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MONITORING OF CUTTING FORCE USING SPINDLE DISPLACEMENT SENSOR

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ABSTRACT

In order to obtain higher productivity under unmanned operations in end milling, a reliable technique for process monitoring and control is required. This paper presents a monitoring method of cutting forces by using high-accuracy displacement sensors installed in a spindle of a machining center. Its estimation performance is experimentally investigated by machining tests on carbon steel under different cutting conditions. It is found that the estimation error is caused mainly by the drift in the displacement sensor output. With its compensation scheme implemented, the experimental result shows that the monitoring of small and medium scale cutting forces is possible, if cutting process is intermittent.

1. INTRODUCTION

The requirement for higher quality, higher efficiency, and further reduction of production cost are continuous demands in machining processes. Current CNC-servo systems are getting so flexible that they can change CNC and servo parameters on-line and offer the information of the operation status and internal information such as motor current, motor speed and so on. There are several researches found in the literature on the monitoring and control of the machining process based on such internal information [1,2,3,4]. For drilling and tapping processes, the estimation of cutting forces by monitoring the motor current in spindle and/or feed drive units is effective. In end milling processes, however, it is difficult to estimate a cutting force smaller than 200N by this method, since in end milling processes the magnitude and the direction of cutting force may rapidly change. Furthermore, the cutting force component in motor current is difficult to be distinguished from friction and inertia force components introduced under the motion of machine drive.

Tu and Jeppsson utilized strain gauges for the monitoring of cutting forces in end milling process [5]. Mathias controlled the milling process based on the cutter load by sensing the deflection of the spindle [6]. Matsubara et al. reported that smaller cutting forces can be monitored by using spindle displacement sensors [7].

Such external sensing methods, however, may suffer from noise problems caused by thermal and dynamic behavior of machine components. The spindle displacement sensor method, especially, suffers from a sensor drift, which leads to monitoring errors.

This paper studies the stability of cutting force monitoring by using spindle displacement sensors. By comparing the estimate with the measured cutting force by using a dynamometer, the drift in sensor output is investigated, and its compensation scheme is proposed. The experimental result shows that the monitoring of cutting forces of 20~200N is possible by the proposed method in trochoidal grooving, which includes an intermittent air-cut.

2. MONOTIRING SYSTEM AND CALIBARATION

2.1 Monitoring System [7].

Figure 1 shows the monitoring and calibration system

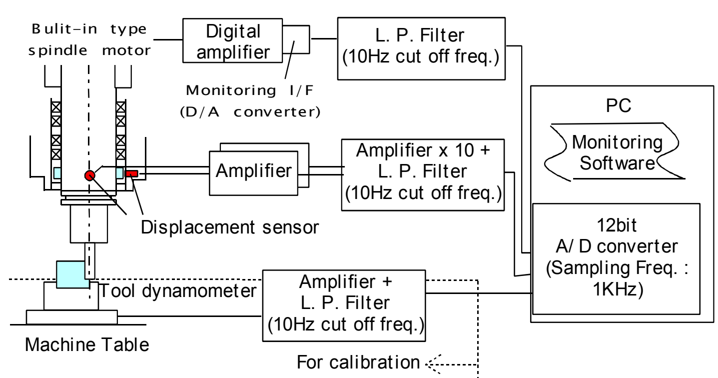


Fig. 1 Experimental setup

Table 1 Specifications of the machining center

Spindle	Spindle speed (rpm)	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
Sensitivity (mm/V)	0.2
Linearity (% of full scale)	±1
Dynamic range (kHz)	1.3 (-3dB)

Table 3 Cutting conditions in the calibration tests

Spindle speed (rpm)	1500, 3000, 4500
Feed per tooth (mm)	0.5, 1.0, 1.5, 2.0
Axial depth of cut (mm)	10
Cutting direction	X and Y direction
Cutting tool	Coated carbide end mill, diameter: 10 mm, numbers of flute: 4
Projection distance (mm)	35
Radial depth of cut (mm)	0.5, 1.0, 1.5
Cutting mode	Down cut
Coolant	Air
Workpiece material	Carbon steel

used in this research. The displacement sensors are installed near a set of front bearings inside a spindle unit of a machining center. The spindle displacement sensors can detect the displacement of the spindle in X and Y directions. Tables 1 and 2 respectively show the specifications of the machining center and the displacement sensor used in this research.

