantly compared with the support stiffness of 1e10N/m.

Generally, the preload stiffness of the rolling bearing in this study is 2.3e8N/m under light preload and 4.9e8N/m under heavy preload. As shown in Figure 6, under these two preloading conditions, the first-order natural frequency of the spindle shaft rotor system is higher than 1100, and the corresponding first-order critical speed of the rotor is higher than 6e4rpm. It is much higher than the working speed of the rotor, so we can draw such a conclusion: when the machine tool spindle rotor works under the normal preloading condition, the working fundamental frequency will not cause the
spindle rotor system to resonate. If the resonance occurs, the reason is likely to be that the bearing preload is too loose, resulting in the bearing support stiffness less than 1E7N/m.

![Figure 6. Bearing support stiffness and the first six natural frequencies of rotor system.](image)

When \( n = 8000 \text{ rpm}, \) \( K_{xx}=K_{yyy}=13e9 \text{ N/m}, \) the vibration modes of the main shaft rotor system are shown in Fig. 7.

![Figure 7. N=8000rpm, Kxx=Kyyy=13e9 N/m, The first six modes of shaft.](image)

5. Conclusion
Through the above analysis, it can be seen that for the machine tool spindle rotor, such as the "small size hollow shaft supported by rolling bearing", its own stiffness is very high, and the first-order vibration frequency under normal preloading condition has reached 1323.65Hz, which is far higher than the fundamental frequency of the spindle shaft. Moreover, with the increase of the bearing support stiffness, the first six natural frequencies of the main shaft do not change too much. The increase of bearing stiffness caused by bearing heating does not change the natural frequency of rotor system to a great extent. This conclusion is helpful to the scholars who study the vibration of the spindle rotor system.
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