High-Precision Machining by Measuring and Compensating the Error Motion of Spindle's Axis of Rotation in Radial Direction

Ahmed A. D. Sarhan, M. A. Hassan, Atsushi Matsubara, and M. Hamdi

***Abstract*—This paper deals with cutting force monitoring for high precision machining. The authors have employed displacement sensors to monitor the cutting forces, as they are cheap and small enough to be built in the spindle structure. A monitoring method, which utilizes sensitive displacement sensors, is discussed. The sensors are installed in X Y directions near the front bearings of the spindle, to detect the small displacements of a spindle caused by cutting forces. Monitoring tests are carried out under end milling operations and the cutting forces are estimated from the displacement signals by the simple signal processing technique. However, as the displacement sensor measures the variation of the gap size between the sensor head and the target surface, it also records displacements due to error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface. By comparing the cutting force estimated from displacement sensors with the cutting force measured by using a dynamometer, the machine tool spindle error motions is investigated, and its compensation scheme is proposed. The test results show that the monitoring system is reliable for the adaptive control of machining accuracy for end milling process.**

***Index Terms*— High Precision Machining, Cutting Force, Displacement Sensor, Spindle Error Motion**

I. Introduction

THE present global market competition has attracted the manufacturer's attention on automation and high precision machining via condition monitoring of machine tools and processes as a method of improving quality of products, eliminating inspection, and enhancing manufacturing productivity [1-6]. The cutting forces are the most important indicator for that as they could tell limits of cutting conditions, accuracy of the workpiece, tool wear, and other process information, which are indispensable for process feedback control [7-14]. Hence, reliable cutting force measurement systems are investigated. The most common method to measure cutting forces in machining operations is through table dynamometers. Although table dynamometers provide accurate and effective force measurement, they are more suitable for laboratory or experimental use rather than for practical application on production machines, due to the limitation of workpiece size, mounting constraints, high sensitivity to overload, and high costs [15-17]. Furthermore, the dynamic characteristics of table dynamometers are strongly dependent on the workpiece mass, which may change during machine operation. To overcome limitations of workpiece mass and size, a force sensor can be integrated to the spindle itself instead of installing it on the machine table, thus converting an ordinary spindle into a called monitoring spindle [18-20].

The authors have employed displacement sensors, as they are cheap and small enough to be built in the spindle structure. Displacement signals are translated into cutting force information by the calibration. However, the monitoring quality is a problem, because sensors also detect the displacement caused by machine tool spindle error motions in the radial direction [21-26]. In this research, we develop a spindle with displacement sensors in X and Y-axis directions near the front bearings of the spindle, to monitor the spindle displacement. Cutting forces are estimated from the displacement signals by the simple signal processing technique. Monitoring tests are carried out under end milling operations on cast iron workpieces. By comparing the estimate with the measured cutting force by using a dynamometer, the machine tool spindle error motions in sensor output is investigated, and its compensation scheme is proposed. With its compensation scheme implemented, the experimental result shows that the monitoring system is reliable for the adaptive control of machining accuracy for end milling process.

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II. Measurement of the Spindle Displacement to Investigate the Spindle's Axis Error Motions

A. *Experimental set-up*

In order to measure the machine tool spindle displacement caused by cutting force during cutting to

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investigate the error motion of spindle's axis of rotation, displacement 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 20000 min^{-1}. Four eddy-current displacement sensors are installed on the housing in front of the bearings to detect the radial motion of the rotating spindle. Tables 1 and 2 respectively show the specifications of the machining center and the displacement sensor used in this research. A thin collar with a fine cylindrical surface is attached to the spindle as a sensor target. Figure 1 shows the sensor locations. The two sensors, S_1 and S_3, are aligned opposite in the X direction, and the other two sensors, S_2 and S_4, are aligned opposite in the Y direction.

TABLE 1. SPECIFICATIONS OF THE MACHINING CENTER

Spindle	Spindle speed (min^{-1})	200 - 20000
	Power 15min./cont. (kW)	22 / 18.5
	Tool interface	7/24 taper No.40 with nose face contact
Feed drive	Max. rapid traverse rate (mm/min)	33000
	Max. feed rate (mm/min)	10000
	Max. acceleration rate (G)	X-axis: 0.67, Y-axis: 0.64, and Z-axis: 0.56
	Travel distance (mm)	X-axis: 630, Y-axis: 410, and Z-axis: 460
Machine size	Width×Length×Height (mm)	2320×3780×2760
	Mass (kg)	5500
CNC servo system	64bit CPU (RISC processor) + high gain servo amplifier	

TABLE 2. SPECIFICATIONS OF THE DISPLACEMENT SENSOR

Detection principle	Eddy current
Measurement range (mm)	0~1
Output scale (V)	0~5
Diameter mm	5.4
Length mm	18
Sensitivity (mm/V)	0.2
Linearity (%of full scale)	±1
Dynamic range (kHz)	1.3 (-3dB)

B. Experimental procedure

A slot end-milling test is carried out to investigate the machine tool spindle error motion in radial direction. Table 3 shows the tool and cutting conditions. The cutting time for one operation should be short enough to avoid the thermal disturbances on displacement signals.

