DYNAMIC CHARACTERIZATION OF A HEAD UNIT WITH A SMALL HIGH SPEED SPINDLE IN MESO-SCALE MACHINE TOOLS

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INSTRUCTIONS

For machining process using rotation of a tool, spindle error directly affects the quality of the machined parts. Spindle error can be divided into several error components such as radial errors, axial errors, etc.[1,2] Especially, there exist two kinds of error motion in spindle error along the radial direction. Synchronous error motion due to bearing imperfection and misalignment causes out of roundness during cutting a round hole. Asynchronous error motion is related with bearing wear, improper preload and structural vibration and affects the surface finish of the machined parts. Research for identifying the radial error motion was begun long time ago. Tlusty measured spindle error motion by using non-contact capacitance sensors and an artifact such as master ball which is popularly used now.[2] This traditional measurement system assumes that there is no inaccuracy of an artifact used. For more precise measurement, the inaccuracy of the artifact such as eccentricity and roundness should be removed. Many researchers have developed various methods to eliminate the effect of the artifact.[3,4] Although the developed methods like multi-probe and multi-step method has good performance and can be used for nanometer-level measurement, some devices such as turn-table and stylus are required and it takes a lot of time to carry out measurement.[5] For measuring the error of a small spindle system in a meso-scale machine tool, a small precise artifact and an index table are needed to apply the above techniques. It is cost-effective to find an alternative way with a less precise artifact as machining system does not require tens nanometer-level precision. In this study, a method to measure radial error motion of a small spindle is proposed. It is suggested that a new and simple method to separate artifact errors from the measured data without additional devices. The spindle error can be affected by a head structure as well as a spindle itself. The dynamic characteristics of the spindle head and a spindle are the important factors to decide spindle error motion[6]. Moreover, a spindle at over tens thousands revolution per minute is needed to adapt for the required cutting speed as the small tools is used in a meso-scale system. Therefore dynamic characteristics of a head structure with a spindle become more significant in the design of the meso-scale systems. The influence of the dynamic characteristics of a spindle unit on spindle error is examined in this study.

RADIAL SPINDLE ERROR MEASUREMENT

<u>Separation of Eccentricity</u>

In general, the reference artifact is used to measure the spindle error. The artifact must be considered first because it has eccentricity and roundness errors. Initially, a simulation is carried out to analyze the change of measurement data based on eccentricity. Fig. 1 shows the eccentricity of the artifact which is called as master ring in this study. After selecting reference coordinate system with center of the master ring as the origin, the radius R_o is determined. The eccentricity e is expressed as the distance between the origin point of the reference coordinate system and the center of the rotating axis O. When a circle is rotating at arbitrary eccentricity e, the change in the data of circle can be evaluated.

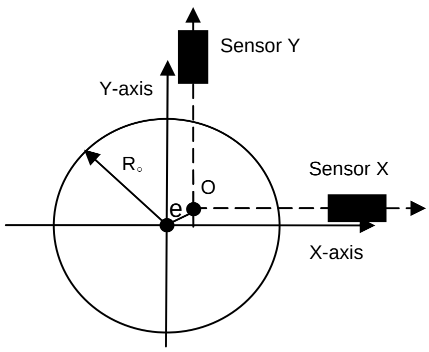


FIGURE 1. Schematic diagram of the master ring with eccentricity.

Positional information of the measured values from each sensor is taken at point O about sensor X and sensor Y as shown in Fig 1. The measured data is expressed into two circles on polar coordinate system. If axes of the sensors and axis of rotation are not coinciding, the radius of circle differ each other on the plot. Therefore, each sensor must be adjusted to get the exact data for actual measurement. Concurrently, the distance between center of the two circles and origin point of polar coordinates will coincide with eccentricity. If a different effect such as spindle error exists, the shape of ideal circle on polar coordinates can't be drawn. In this case, a best fit circle is evaluated using least square method. Hence, the eccentricity is inferred in this way.

Separation of Roundness

After removing the eccentricity of master ring, the roundness and spindle error have to be separated. It can be assumed that roundness of the artifact has a lower frequency comparing with spindle error in most operational process and its frequency has integer multiple times of spindle speed. Also, the roundness is repetitive against rotation. Therefore, the frequency characteristic of the measured data is analyzed using FFT (Fast Fourier Transform) and the cut off frequency is decided from rotation frequency of the spindle. In this experiment, five-times of rotation frequency of the spindle is selected.

EXPERIMENTS

As shown in Fig. 2, a master ring is used, instead of master ball. Non-contact capacitance sensor with 15nm resolution is constructed for measuring displacement of spindle. To measure the speed of the spindle a capacitance sensor (sensor 3) is set up at hollow part of spindle's chuck as shown in Figure 4. Bandwidth of capacitance sensor limits maximum sampling data. The larger the bandwidth is, the more sampling data is securely obtained at the large value of bandwidth. Sampling data number based on rotation velocity is calculated after selecting bandwidth of 16 kHz.

