Development of a New Measurement Method of Central Position of Spindle Rotation*

(1st Report : Steel Ball Method)

Norimitsu OZAWA**, Kiyomatsu TAKEUCHI**
and Takeshi SUGANO**

A precision steel ball is attached to the end-face of the spindle and an electronic capacitance-type transducer mounted on the tool slides of a three-dimensional sliding stage. Relative displacement in the axial direction between the ball and the transducer is detected during spindle rotation. The measurement principle of the central position is based on the fact that the undulation component synchronized with the rotational speed of the spindle in the displacement signal reaches a minimum value at the central position of rotation. The results of preliminary experiments are summarized as follows. (1) The new method allows detection of the central position with a resolution of $0.5\text{ }\mu\text{m}$. (2) In the case of the spindle with hydrodynamic bearings, the rotational speed of the spindle and the resonance vibration of the headstock affect the central position of the spindle rotation.

Key Words: Spindle, Measurement, Spindle Rotation, Central Position, Measuring Method, Hydrodynamic Bearing

1. Introduction

The central position of spindle rotation (CPSR) is affected by the spindle structure, the spindle bearing, rotational speed, machining conditions, external forces and so on. Especially with machine tool spindles, a change in the CPSR affects the machining accuracy of the workpiece. Therefore, it is necessary to measure the CPSR during the machining process and to minimize the amount of fluctuation in the CPSR. Eiju and Matsuda have developed an optical measuring method for the CPSR based on laser Doppler velocimetry⁽¹⁾.

We have also developed a new method of measuring the CPSR. In this paper we describe the principle of the new method and present the results of preliminary experiments.

2. New CPSR Measurement Method

2.1 Measurement principle

A precision steel ball is attached to the end-face

of the spindle and an electronic capacitance-type transducer mounted on the tool slide on a three-dimensional sliding stage, as shown in Fig.1. The relative displacement is measured by detecting the fluctuation in gap distance between the ball and the transducer. Figure 2 shows the principle of the new measurement method. The CPSR is on the Z axis and the steel ball is mounted at a distance "e" from the Z axis.

Fig. 1 New measurement method of central position of spindle rotation using a steel ball

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** Mechanical Engineering Laboratory, Namiki 1-2, Tsukuba, Ibaraki 305, Japan

In the case where the axial error motion is equal to zero, the ball shifts to the "broken line" position after a half-rotation of the spindle. The distance between points D and E varies, i.e., the magnitude of z changes in the form of a sine wave in synchronization with the spindle rotation.

Then, the magnitude changes with the same period as the spindle rotation. As the distance between the transducer and the CPSR decreases, the magnitude of z decreases. The magnitude of z reaches a minimum value at the central position of rotation.

Under the assumption that the ball is an ideal sphere, the magnitude of z can be expressed by the following equation:

$$z^2 + 2z\sqrt{r^2 - (y + e)^2} - 4ey = 0, \quad (1)$$

where the values e and y are very small as compared with radius r of the ball. The magnitude of z can be approximated as follows:

$$2rz - 4ey = 0. \quad (2)$$

Fig. 2 Measurement principle of the CPSR

Fig. 3 Relationship between distance from the center of rotation and undulation component synchronized with rotation (calculated value)

Figure 3 shows the relationship between values y and z based on Eq. (2). The diameter of the steel ball is 12.7 mm. The value of z is proportional to the value of y . The value of z increases with increasing e value.

2.2 Results of the preliminary experiment

The steel ball was bonded with adhesive to the center of the workpiece which was held on the vacuum chuck of a lathe. The ball used had a roundness of 0.025 μm.

The output signal from the transducer was amplified and the undulation component which is synchronized with the rotation z is filtered out using a band-pass filter.

At the beginning of the experiment, the relationship between amplitude of the output signal of the transducer and the gap distance, i.e., the displacement between the ball and the transducer, was investigated. As a result, the gain in the output signal is 1.25 times the measured value for the relative displacement between the flat plane and the transducer.

The noise level of the displacement-measuring apparatus was monitored at the output of the filter. The noise level which was converted into a displacement signal had peak-to-valley variation of about 0.5 nm.