First, the spindle is rotated at 1500 min^{-1} without cutting for 30 min for the first warm-up. Then, the 1st cutting test is carried out at the same spindle speed. The spindle is warmed up again at the speed of 3000 min^{-1} for another 30 min without cutting followed by the 2nd cut at the speed of 3000 min^{-1}.

Similarly, the third and forth warm-up and cutting tests at 6000 and 12000 min^{-1} are carried out. The displacement signals are digitized with a 16-bit A/D board, and the dynamometer signals are digitized with a 12-bit A/D board. The sampling frequency is set so that 40 points per one spindle revolution can be obtained.

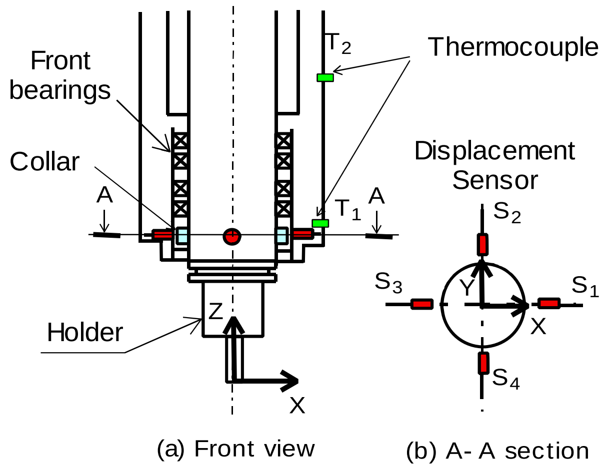


Fig.1 Locations of the sensors

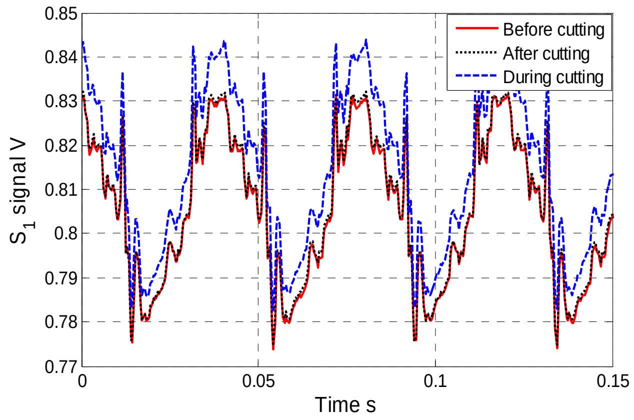
TABLE 3. THE TOOL AND CUTTING CONDITIONS

Spindle Speed (min^{-1})	1500, 3000, 6000, 12000
Axial depth of cut (mm)	10
Feed mm/min	600
Cutting tool	Coated carbide end mill, Diameter: 10 mm,
Holder	BT40-C20 (collet)-20 (extension)
Cutting mode	Down cut
Coolant	No
Workpiece material	Carbon steel (S50C)

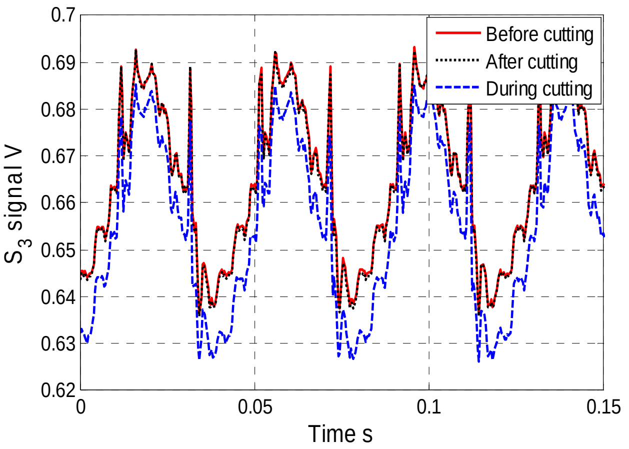
C. Experimental results

Figure 2 shows an example of the output of the displacement sensor signals in X-axis direction before, during, and after cutting at spindle speed of 1500 min^{-1}.