2.2 Calibration Test

Several calibration tests were conducted, where displacement sensor signals were compared with cutting forces measured by using a dynamometer installed on the machine table. Table 3 shows the tool and cutting conditions used in the calibration tests.

The test results shows that the spindle displacement has a linear relationship with the cutting force when the cutting force is less than a certain value (350N in the X-axis direction and 450N in the Y-axis direction). One result is plotted in Fig. 2 as an example. The displacement sensor signal is found to be behind the cutting force signal by about 0.1 sec. This delay may come from the difference between analog filters used for displacement sensors and those used for the tool dynamometer.

In the case where the cutting force is larger than 350N (in the Y-axis case, it is 450N), the relationship between the

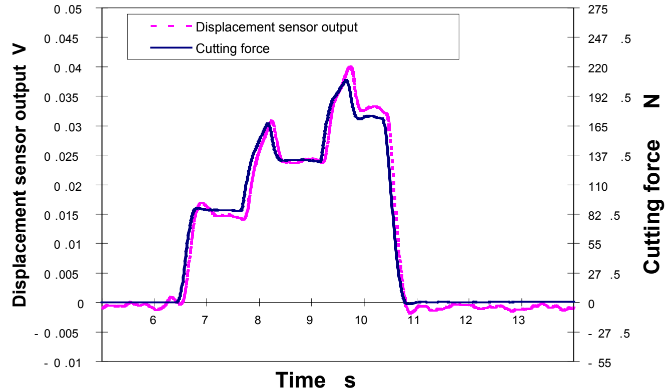


Fig. 2 Comparison of displacement sensor output and the cutting force measured by using a dynamometer (cutting direction: X-axis, spindle speed: 3000rpm, radial depth of cut: 0.5, 1.0, 1.5mm)

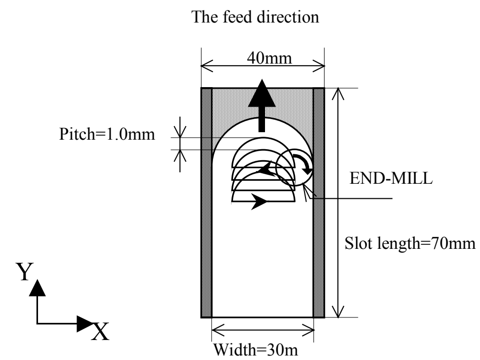


Fig. 3 Slotting process by using trochoidal-canned cycle

spindle displacement sensor output and the cutting force signals shows a nonlinear characteristics.

In order to convert the spindle displacement signal to the cutting force (called as the estimated cutting force hereafter), the following equations are used.

In X-axis direction : $$F_x = 600 \tan^{-1}\left(8.5 V_x\right) \quad (1)$$

In Y-axis direction : $$F_y = 650 \tan^{-1}\left(7.7 V_y\right) \quad (2)$$

Where V_x (V) and V_y (V) are the displacement sensor output voltage in X and Y direction respectively, and F_x (N) and F_y (N) are the estimated cutting force in X and Y directions, respectively. By using Eqs. (1) and (2), the cutting force can be estimated with a 90% confidence interval of ±30.9 N in the X-axis direction, and ±35.4 N in the Y-axis direction.

3. STABILITY IN MONITORING

To investigate the long-term stability of the cutting force monitoring, machining tests of trochoidal grooving were carried out on a workpiece of carbon steel. The machining conditions were: the spindle speed of 1500, 3000, 4500 min^{-1}, the axial depth of cut of 10mm, and the feedrate of 600 mm/min. The schematic of trochoidal grooving tests is shown in Fig. 3.

The estimated cutting force from the spindle displacement sensor and the cutting force measured by using a tool dynamometer are shown in Fig. 4.

