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MEASUREMENT OF SPINDLE STIFFNESS FOR THE MONITORING SYSTEM OF CUTTING FORCES

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ABSTRACT

This paper presents a measurement scheme of the stiffness of rotating spindle in radial directions. The measurement purpose is to characterize the spindle stiffness that is needed for the monitoring of the cutting forces in a sensor-integrated spindle. The spindle has been developed for an intelligent machining center, having four eddy current sensors that detect the radial displacements of the spindle in X and Y directions. The sensor signals are interpreted as the forces applied on the tool-holder-spindle system by using the force-displacement relationship (spindle stiffness) obtained from the calibration tests. In order to measure the stiffness of the rotating spindle, a loading unit is fabricated. Several loading tests are carried out and the force-displacement relationship is investigated under different running conditions. It is found that the force-displacement relationship with the rotating spindle has nonlinear characteristic.

1. INTRODUCTION

The development of high-speed spindle has been one of the major trends in machine tool technologies. In the development of high-speed spindles, the DmN number reaches 2-3 millions to balance rough cutting and fine finishing capabilities. In order to utilize such high-speed spindles for high productive machining, the following functions should be integrated in the machine tools: bearing preload control, the monitoring of mechanical damages of the bearings, the monitoring of the spindle temperatures, thermal displacement control, and the monitoring of cutting forces.

Compared to above-mentioned functions, the control of spindle stiffness may be less argued in the literatures. Recent high-speed spindles use the preload design and control to avoid the burnout of the bearings at high speeds, but this design sacrifices the spindle stiffness at low speeds. For high productivity, the control of spindle stiffness is an important issue for users and makers of machine tools. Furthermore, several researchers showed the feasibility of monitoring method of cutting forces by using spindle displacement sensors [1-3]. This method is simple and economical, but requires a precise model of the spindle stiffness for the estimation of cutting forces. However, most of the tests to measure the spindle stiffness are conducted under non-rotating conditions, while the spindle stiffness to be measured and modeled is the stiffness when it is rotating.

Tsuneyoshi developed a measurement system of the rotating spindle's stiffness in the axial direction [4]. He indicated that the relationship between the applied load and spindle displacement has nonlinear characteristics. The spindle stiffness becomes smaller under non-loading condition, which is caused by the preload setting of the bearing system in his analysis. However, the behavior of the spindle stiffness in the radial direction is not well known.

This paper presents the measurement of the stiffness of rotating spindle in radial directions. The measurement purpose is to characterize the spindle stiffness for the monitoring of the cutting forces in a sensor integrated spindle. The spindle has four eddy current sensors that detect the radial displacements of the spindle in X and Y directions. The sensor signals are interpreted as the forces applied on the tool-holder-spindle system by using the force-displacement relationship (spindle stiffness) obtained from the calibration tests. In order to measure the stiffness of the rotating spindle, a loading unit is fabricated. Several loading tests are carried out and the force-displacement relationship is investigated under different running conditions. It is found that the force-displacement relationship in the rotating spindle has nonlinear characteristic.