As can be seen in Fig. 2, before cutting, all the displacement profiles involve periodical type of fluctuation. These periodic fluctuations are related to the error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface. During cutting, it is observed that, the displacement profile shifts but it returns back to its original position after the end of cutting.



(a) The output of the S_1 sensor signals



(b) The output of the S_3 sensor signals

Fig. 2. The output of the displacement sensor signals at 1500 min^{-1}

III. The Compensation of the Error Motion of Spindle's Axis of Rotation in Radial Direction

As can be seen in Fig.2, the displacement sensor measures not only the variation of the gap size between the sensor head and the target surface but also the displacements due to error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface. These errors are simply compensated by subtracting the displacement signals measured while air cutting from the displacement signals measured while cutting.

A. The concept of the error motion compensation scheme

Figure 3, shows the concept of the spindle displacement measurement. When the spindle axis shifts by Δx μm in X direction due to the cutting force, the displacement signals from S_1 and S_3 are as follows.

$$S_1(\theta) = G[R_1 - r(\theta) - \Delta x] \quad (1)$$

$$S_3(\theta) = G[R_3 - r(\theta + \pi) + \Delta x] \quad (2)$$

Where G: sensor sensitivity [mV/μm], R_i: the distance between the spindle center and detection surface of the sensor S_i [μm] (i=1,..,4), θ: rotation angle of the spindle [rad], $r(\theta)$: the sum of the radial error motion and surface roughness of the sensor target [μm].

Subtracting the displacement signals and dividing the subtraction by two, we obtain;

$$S_x(\theta) = [\ S_3(\theta) - S_1(\theta)\ ]/2 \quad (3)$$

Letting $S_x(\theta) = S_{xo}(\theta)$ at air cutting such that $\Delta x = 0$, and subtracting $S_{xo}(\theta)$ from $S_x(\theta)$ to compensating the radial error motions.

$$S_x(\theta) - S_{xo}(\theta) = G \cdot \Delta x \quad (4)$$

Then we obtain the axis shift Δx after the compensation as follows.

$$\Delta x = [\ S_x(\theta) - S_{xo}(\theta)\ ]/G \quad (5)$$

Similarly, the axis shift in Y direction, Δy, is calculated from the displacement signals from S_2 and S_4. The axis shift is called the spindle displacement hereafter.

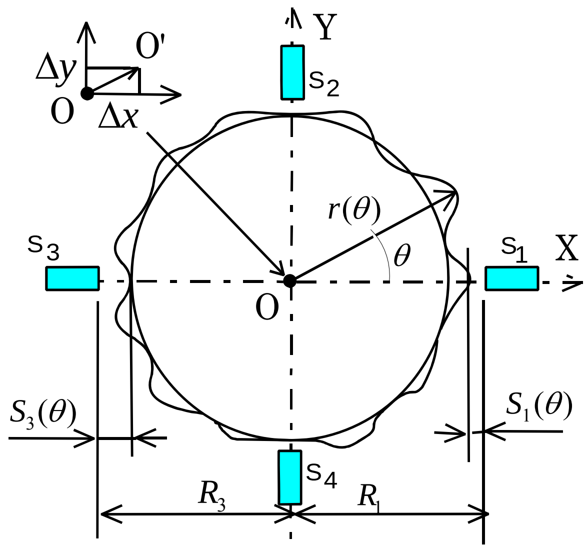


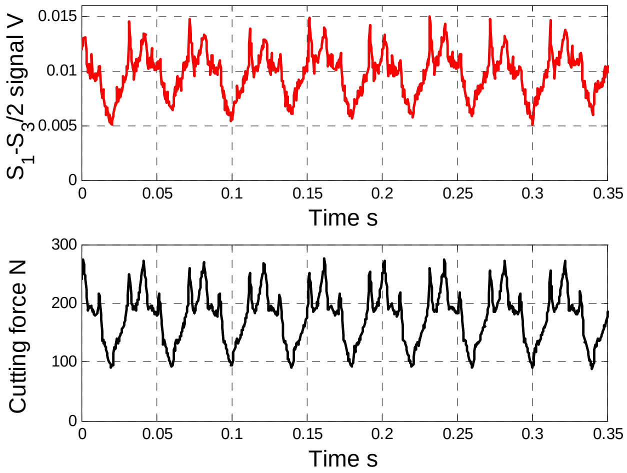
Fig.3. The concept of the spindle displacement measurement