One hundred seconds later from the start of measurement, an error between estimated and measured cutting forces is about 20 N (shown in Fig. 4 (a)). Four hundred seconds later from the start of measurement, however, the difference reaches about 50 N (shown in Fig. 4 (b)). The similar result was obtained from the cutting test in the Y-axis direction. A clear correlation of spindle speed and this steady-state drift error could not be observed.

4. SENSOR DRIFT COMPENSATION

When the machining process contains an intermittent air cut, such a drift can be compensated by simply resetting it at each air cut. For example, trochoidal canned cycles shown in Fig. 3 contain an air cut at every cycle. To recognize an air cut, we monitor the armature current in a spindle motor, as well as that in servomotors. When the spindle motor load is smaller than the prescribed threshold, we judge that the process is in an air cut. The mean of the displacement sensor output over each air cut region is taken as the estimate of drift error. The estimate of cutting force can be compensated by subtracting this value.

A similar trochoidal grooving test was conducted under the feedrate varied as 600, 900, and 1,200 mm/min. Figure 5 shows an estimated cutting force in the X-direction (without the drift compensation). It can be observed that the estimate is subject to a drift error of –20 N at the end of the test. It was about -12 N in the Y-direction estimate.

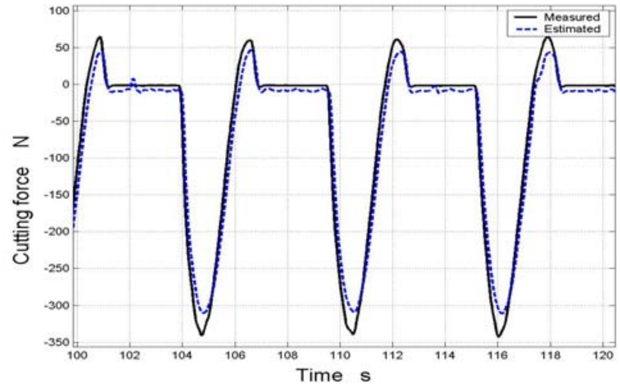
The estimated drift error is shown in Fig. 6. At the end of the test, the estimated drift error is –18.5 N, which matches well with the result above. It was –11.6 N in the Y-direction estimate. It can be also observed that the variation of the estimated drift error within each trochoidal cycle is at most 3~5N in the X-direction estimate. It is at most 3~6N in the Y-direction estimate.

Figure 7 compares estimated cutting forces with and without the drift compensation (spindle speed: 3000 rpm, axial depth of cut: 10mm, feedrate: 600, 900, 1200 mm/min). Under the feedrate of 600 mm/min (Fig. 7 (a)), where the cutting force is relatively small, the estimate without the compensation is subject to the drift error of about –20 N. By performing the drift compensation, it is reduced to about –2 N. In Fig. 7(b), where the cutting force is relatively large under the feedrate of 1200 mm/min, the estimate without the compensation is subject to an error of about –17 N at an air cut. By applying the drift compensation, it is reduced to about –2 N. It should be noted, however, that an estimation error during the cutting (e.g. at 291 seconds) is larger when the compensation is applied (35N with the compensation, and 19N without the compensation).

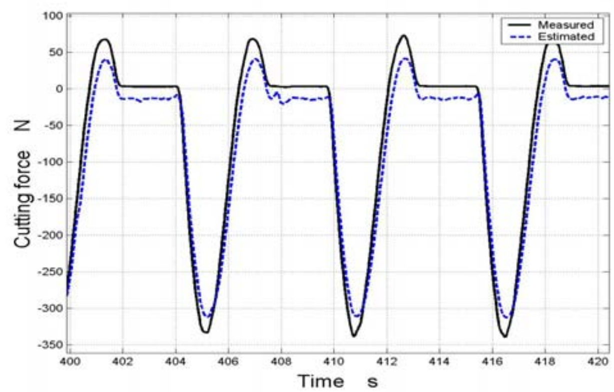
A similar result was obtained from the cutting test in the Y-axis direction. This error may be caused by a conversion error of displacement sensor output voltage.

