Experimental study on bearing preload optimum of machine tool spindle

Tao Xu¹, Guanghua Xu¹,², Qin Zhang¹,², Cheng Hua¹, Hu Zhang¹ and Kuosheng Jiang¹
¹School of Mechanical Engineering, Xi’an Jiao tong University, Xi’an, China, 710049
²State Key Laboratory for Manufacturing System Engineering, Xi’an Jiao tong University, Xi’an, China, 710049
xjxutao929@gmail.com, xugh@mail.xjtu.edu.cn

Abstract. An experimental study is conducted to investigate the possibility and the effect of temperature rise and vibration level of bearing by adjusting axial preloads and radial loads in spindle bearing test rig. The shaft of the test rig is driven by a motorized high speed spindle at the range of 0~20000 rpm. The axial preloads and radial loads on bearings are controlled by using hydraulic pressure which can be adjusted automatically. Temperature rise and radial vibration of test bearings are measured by thermocouples and Polytec portable laser vibrometer PDV100. Experiment shows that the temperature rise of bearings is nonlinear varying with the increase of radial loads, but temperature rise almost increases linearly with the increase of axial preload and rotating speed. In this paper, an alternate axial preload is used for bearings. When the rotating speed passes through the critical speed of the shaft, axial preload of bearings will have a remarkable effect. The low preload could reduce bearing vibration and temperature rise for bearings as well. At the others speed, the high preload could improve the vibration performance of high speed spindle and the bearing temperature was lower than that of the constant pressure preload spindle.

Key words: machine tool spindle, alternate axial preload, temperature rise, bearing radial vibration

1. Introduction
In order to carry out ultra-precision machining at high speed and with efficiency, both heavy cutting at the low speed and light cutting at high speed must be enabled in series in a single machine tool spindle. Modern tool spindle needs high speed rotation performance along with a wide range of using rotation [1]. However, as the speed of spindle increases, spindle thermal and vibration growth become the critical factors to be considered.

Without considering the windage losses in spindle system, heat is mainly generated at bearing raceways and balls due to the friction influenced by speed, preload and lubricant. All temperature of spindle system increases almost linearly with the increases of rotational speed and preload [2]. Rolling bearings represent internal clearance in general. The preload adjusts internal clearance that can improve the friction, stiffness and rotational accuracy of bearings [3]. Compared with other inaccurate readings using a traditional thermo-coupler, a direct displacement measuring system can accurately monitor and compensate the thermal growth associated with motorized high speed spindles [4].

At the same time, some researchers have investigated the effect of the preload on the performance of the spindle system, and found the preload can enhance the stiffness and natural frequency of the
spindle [5, 6, 7, 8]. The intimal axial preload applied on the bearings plays a significant role in reducing the vibration levels of grinding machine spindle system [9]. There are certain preload values that ensure higher service life for the tested bearings and lower vibration levels of the test spindle [10].

When the rotating speed passes the critical speed of the shaft, the rotation performance of spindle system will change. This paper mainly studies the relationship among preload, radial vibration and temperature rise of bearings by experiments. An alternate axial preload is used for bearings. As the rotor through the critical speed, the low preload is applied on bearing that can decrease the vibration of system. Meanwhile, the radial vibration and safety limit temperature of the rotor are considered as the constraints to confirm the preload. The result shows that the method has a good performance in keeping the machining accuracy of spindle in spindle bearing test rig.

2. Experiment Setup

2.1. The spindle bearing test rig

To verify the proposed method for alternate axial preload in this paper, an experimental set-up for the spindle bearing is developed, as shown in Figure 1. The shaft of spindle bearing is driven by a motorized high speed spindle at the range of 0~20000 rpm. The shaft is supported by two pairs of angular contact ball bearings, which are preloaded by a hydraulic chamber. The hydraulic pressure induces displacement in the axial direction, then pushes the outer ring of the rear bearing, and eventually the displacement is transferred to the inner ring of rear bearing through the shaft. Therefore, the displacement caused by hydraulic pressure is converted into axial force, which increases the preload of bearings, and the preload of each bearing is equal to one half of the hydraulic pressure. The bearings are the oil-air lubricated in this study. The motorized high speed spindle housing around the power zone is cooled by a compulsive cooling water circuit to disseminate the heat generating.

The operating principle of the preload is illustrated as follows. The rotational speed of the motorized high speed spindle is controlled by frequency converter. Subsequently, the axial preload and radial loads are adjusted by proportional of hydraulic system. The data of speed, loads, current, vibration, temperature are sent to the control centre automatically. As shown in Figure 2, the temperature rise of bearings is measured by thermocouple. The vibration of test shaft is detected by portable laser ride meter PDV100.
Table 1 gives the parameters of test bearing B7007C and Table 2 gives the parameters of the motorized high speed spindle used in this study.

