Development of a Spindle System with an Adjustable Preload Mechanism Using a Piezoelectric Actuator*

Satoshi TSUTSUI**, Tojiro AOYAMA**
and Ichiro INASAKI**

Ball bearings are usually used for the spindle system of machine tools under preloading to achieve high stiffness of the main spindles. However, in the case of high speed cutting, too high a degree of preloading results in excessive temperature rise and, consequently, bearing seizure. Therefore, several mechanisms have been proposed to adjust the preload on bearings. Most of them, however, have some problems. In this study, a simple and practical mechanism for preload adjustment is developed using piezoelectric actuators, and the preload is successively adjusted while the spindle is in rotation.

Key Words: Ball Bearing, Main Spindle, Machine Tool, Preload, Piezoelectric Actuator, Stiffness

1. Introduction

The performance of the main spindle system is an important factor affecting the machining ability of machine tools. A few sets of ball bearings are assembled into the spindle system under preloading to achieve the high stiffness of the main spindles. Therefore, a higher preload is applied to main spindles for heavy cutting. However, an excessively high degree of preloading causes excessive temperature rise and bearing seizure at high-speed operations^{(1),(2)}. Hence, the preload on bearings should be adjusted to a relatively lower setting during high-speed cutting.

Angular contact ball bearings are usually used for the high-speed main spindles of machine tools. For this type of bearing, the preload is permanently applied by making a relative displacement between the outer and inner rings in the axial direction. In this manner, it is not possible to change the preload according to the variation of the spindle-rotating

speed. There is a great need to develop a variable adjustment mechanism which enables suitable preloading for a wide range of rotational speeds. Up to this time, a screw driving adjustment mechanism and a hydraulic adjustment mechanism have been developed and applied to spindle systems of machine tools⁽³⁾. However, some disadvantages are found in these mechanisms. The screw driving mechanism is not adequate for fine adjustment while the mechanism with hydraulic actuators requires an extra hydraulic supply system.

In this study, the effect of the preload on bearing performances is experimentally investigated, and a simple and practical mechanism for preload adjustment is developed using piezoelectric ceramics (PZT) as actuators.

2. Influence of Preload on Bearing Performance

2.1 Experimental equipment

In order to develop a preload adjustment mechanism, it is necessary to quantitatively investigate how the preload affects the bearing performance.

A specially designed bearing test stand used to measure the variation of bearing temperature and

* Received 23 rd December, 1987. Paper No. 87-2036 B

** Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, 223, Japan

frictional power consumption in response to the variation of applied preload is shown in Fig. 1. A test bearing (type: JIS 7011 C) of angular-contact type is assembled in the test stand. The inner and outer diameters of this bearing are 55 mm and 90 mm, respectively. The outer ring holder of the test bearing is out of contact with the housing. The thrust load on the bearing, i. e., the preload, is adjustable by rotating the preloading screw. The applied preload is measured by the load cell attached to the preloading screw. The temperature variation is measured at the outer face of the outer ring by a CC thermocouple. The frictional power consumption is detected by measuring the electrical power consumption at the spindle driving motor. The test bearing is lubricated by oil-air lubrication.

2.2 Effect of preload on bearing temperature and frictional power consumption

The effect of the preload change on bearing temperature and frictional power consumption is shown in Fig. 2. The spindle rotational speed is maintained at 10 000 r/min (i. e., $dm \cdot n = 725\,000$) through out the experiment.

At the beginning of the running test, the thrust load is fixed at about 1 500 N. After the bearing tem-

Fig. 1 Bearing test stand

Fig. 2 Effect of the preload on bearing temperature rise and driving power consumption

perature and frictional power consumption come to steady values, the thrust load is decreased manually step by step. The bearing temperature and the frictional power consumption are strongly affected by the preload on the bearing. The amount of temperature rise decreases in response to the decrease of applied preload. It is concluded through this experiment that the adjustment of the preload is very effective in suppressing the rise of bearing temperature.

3. Performance of the Piezoelectric Ceramics Actuator

One method of preload adjustment is by varying the spacer length between a pair of bearings. In this study, special attention is paid to the piezoelectric actuators as the elements of the variable spacer because of their quick response, high stiffness and simplicity as a mechanism installed in the spindle system. The piezoelectric ceramics actuator has a property of elongating in proportion to the applied electrical voltage. The dimensions of the piezoelectric actuator used in this study are shown in Fig. 3. The axial length and the diameter of piezoelectric actuator is 75 mm and 16 mm, respectively.

The piezoelectric actuator used in this study has two basic characteristics: it is capable of elongating as much as 35~40 μ m at DC 400 V charged to the actuator, although some hysteresis exists; and its maximum capable load is about 700 N.

It must be kept in mind that although the piezoelectric actuator can withstand compressive force in the axial direction, it is vulnerable to torsional and bending forces.

