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ORIGINAL ARTICLE

Investigate the spindle errors motions from thermal change for high-precision CNC machining capability

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Abstract As the demand for high speed and highly accurate machines has significantly increased, error motions from thermal change, which is up to 70 % of the total machining error, is found to be the main hurdles to overcome in improving the accuracy of CNC machine tools. In this research work, the authors installed four eddy current displacement sensors in the spindle structure near to the front bearing to monitor the spindle offset in the bearing level, which is mainly attributable to the thermal error motions of the spindle. In addition, another three capacitance sensors are mounted on the machine table level and aligned with the x-, y-, and z-axis of the machine to monitor the spindle shift in the table level to find out the correlation between temperature change and the thermal error motions of the spindle. To measure the temperature changes, we attached thermal sensors in the machine and cooling system. The estimation of the spindle thermal displacement based on temperature data from these thermal sensors can provide more information for the monitoring of thermal error motions of the spindle.

Keywords Machine tool spindle · Thermal error motions · High-precision machining · Displacement sensors

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1 Introduction

Modern machine tools must provide high-precision machining capability and also high productivity. Spindles are fundamental to most machine tools. Some people have gone so far as to describe a machine told as a spindle with support hardware and advanced design machine tools tend to confirm this point of view [1] and [2]. Modern machine tools have stiff structure and accurate positioning capabilities. However, the weak link in a machine tool is often the spindle; so, spindle analysis is highly needed to identify the factors that are limiting manufacturing processes [3].

A rotating spindle generates an axis of rotation. This is a theoretical line about which rotation occurs. This axis line has six degrees of freedom or six different independent motions that can be experienced. These six degrees of freedom are linear motion in x-, y-, and z-axis directions; tilt along the axis of rotation in the x- and y-axis directions; and rotation about the z-axis line. An ideal spindle allows motion in only one degree of freedom, which is rotation about the z-axis line. Motions in the other five degrees of freedom are undesired error motions. These undesired errors in motions cause degradation in surface finish, roundness, and geometrical accuracy which in consequence, will lead to reduction in product quality [4–6].

The undesired error motions can be classified as geometrical errors, temperature rise errors, dynamic errors, etc. According to relevant studies, errors caused by thermal changes are typically the largest positional error in a properly installed and operating machine tool [7] and [8]. It is reported that 40–70 % of errors of machine tools result from the errors caused by thermal changes [9], where the main source of heat lies in the friction between the spindle and transmission belt,

Table 1 Specifications of the machining center GV-503

Spindle	Spindle speed (rpm)	200–20,000
	Power 15 min./cont. (kW)	22/18.5
	Tool interface	7/24 taper No.40 with nose face contact
Feed drive	Max. rapid traverse rate (mm/min)	42,000
	Max. feed rate (mm/min)	42,000
	Max. acceleration rate (m/S^2)	x-axis:4.7, y-axis:5.1, and z-axis:7.9
	Travel distance (mm)	x-axis: 610, y-axis: 510, and z-axis: 460
Machine size	Width × length × height (mm)	2,232×3,987×2,892
	Mass (kg)	10,100
CNC servo system	64bit CPU (RISC processor) + high gain servo amplifier	

and that between spindle and ball bearings. Cooling is provided by a built-in cooling system in the spindle housing; therefore, the dynamic balance of heat flux stabilizes after a while, and so do temperatures. However, temperature fluctuations of a few degrees, plus or minus, are inherent [10] and [11]. These thermal error fluctuation motions occur simultaneously on different directions, so measuring the thermal error motions as the spindle is rotating at operation speeds is the most important theme to solve for the machine tool designer and also for the industrial engineer who use this equipment on the workshop.

In this research work, we examined the machine tool spindle and/or bearing error motions caused by the thermal changes. To investigate these error motions, we have integrated the machine with displacement sensors system at different levels, temperature sensors system, and a signal acquisition and data analysis system to construct an independent module measurement system of spindle, by means of which it can be easy to find out the correlation between temperature change and thermal error motions for the spindle. This can be used to test the quality of spindles and also provides the basis for compensation of thermal error motion during practical manufacturing process.

2 Experimental set-up to investigate the spindle thermal error motions

In order to investigate the machine tool spindle and/or bearing thermal error motions, displacement sensors and thermal sensors are installed on the spindle unit of a high-precision machining center. The machine used in the study is a vertical-type machining center (GV503 made by Mori Seiki Co., LTD.). The spindle has constant position preloaded bearings with oil–air lubrication and the maximum rotational speed is 20,000 min^{-1}. Table 1 shows the specifications of the machining center used. Four eddy current displacement sensors are installed on the housing in front of the bearings to detect the radial motion of the rotating spindle. The specifications of the sensor are as follows: the diameter is Ø 5.4 mm and the length is 18 mm; measurement range is 1 mm; nominal sensitivity is 0.2 mm/V; dynamic range is 1.3 kHz; and linearity is ±1 % of full scale. Table 2 shows the specifications of the Eddy current displacement sensor. A thin collar with a fine cylindrical surface is attached to the spindle as a sensor target. Figure 1a, shows the Eddy current displacement sensor locations. The two sensors, S_1 and S_3, are aligned oppositely in the x direction, and the other two sensors, S2 and S4, are aligned opposite in the y direction. In order to measure spindle temperature, several thermocouples are attached to the spindle structure. Those thermocouples include T_1 and T_2 shown in Fig. 1a. The thermocouple T_1 is installed in the same hole where the displacement sensor S_4 is installed, while the other thermocouple T_2 is installed on the body of the spindle unit, which is near the windings of the built-in motor. The sampling time and sensor resolution are 60 s and 0.1 °C, respectively.

In addition, another three capacitance sensors C_1, C_2, and C_3 are mounted on the machining table and aligned with the x-, y-, and z-axis of the machine as shown in Fig. 1b and in Fig. 2. The sensors C_1 and S_3 are located in the same side in x direction, and the sensors C_2 and S_4 in y direction. The target of the sensors C_1, C_2, and C_3 is a precision ball mounted onto the spindle using an adjustable holder. Table 3 shows the specifications of the capacitance displacement sensor used in this experiment. The sampling frequency for the measurement is 1 Hz.

3 Experimental result

The displacement and temperature are measured during the spindle rotation without cutting. The spindle is started at 1, 500 min^{-1} and kept rotating for 1 h. After that, the spindle

Table 2 Specifications of the eddy current displacement sensor

Detection principle	Eddy current
Measurement range (mm)	0~1
Output scale (V)	0~5
Sensitivity (mm/V)	0.2
Resolution (μm)	0.4
Dynamic range (kHz)	1.3 (−3 dB)