5. CONCLUSION

On a high-speed and high-acceleration machining center, this paper studied the estimation of cutting forces in end milling by using displacement sensors installed in a spindle unit. The estimation performance was experimentally investigated by trochoidal grooving tests. A critical issue with this



(a) 100 seconds after the measurement starts



(b) 400 seconds after the measurement starts

Fig.4 Estimated and measured cutting forces in the direction of X-axis (Spindle speed : 3000rpm, Axial depth of cut: 10mm, and Feed: 600 mm/min).

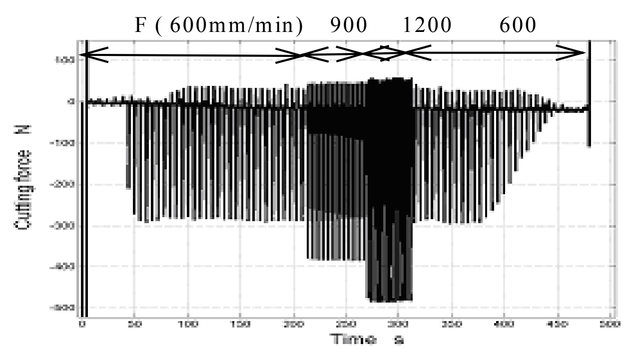


Fig. 5 Estimated cutting force in the X-direction

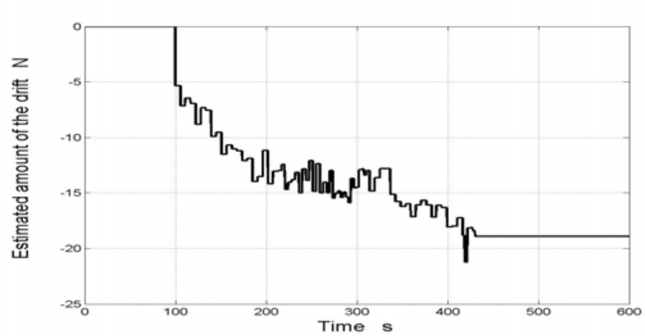


Fig. 6 Estimated drift error in the X-direction

estimation scheme is that the estimate is often subject to a steady-state drift error. By performing the present compensation scheme, this error can be reduced.

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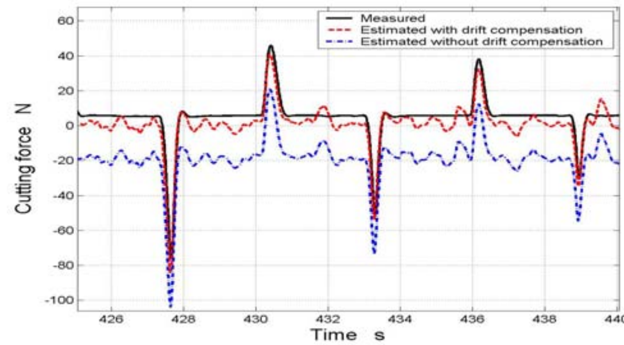
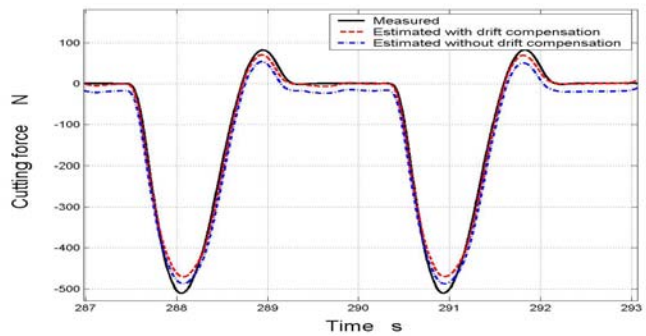


(a) Under the feedrate: 600 mm/min



(b) Under the feedrate: 1200 mm/min

Fig. 7 Comparison of estimated cutting forces with and without the drift compensation, and the measured cutting force in the X-direction.