B. Investigate the accuracy of the compensation

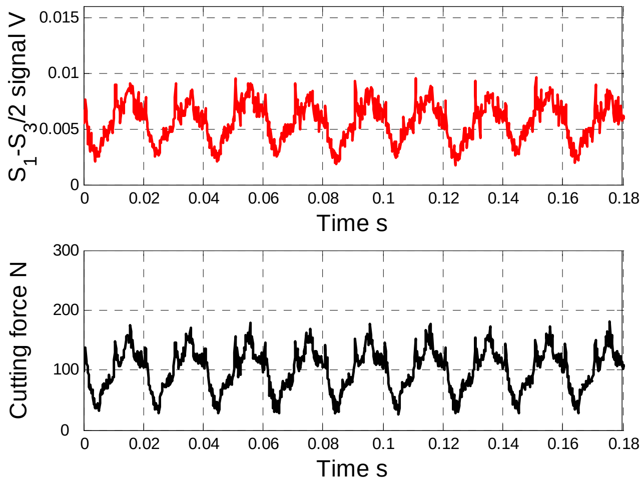
The accuracy of the compensation is investigated by comparing the compensated spindle displacement with cutting forces measured by using a table type tool dynamometer (Model 9257B made by Kistler). Figure 4 shows the compensated spindle displacement and measured cutting force with the dynamometer at different spindle speeds. As can be seen in Fig. 4, the displacement profiles looks similar to the force profiles.

Figure 5 shows the relation between the spindle displacements and cutting forces at different spindle speeds.

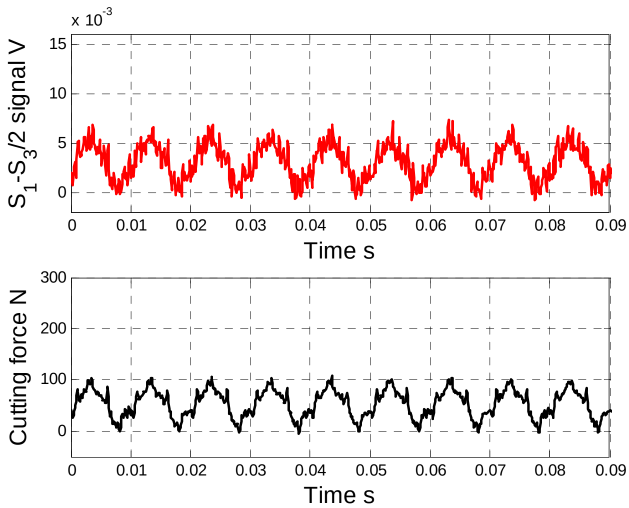
The quantization error in digital measurement system is 0.1526 mV. As can be seen in Fig. 5, the spindle displacement has a linear relationship with the cutting force when the spindle speed is less than 12000 min^{-1}. In the case where the spindle speed is 12000 min^{-1}, the relationship between the spindle displacement and the cutting force shows an unstable characteristic. This characteristic may come from the dynamics limitations of the measurement system.