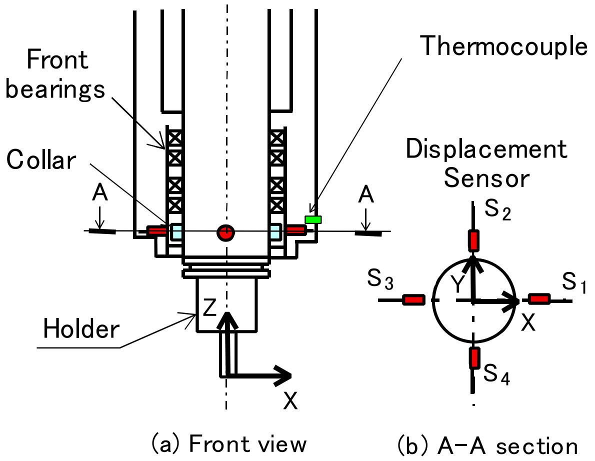


Figure 1: Sensor locations in the spindle

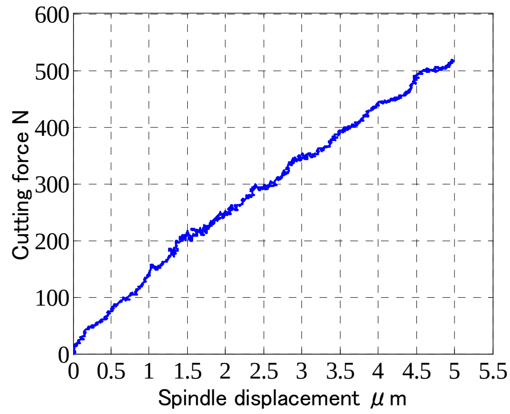


Figure 2: Measured relationship between cutting force and displacement

2. INTELLIGENT SPINDLE WITH ADDITINAL SENSORS

Figure 1 shows the configuration of the developed spindle [3]. This spindle employs a built-in motor (the rated power: 7.5kW), a jacket-cooling system, and the tapered shank holder interface. The maximum spindle speed is 20000 min^{-1} . The bearing employs the configuration of four rows in the front and one row in the rear. The preload type is constant-position type.

The spindle has two pairs of displacement sensors in X- and Y-axis directions; each has two eddy current displacement sensors opposite to each other. The signals of the opposite sensors are subtracted and divided by two, and the displacement of the spindle center is estimated.

As the displacement signals contain the component of the thermal displacement, several temperature sensors are installed to monitor the thermal status of the spindle. Especially, the temperature measured with the sensor installed near displacement sensors is important to estimate the preload change due to the thermal expansion of the spindle. This temperature is denoted "the spindle temperature" hereafter.

The spindle is built in a machining center and several cutting tests are conducted. Cutting forces are measured by a table type tool dynamometer, and the spindle displacements are measured by the installed sensors. Thus, the relationship between the cutting force and the spindle displacement is obtained.

Figure 2 shows an example of measured results. As shown in this figure, force-displacement relationship is almost linear, when the cutting forces are less than 200N. In this case, linear fitting have good agreements with measured relationships. However, if the cutting force is getting larger nonlinear characteristic is observed. It could be seen that the spindle stiffness is getting smaller as the displacement increases. This could not be explained by Herz contact theory.

3. MEASUREMENT OF SPINDLE STIFFNESS

3.1 Loading unit and measurement system

For the analysis of the spindle stiffness that includes nonlinear characteristics, loading force should be carefully controlled. However, it is difficult to control the loading force in the cutting tests. Furthermore, it is difficult to separately measure the deflection of the holder and the spindle system due to measure in the cutting tests. For this reasons loading unit is fabricated and installed on the machine table.

Figure 3 shows the schematic of the loading unit for a rotating spindle and the measurement system of the spindle stiffness. A dummy tool is attached to a measurement holder. The end of the tool shaft is supported by a bearing unit, which is connected to a tool dynamometer through a universal joint and a shaft. By moving the machine table, the load is applied to the rotating shaft-holder-spindle system. The spindle displacements are measured by using the displacement sensors

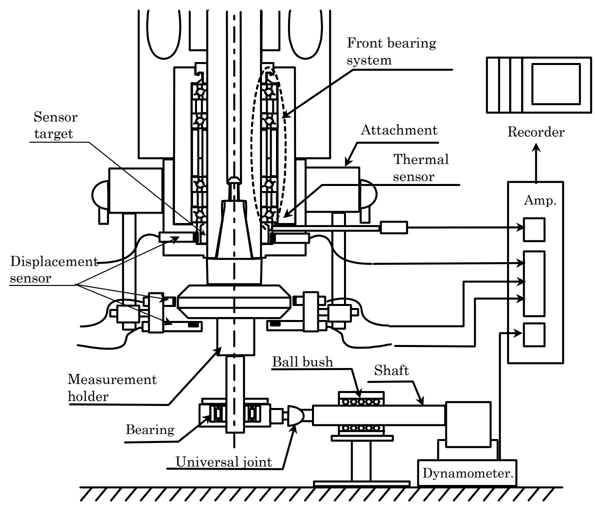


Figure 3: Loading unit and measurement system of spindle stiffness

shown in Fig.1 This displacement is called the nose displacement hereafter. In addition to this measurement, the displacements of the holder are also measured. In the radial direction, two pairs of eddy current sensors are installed targeting of the side and the bottom of the holder. S_{h1} and S_{h2} are the displacements measured at side surfaces; z_{h1} and z_{h2} the displacements at the bottom surfaces. This displacement is called the holder displacement and used to identify how the holder-spindle system moves due to the applied load.