Figure 4 shows the results of the preliminary experiment. In this figure, the horizontal axis represents the transverse displacement of the transducer which was measured by another displacement transducer with a resolution of 1 μm.

The transducer was first moved in the +Y direction and then in the negative direction. Consequently, characteristics of z exhibited a "V"-shaped, as illustrated in Fig. 4. The magnitude of z is directly proportional to the displacement y . The ratio of z to y is 2.8 (nm/μm). The minimum value of z is about 4 nm. It may be considered that the residual component of z

Fig. 4 Experimental result of the relationship between distance from the center of rotation and undulation component synchronized with rotation

was caused by the effect of axial error motion and vibrations. Results of the experiment may be summarized as follows.

- 1) The CPSR exists in the region where the magnitude of z falls below a few nanometers.
- 2) The measuring resolution of the new method depends upon the positioning accuracy of the three-dimensional sliding stage.
- 3) Eccentricity e of the steel ball can be calculated by means of Eq. (2).

3. Measurement of the CPSR of Workpiece Mounted on a Hydrodynamic Bearing Spindle

3.1 Measurement procedures

Figure 5 shows the structure of the hydrodynamic bearing spindle (FAG Corp., Type HDKO). This bearing is separated into 6 peripheral segments. The gap between the spindle and the bearing is about $2\text{ }\mu\text{m}$.

In the journal bearings, a wedge-shaped oil film generally fills the gap between the bearing and the spindle during rotation. The spindle rotates at the position where the oil film pressure is balanced with external forces.

Therefore, it may be assumed that the CPSR in this bearing and spindle system fluctuates according to rotational speed, rotational direction, external forces, oil viscosity and so on.

From these factors, we attempted to clarify the relationship between the CPSR and the rotational speed of the spindle. The three-dimensional sliding stage used in this experiment had the following properties: lowest scale reading ; $0.5\text{ }\mu\text{m}$, straightness ; $2\text{ }\mu\text{m}/13\text{ mm}$, pitch ; 8 seconds and yaw ; 4 seconds.

3.2 Experimental results

At the beginning of the experiment, the spindle was operated at 1 200 rpm for 30 minutes. Measurements of the CPSR were carried out at 200 rpm speed increments in the range from 400 rpm to 1 200 rpm. Figure 6 illustrates the locus of the CPSR in the X - Y

plane. In this figure, the solid lines show the locus of the case where the rotational speed was decreased. In the case where the rotational speed was increased, the locus is shown by the broken lines.

The CPSR moves in the same direction as the spindle rotation with increasing rotational speed, except at 1 000 rpm. Aoki studied full journal bearings of finite lengths⁽²⁾. Good agreement was found regarding the locus of the CPSR with increasing rotational speed between our experimental results and the analytical results obtained by Aoki.

At 1 000 rpm, the CPSR locus exhibited a singular behavior; hence, the CPSR measurement between 800 rpm and 1 200 rpm was carried out in 100 rpm speed increments. Figure 7 shows the results of the measurements. In this figure, the solid and the broken lines show the locus in the same experimental conditions as Fig. 6. The locus of the CPSR moves in a counter-clockwise direction with increasing rotational speed. In order to clarify this phenomenon, measurements of vibration amplitude on the headstock versus rotational speed of the spindle were carried out.

Fig. 6 Locus of the CPSR on X - Y plane (1)

1,2 : Hydrodynamic bearing

Fig. 5 Structure of the hydrodynamic bearing spindle

Fig. 7 Locus of the CPSR on X-Y plane (2)

Figure 8 shows the measurement results. Vibration amplitudes measured on the headstock revealed a maximum value at 980 rpm (16.3 Hz). This is the resonance vibration of the headstock. It is thought that the resonance vibration has a significant influence on the locus of the CPSR at 1000 rpm.

4. Conclusions

The results of these studies are summarized as follows.

- 1) The new measuring method developed allows detection of the central position of spindle rotation with a resolution of 0.5 μm .
- 2) In the case of the spindle with hydrodynamic bearings, the rotational speed of the spindle and the resonance vibration of the headstock affect the central position of the spindle rotation.

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Fig. 8 Vibration amplitudes measured on the headstock

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