### Table 1. Parameters of test bearing B7007C.

| Parameter          | Value          |
|--------------------|----------------|
| Type               | B7007C/p4      |
| Material           | Steel          |
| Inner diameter     | 35 mm          |
| Outer diameter     | 62 mm          |
| Width              | 14 mm          |
| Number of balls    | 17             |
| Contact angle(deg.)| 15             |
| Axial preload (max)| 600N           |

### Table 2. Parameters of the motorized spindle.

| Parameter      | Value          |
|----------------|----------------|
| Type           | 150MD36Y11     |
| Rotational speed| 0~36000 (rmp) |
| Power          | 11(KW)         |
| Current        | 30(A)          |
| Voltage        | 350(V)         |
| Frequency      | 600(HZ)        |

2.2. Experiment setup

Figure 2 shows the schematic for the spindle bearing experiment setup. The oil/air lubrication system of test shaft used in this study is an integrated oil/air mixer generator. The outlets of the mixers are connected to two separate lubrication channels that terminate at front bearing and rear bearing respectively. The cooling system keeps the driving motor at a lower temperature. The entire experimental setup is installed in a temperature-and humidity-controlled environment.

![Figure 2. Schematic of the spindle bearing test rig.](image-url)

3. Experiment Procedure

3.1. Temperature rise measurement

Two temperature sensors are used to measure the bearing temperature at the locations of the front and rear bearings as shown in Figure 2. To analyse the temperature rise of the bearings, the temperature sensors are located beside the outer rings of bearings. The control centre records and updates bearing temperature every ten seconds. The room temperature is measured by thermometer. The measured temperature rise is compensated by the elimination of variation in the room temperature. To obtain the
maximum temperature rise in a spindle precisely, all temperatures are measured simultaneously. When the temperature rise of the test bearings approaches safety limit temperature, the spindle is turned off and the highest temperature rise is recorded.

### 3.2. Vibration measurement
In the high speed spindle, the vibration level is considered as the most important characteristic. Apart from the size of the bearing and rolling element, the preload of bearing influences the thermal characteristics of the spindle and the vibration level of the shaft. The vibration of outer rings of bearing can reflect the operation stability of the rotor system. In this paper, the vibration of the rotor in different speed, axial and radial loads are analysed by experiments. The Polytec portable laser vibrometer PDV100 can be used to measure the vibration of its outer ring. The vibration data will be transferred to PC control centre and saved.

### 4. Results and Discussion

#### 4.1. Effect of each factor on temperature rise
The preload, radial load and rotor speed affect the temperature rise of bearing. In certain lubricate condition, with the increase of rotor speed, the temperature rises and the preload of bearing also increases.

#### 4.1.1. Effect of preload for bearing
The air compressor provides 0.8MP compressed-air that can supply oil-air mixture for lubricating bearing. As the Figure 3 shows, the bearing temperature is changed since different axial preloads and speeds. The thermal from frictions for inner and outer rings of bearings makes bearing temperature rise and the temperature rise be proportional to the rotor speed. With the increase of speed, the ability of preload affecting temperature rise will be reduced.

![Figure 3. Temperature with different preloads and rotational speeds.](image)

#### 4.1.2. Effect of radial load for bearing
In Figure 3, the radial load is applied to rotor, so the bearing temperature is increased. Compared with Figure 3, the temperature rise percentage is reduced with the increase of speed in Figure 4.

![Figure 4. Temperature rise percentage vs. speed.](image)
4.2. Effect of each factor on vibration level
In Figure 5, when the rotating speed through the critical speed of the shaft (8000rpm), the rotor has a stronger vibration than before. In this area, the big preload could provide higher vibration than low preload. In other areas, the vibration is small. Compared with constant preload, we can use alternate preload for bearings. As the rotor passes or goes through the critical speed, the low preload (200N) is applied to bearing that can reduce the system vibration. At other speeds, the high preload (600N) is used on bearing that can improve the stiffness of the spindle system.

5. Conclusion
This paper studies the influence of axial preload and radial load on temperature rise and vibration of bearing for a high speed rotor by experiments. The entire range of speed is divided into critical speed and at other speeds areas. The optimum preload is determined according to the safety limit temperature rise and vibration level of bearing. Through the critical speed area, the low preload is applied to bearing that is the lowest recommend preload. At other speed areas, the high preload is applied for bearing that is the highest proposed load. To the conclusion, the optimum preload is
determined according to the safety limit temperature rise and the highest recommended load of bearing. The alternate preload method has been verified by the experimental study.

Compared with the traditional constant preload method, the alternate preload method can reduce the vibration and temperature rise of bearing. Furthermore, the temperature rise will become high with the increase of radial load rising and slow down with the increase of preload rising. The optimum radial load for bearing is determined by the safety limit temperature rise of bearing. And vibration is determined according to the demand.

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