Fig. 3 Piezoelectric actuator

4. Application of the Piezoelectric Actuator to the Spindle System

4.1 Development of the piezoelectric spacer

For angular contact ball bearings, it is required to give the outer ring a small displacement in the axial direction relative to the inner ring in order to get the desirable preload. The quantitative relation of the relative displacement and the preload depends on the type of bearings. In the case of the 7011 C-type bearings used in this study, the relation between them is given by Fig. 4⁽⁴⁾. As can be seen from the figure, displacement capacity of 10 μm in the axial direction is required for a spacer to obtain a change from 100 N to 300 N in the thrust load (i.e., preload). The piezoelectric actuator fulfills the above-mentioned requirements of a spacer in terms of the displacement capacity.

The piezoelectric spacer developed in this study is shown in Fig. 5. The piezoelectric spacer is constructed with three sets of piezoelectric actuators and a specially designed casing which protects the actuators

Fig. 4 Relationship between displacement and preload

Fig. 5 The piezoelectric spacer

from bending and torsional forces. The axial length of the spacer is about 70.5 mm, and the inner diameter and the outer diameter are about 65 mm and 110 mm, respectively. Three piezoelectric actuators are assembled in parallel within the casing. The maximum total permissible load on the developed piezoelectric spacer rises to about 2 100 N, which is considered to be sufficient for practical application. The casing consists of Parts A and B as shown in Fig. 5. There are three tapped holes in Part A, positioned for the installation of three columnar holes through the rims of the cylindrical spacer. After the installation of columnar actuators in each of the tapped holes of Part A, Part B is installed as a cover.

The holes C of Part B are designed so that hole diameter is slightly larger than that of the piezoelectric actuators to allow for the actuators to freely elongate and shrink in the axial direction.

4.2 Test spindle system for preload adjustment

A test spindle system for preload adjustment is schematically shown in Fig. 6. A set of angular contact ball bearings (type: JIS 7011 C) are assembled in the test spindle system with the piezoelectric spacer. When the charged voltage of piezoelectric actuators increases, the piezoelectric spacer itself elongates in the axial direction, thereby, making it possible to increase the preload on both sides of the bearings. The preload will be decreased by decreasing the charged voltage to the piezoelectric actuators. In order to evaluate the performance of the piezoelectric spacer, the variation of the thrust load (i.e., preload) on rotating bearings is measured. The variation of the preload on each bearing is monitored by sensing the dynamic strain of the bearing outer rings, which is caused by the rotation of balls in each bearing⁽⁵⁾.

4.3 Preload adjustment test

The results of the preload adjustment test are shown in Figs. 7 and 8. In Fig. 7, the charged voltage to the piezoelectric spacer is increased from 0 V to

Fig. 6 The test spindle system for the preload adjustment

Fig. 7 The result of the preload adjustment test under constant rotational speeds

350 V by 50 V, and decreased to 0 V, while the rotational speed is fixed at 3 000 r/min. The thrust load, i.e., the preload, on bearings increases and decreases in response to the change in charged voltage. The transition of the thrust load is traced in accordance with the step-by-step change of the charged voltage. This means that the preload on bearings can be successfully controlled by the developed piezoelectric spacer.

It is supposed that the difference in the rising proportion and the declining proportion of the preload curve is due to the hysteresis of piezoelectric actuators.

When the spindle rotational speed rises, the preload on bearings increases due to the centrifugal force of balls and inner rings. The centrifugal force causes the expansion of inner rings in radial direction. The thermal expansion of the inner ring, which is caused by the excessive temperature rise due to the gyro-action of balls^{(6),(7)}, also causes the increase in the preload. In this study, it is tried to maintain the preload at a certain level regardless of the increase of the spindle rotational speed.

The results of the trial are shown in Fig. 8. The strain amplitude which is in proportion to the preload is initially maintained at 15.5×10^{-6} strain, while the rotational speed is increased from 2 000 r/min to 6 000 r/min. A subtle rise of the strain amplitude beyond 15.5×10^{-6} strain is observed when the rotational speed is increased from 2 000 r/min to 4 000 r/min, and from 4 000 r/min to 6 000 r/min. However, the preload decreases to the control level (i.e., 15.5×10^{-6} strain) again by decreasing the charged voltage. Such preload adjustment is possible until the spindle rotational speed reaches 8 000 r/min. However, preload on bearings is beyond control when the rotational speed exceeds 8 000 r/min. This seems to be because the friction between the housing and the piezoelectric

Fig. 8 The result of the preload adjustment test under various rotational speeds

spacer becomes larger than the characteristics of the piezoelectric actuator.

In this study, the creep test of the piezoelectric spacer was carried out. The spindle rotational speed is fixed at 5 000 r/min. The running test is continued for 11 hours. The creep phenomenon was not observed in this experiment.

5. Conclusion

In this study, a new mechanism for preload adjustment is developed by applying piezoelectric ceramics actuators. The performance of the proposed mechanism is evaluated by assembling it into a test spindle system.

The conclusions of this study are summarized as follows:

- (1) It is effective to maintain the preload at a certain level in order to suppress the temperature rise of bearings.
- (2) The piezoelectric ceramic actuator is suitable as the element of the preload adjustment mechanism in terms of elongation and durability.
- (3) The preload on bearings is adjustable even when the spindle rotates by installing the developed piezoelectric spacer instead of the conventional spacer.
- (4) The creep phenomenon of the piezoelectric spacer was not observed.

The authors wish to thank Makino Seiki Co., Ltd. for their technical assistance.

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