Table 1 shows the results of experiments and real error values of an artifact. Before conducting the experiments, inaccuracy of the artifact was measured to compare with the analyzed values using a CMM. The eccentricity and roundness of the artifact are 40.5 ㎛ and 1.8 ㎛, respectively. Experiments are carried out from 2,500 to 60,000 RPM. It is observed that the calculated eccentricity of the artifact increases as rotating speed is increased. As rotation speed increases, estimated eccentricity has more error. It shows that fitting error in separation of eccentricity increases as asynchronous error motion increases. In the case of roundness error, it is difficult to select the cut off frequency since the number of measured data per revolution decreases at over 20,000 PRM of spindle speed. Therefore, separation of the roundness error was done by using the analyzed roundness value at 20,000 RPM where the frequency analysis is clear. In this study a ball bearing spindle is used. As compared with fluid and air bearings spindle, ball bearing spindle displays the largest amount of asynchronous error motion.

DYNAMIC CHARACTERISTICS OF SPINDLE SYSTEM

The rotation of a spindle causes vibration of a machine tool. Structural analysis for vibration is needed to miniaturize a machine tool. Deviation of dynamic characteristics and spindle error in radial direction according to structure of spindle unit was analyzed.

Two clamping cases are selected according to headstock location as shown in Fig. 3 and a change of spindle error was analyzed in both cases during operation. To make experiments simpler, a cylinder shape artifact was used to find not quantitative result but relative difference. Therefore, measured error values include eccentricity and roundness of the artifact and chucking error. The diameter of sensors is 1.7 ㎜ and minimum target diameter is 2.3 ㎜. can be used, the diameter of the artifact is bigger than minimum target diameter.

TABLE 1. The result of experiments. (Unit: ㎛)

RPM	Eccentricity	Roundness	Spindle error	
			X-data (max, min)	Y-data (max, min)
2,430	39.80	1.94	5.59, -4.36	4.79, -4.76
4,990	39.98	1.68	4.76, -4.90	4.67, -3.98
9,380	40.15	1.92	4.05, -3.05	3.07, -2.81
14,990	40.14	1.67	3.98, -3.49	3.56, -3.39
19,990	40.55	1.62	3.66, -2.87	2.85, -2.98
25,010	41.64	-	3.82, -2.44	3.40, -2.67
28,300	42.21	-	3.31, -2.02	3.53, -2.56
40,110	44.94	-	4.28, -3.05	3.10, -3.73
60,730	49.60	-	7.90, -11.71	5.39, -6.01

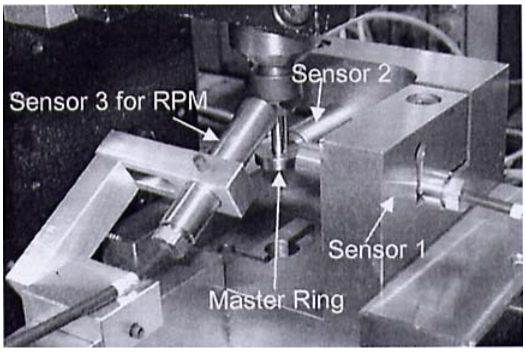


Figure 2. Experimental set-up.

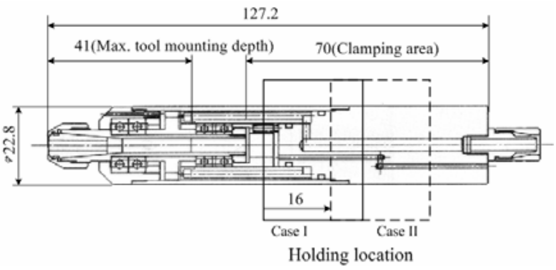


FiGURE 3. Schematic diagram of spindle (showing Case I and II).

Because the size of collet chuck is 3 ㎜ and the cylindrical shape artifact with 3 ㎜ of diameter However, target shape should be considered. Since non-contact capacitive sensors are calibrated with a flat target, measuring a target with a curved surface will cause errors. Linearity of sensing with the target was tested using a laser interferometer.

For travel range from 0 to 100 ㎛, mean value of the ratio of step displacement to a change of voltage is 22.38 [㎛/V] and standard deviation is 0.25 [㎛/V]. Because spindle error is generally within 50 ㎛ and measuring device has good linearity within 100 ㎛, measurement with the target is applicable. Table 2 shows the measured spindle error result. Both cases has similar trend that error becomes bigger as the speed increases. However, a large error occurred in case I and a small error exists in case II at 75,000 rpm. It can be assumed that this phenomenon is due to the structure of spindle unit including a headstock. Vibration test was done to verify this assumption. Through vibration test, the influence of vibration characteristic on spindle error was analyzed.

An accelerometer is attached at the end of the stator part of a spindle and impulse force is applied at near sensor position using an impact hammer.

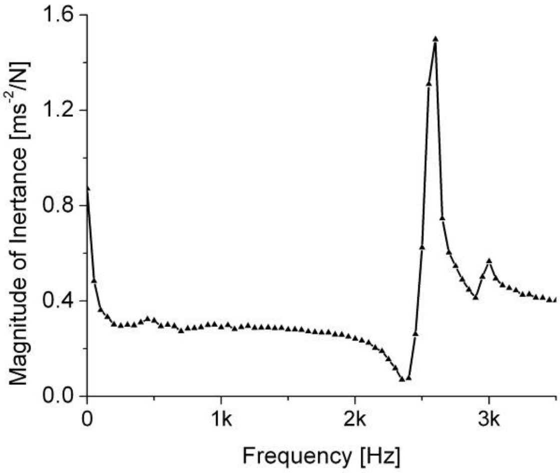


FIGURE 4. FRF plot of a spindle.