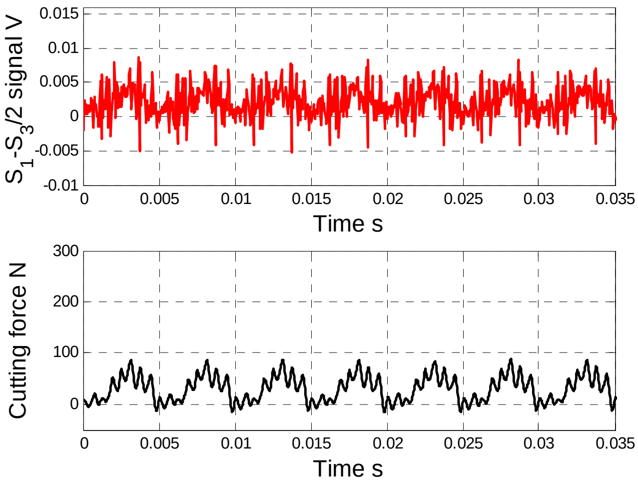
(a) Spindle speed: 1500 min^{-1}



(b) Spindle speed: 3000 min^{-1}



(c) Spindle speed: 6000 min^{-1}



(d) Spindle speed: 12000 min^{-1}

Fig. 4. The compensated spindle displacement and measured cutting force

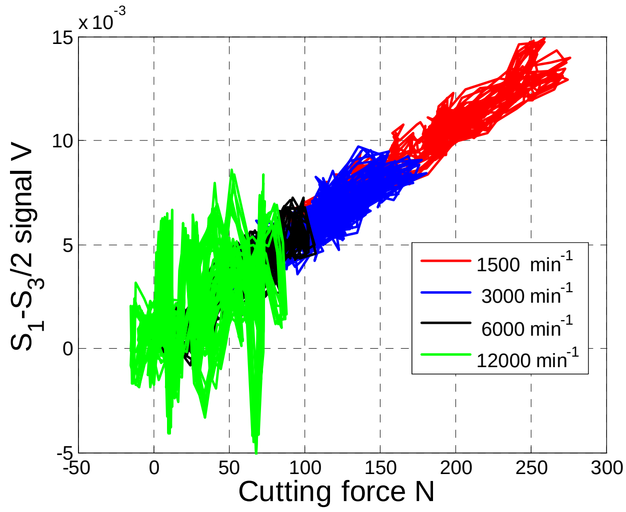
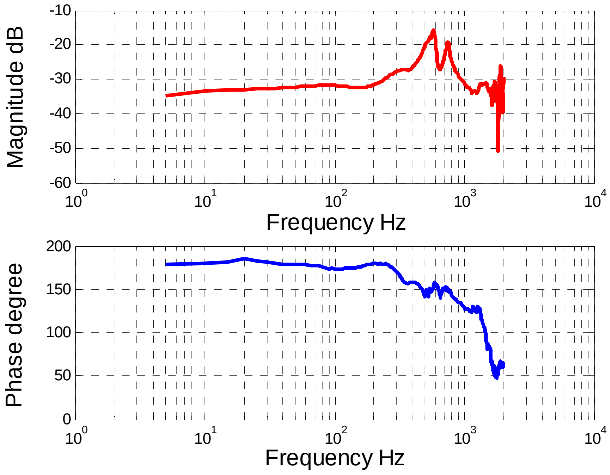


Fig. 5. The relation between the spindle displacements and cutting forces at different spindle speeds.

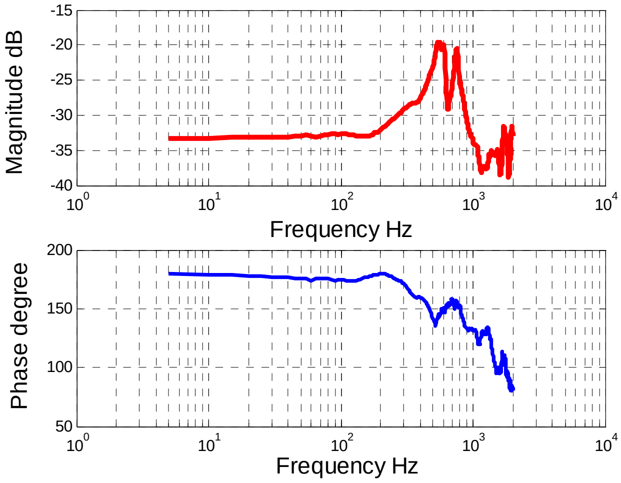
C. *The dynamics limitations of the measurement system*

To investigate the dynamic limitations of the measurement system, the spindle structure is excited on the tool tip and tool holder. The spindle is hammered by an impact force hammer while the spindle is stopping. Both impact force and displacement are record synchronously and processed using a Fourier analyzer system to identify the frequency bandwidth. The sampling frequency used is 5 kHz. Figure 6 shows the frequency response of displacement sensor S_3. The first major resonance peak is at approximately 570 Hz and the second one is at 750 Hz. The transfer function measurements indicate that the sensor system can respond cutting forces which bandwidth is 200 Hz whereas the magnitude and phase shift remains almost invariant. Hence, the sensor system can measure the force components precisely at the spindle speeds up to 12000 min^{-1}, which is totally matching with the results shown in Fig. 5.

Similar results are obtained from the other displacement sensors.



(a) Frequency response from tool tip to sensing point



(b) Frequency response from tool holder to sensing point

Fig. 6 Frequency response of displacement sensor S_3

IV. Conclusion

Displacement sensors are installed in the spindle structure of a machining center for the monitoring of cutting forces. We present how to monitor the spindle displacement more precisely by using four eddy-current displacement sensors. The displacement sensor measures not only the variation of the gap size between the sensor head and the target surface but also the displacements due to error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface. The error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface are compensated by subtracting the displacement signals measured while air cutting from the displacement signals measured while cutting. The accuracy of the compensation is investigated by comparing the compensated spindle displacement with cutting forces measured by using a table type tool dynamometer. The test results show that the monitoring system is reliable for the adaptive control of machining accuracy for end milling process. However, in the case where the spindle speed is 12000 min^{-1}, the relationship between the spindle displacement and the cutting force shows an unstable characteristic. This characteristic may come from the dynamics limitations of the measurement system.

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