4. MEASUREMENT PROCEDURE AND RESULTS

4.1 Measurement procedure

To investigate the spindle stiffness under the rotating and non-rotating conditions and the effect of the spindle temperature, the measurement is conducted as follows:

Step1 (at cold start): After providing the main power to the machine, the spindle is rotated at 0, 1500, and 3000 min^{-1}. The force-displacement relationship is obtained at each speed by the loading test.

Step2 (after warming up): Keep the speed at 7000 min^{-1}. After the spindle temperature gets stable, the loading test is carried out at each speed.

Step3 (after cooling down): Stop the spindle rotation. After the decrease of the spindle temperature stops, the loading test is carried out at each speed.

4.2 Force-displacement relationship

At cold start, the spindle temperature was about 22° C. Figure 4 shows the relationships between force and displacement in the radial direction measured at different spindle speeds. As seen in these figures, the force-displacement relationship shows the same nonlinearly obtained in the cutting test. Furthermore, a hysteresis loop is observed under the non-rotating condition shown in Fig.3(a). As spindle speed increases to 1500 and 3000 min^{-1}, the hysteresis loop is getting smaller (Fig.4 (b) and (c)).

After the cold-start measurement, spindle speed was increased to raise the spindle temperature. After the spindle temperature reached 25° C and kept constant, the warming up operation was terminated and then loading tests were conducted. Figure 4 shows the relationships between force and displacement measured at different spindle speeds. As shown in Fig.5 (a), the hysteresis still remains at the spindle speed of 0 min^{-1}

After cooling down the spindle, the temperature became stable at 22.5° C. Then the loading test was carried out. The obtained force-displacement relationship is almost same as those obtained after warming up. However, under the non-rotating condition, large displacement shift was observed as shown in Fig, 6. This is probably due to the change of the contact angle of the bearings.

4.3 Deflection mode

Since the holder displacement is larger than the nose displacement, it is estimated that the holder and spindle nose are deflected. Figure 7 shows the two-dimensional plot of holder displacements (S_{h1}, z_{h1}) and (S_{h1}, z_{h1}).

From this figure, it can be observed the measurement holder is tilted from the spindle rotation axis.

The tiling angle of the holder is estimated by the following equation:

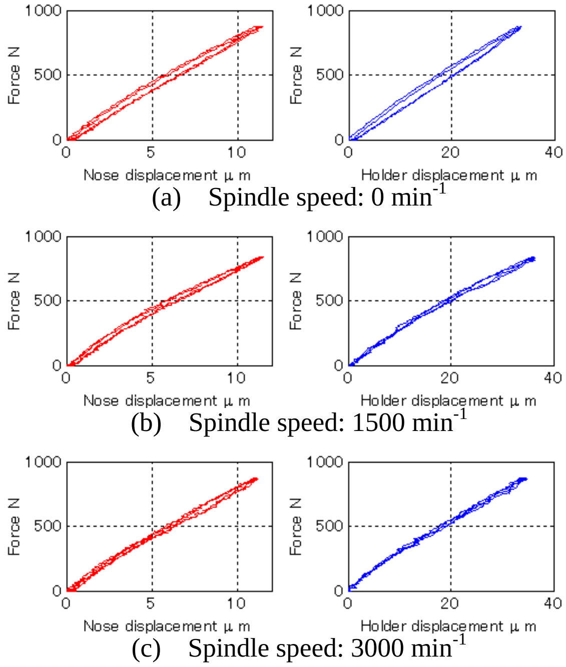


Figure 4: Force-displacement relationship measured at cold start

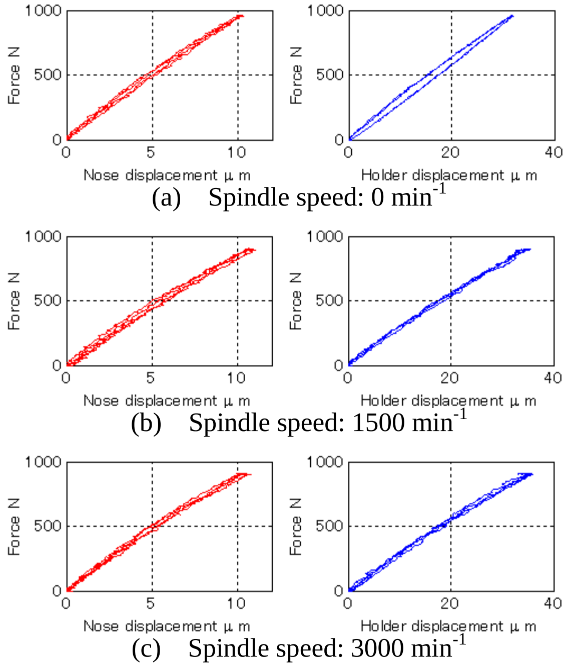


Figure5: Force-displacement relationship measured after warming up

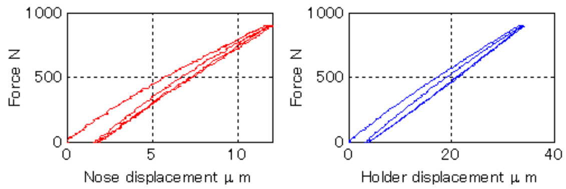


Figure6: Displacement shift measured (Spindle speed: 0 min^{-1}, after cooling down)

$$\theta_z = (Z_{h2} - Z_{h2}) / L_{hz} \quad (1)$$

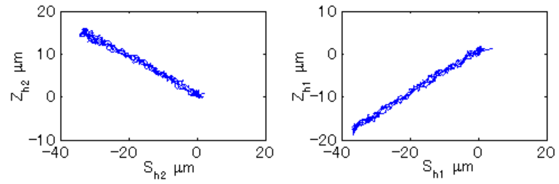
where $\boldsymbol{L_{hz}}$ is the horizontal distance between axial displacement sensors.

The deflection angle of the holder-spindle system is estimated from the following equation:

$$\theta_s = (S_{h2} - S_{h2}) / L_s \quad (2)$$

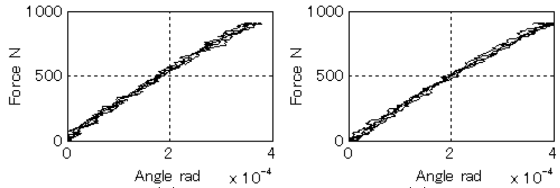
where $\boldsymbol{L_a}$ is the vertical distance between the nose and holder displacement sensors.

The tilting and deflection angles estimated by Eq.(1) and (2) are shown in Fig. 8. As seen in this figure, the tilting angle of the holder and the deflection angle of the holder-spindle system are almost the same. This implies that the rotation of the holder-spindle system with respect to the supporting center is dominant to cause the spindle displacement.



(a) (S_{h2}, z_{h2}) (b) (S_{h1}, z_{h1})

Figure 7: Holder displacement



(a) θ_z (b) θ_s

Figure 8: Tilting angle of the holder and deflection angle of the holder-spindle system

(Spindle speed: 3000 min^{-1}, after warm up)

CONCLUSIONS

In order to measure the stiffness of the rotating spindle, several loading tests are carried out and the force-displacement relationship is investigated under the different running conditions. The results are summarized as follows:

(1) Under the non-rotating conditions, the hysteresis is observed in the force-displacement relationship.

(2) It was found that the force-displacement relationship in the rotating spindle has soft-spring nonlinear characteristic.

(3) The spindle nose displacement is dominated by the tilting motion of the tool-holder-spindle system.

ACKNOWLEDGMENTS

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REFERENCES

[1] Albrecht, A., Park, S. S., Altintas, Y., and Pritschow, G., 2005, ”High Frequency Bandwidth Cutting Force Measurement in Milling using Capacitance Displacement Sensors,“ International Journal of Machine Tools and Manufacture, 45(9), pp.993-1008.

[2] Kim, J. H., Chang, H. K., Han, D. C., Jang, D. Y., and Oh, S. I., 2005, “Cutting Force Estimation by Measuring Spindle Displacement in Milling Process”, CIRP Annals - Manufacturing Technology, 54(1), pp.67-70.

[3] Sarhan, A. A. D., Matsubara, A., Sugihara, M., Saraie, H., Ibaraki, S., Kakino, Y., 2006, “Monitoring Method of Cutting Force by using Additional Spindle Sensors,” JSME International Journal, Series C, 49(2), pp.307-315.

[4] Tsuneyoshi, T., 2007, “Spindle Preload Measurement and Analysis,” Proc. of the 2007 ASPE Summer Topical Meeting, ASPE, June 11 and 12, State College, PA, pp.35-38.