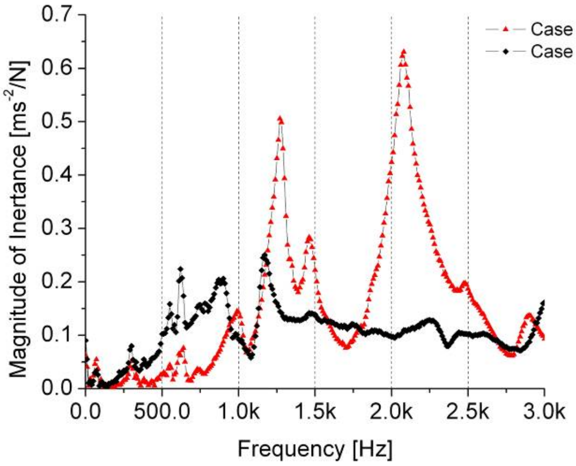


FIGURE 5. Magnitude plot of both cases.

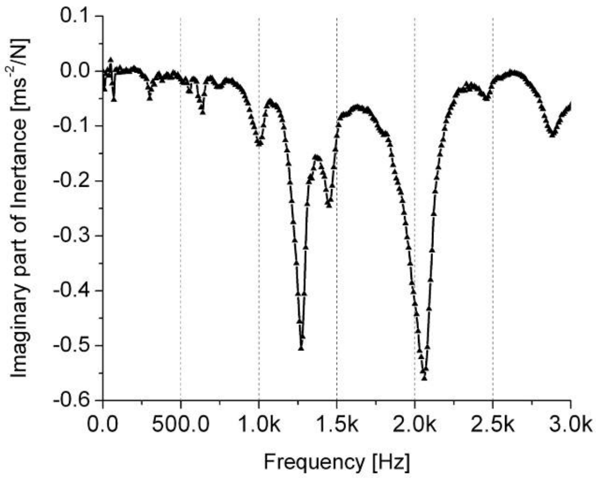
As shown in Fig. 4, a spindle has a mass-dominant characteristic at low frequency region and its resonance frequency is 2.6 kHz. This frequency is not a matter of concern as maximum operating speed is 120,000 rpm.

There occur dominant peaks at 1258 Hz and 2060 Hz in the case I and at 610 and 1183 Hz in the case II as shown in Fig. 5 and Fig. 6. It is observed that spindle error become larger at the peak has the largest magnitude is 1258 Hz (75540 rpm, Case I) and 1183 Hz (70980 rpm, Case II). Proper spindle speed should be found according to structure to minimize the influence of vibration. Considering dynamic feature in case I, the structure is stable over 90,000 rpm.

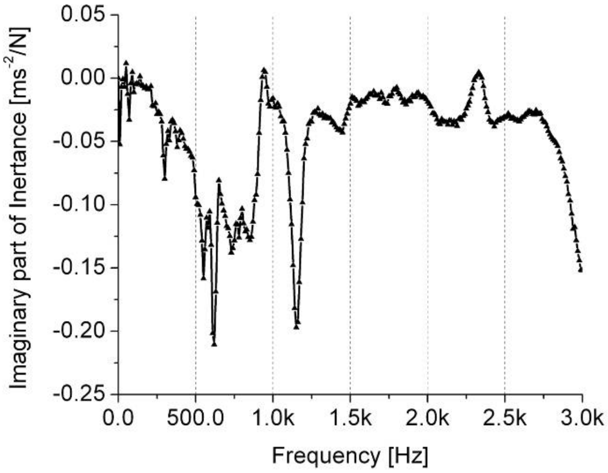
However, unbalance effect become bigger as speed increases so that spindle error becomes larger.

TABLE 2. Spindle error according to spindle speed and cases.

Spindle speed [rpm]	TIR [μm] (Total Indicator Reading)	
	Case I	Case II
30000	10.18	12.35
45000	10.68	13.10
60000	15.60	17.03
75000	21.65	9.28
90000	13.08	16.38



(a) Case I



(b) case II

FIGURE 6. Imaginary part of FRF plots.

CONCLUSIONS

In this paper, radial error of a high speed meso-scale spindle is analyzed at various speeds. By using a new data analysis method, the radial error of high speed meso-scale spindle is effectively determined. The difference between calibrated real values of eccentricity and roundness error obtained using CMM and the present algorithm is less than 1 μm for 2,500 to 20,000 RPM. Using the method presented in this paper for radial error analysis, it is possible to analyze the small-sized and high-speed spindle measurement data.

Though modal testing, relationship between the structure of spindle unit and spindle error were studied. Under structural limitation due to miniaturization and requirement of high speed spindle, dynamic analysis according to the structure of spindle unit is necessary to design a meso-scale machine tool.

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