Investigation about the characterization of machine tool spindle stiffness for intelligent CNC end milling

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ABSTRACT

This paper describes how to investigate the characterization of the machine tool spindle stiffness in radial direction for precise monitoring of cutting forces in end milling process by using displacement sensors. Four sensitive eddy-current displacement sensors are installed on the spindle housing of a machining center so that they can detect the radial motion of the rotating spindle. Thermocouples are also attached to the spindle structure, and the stability of the displacement sensing is examined. The change in spindle stiffness due to the spindle temperature and the speed is investigated. Finally, monitoring results of small and medium scale cutting forces in end milling operations are shown as a case study.

1. Introduction

In order to realize high productive and flexible machining systems, intelligent machining functions have been developed for NC machine tools [1]. Among those intelligent functions for machining centers, monitoring functions of cutting forces are important issues [2], 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 in intelligent machining [3]. In the researches on cutting force monitoring, there are two approaches: internal sensor approach and external sensor approach [4]. Some researchers have succeeded in the cutting force monitoring by utilizing motor currents in CNC-Servo systems [5]. However, it is difficult to use motor currents for the monitoring of cutting forces in an end-milling process, since the magnitude and the direction of cutting forces change frequently and the friction change on guideways influences the monitoring accuracy [6]. For such applications, external sensor approach is promising, and there are many researches on cutting force monitoring by using several types of sensors such as strain gauges, force sensors, acceleration sensors and so on [7].

Among those external sensors, the authors have employed displacement sensors, as they are cheap and small enough to be built in the spindle structure [8]. Displacement signals are translated into cutting force information by using the spindle stiffness model [9]. For the monitoring of cutting forces using displacement sensors, however, the spindle stiffness should be constant in the cutting process. For this reason, characterization of the spindle stiffness in radial direction should be investigated as well as the factors that affect the spindle stiffness [10]. It is well known that the spindle speed and the temperature parameters are mainly responsible for changing the state of ball contact and the preload of the bearing systems [11]. Therefore, it is likely that the spindle speed and temperature influence the spindle stiffness. For this reason the effect of these parameters on the spindle stiffness is investigated. In this research, a spindle with displacement sensors and thermal sensors is developed to monitor the spindle displacement and stiffness. First, the behavior of the spindle displacement in radial direction is investigated by using four displacement sensors. Second, the change in spindle stiffness due to the spindle speed and temperature is identified. Finally, tests for the monitoring of cutting forces in end milling operations are carried out.

2. Measurement of the spindle displacement

2.1. Experimental setup

In order to develop monitoring functions, 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).

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The spindle has constant position preloaded bearings with oil–air lubrication, and the maximum rotational speed is 20,000 rpm. 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: measurement range is 1 mm; nominal sensitivity is 0.2 mm/V ± 1%; dynamic range is 1.3 kHz; linearity is ± 1% of full scale. Fig. 1 shows the sensor locations. The two sensors, S_1 and S_3, are aligned opposite in the X direction, and the other two, S_2 and S_4, 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. 1. T_1 is installed on the bearing retaining cover, and T_2 is installed on the body of the spindle unit, which is near the windings of the built-in motor.

2.2. The concept of the displacement measurement

Fig. 2 shows the concept of the spindle displacement measurement. When the spindle axis shifts by Δx μm in the X direction due to the cutting force and thermal effects, the displacement signals from S_1 and S_3 are as follows.

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

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

where G is the sensor sensitivity [mV/μm], R_i is the distance between the spindle center and detection surface of the sensor S_i [μm] ($i = 1,\ldots,4$), θ is the rotation angle of the spindle [rad], $r(\theta)$ is 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

$$S_x(\theta) = [S_3(\theta) - S_1(\theta)]/2 \tag{3}$$

Letting $S_x(\theta) = S_{xo}(\theta)$ such that $\Delta x = 0$, and subtracting $S_{xo}(\theta)$ from $S_x(\theta)$

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

Then we obtain the axis shift Δx as follows.

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

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

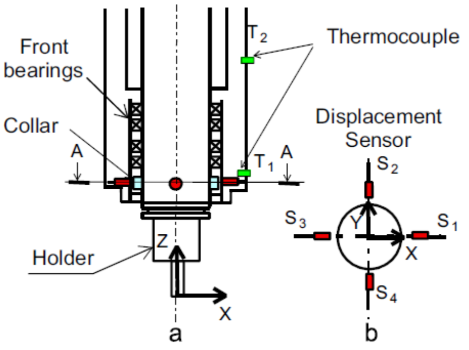

Fig. 1. Locations of the sensors. (a) Front view and (b) A-A section.

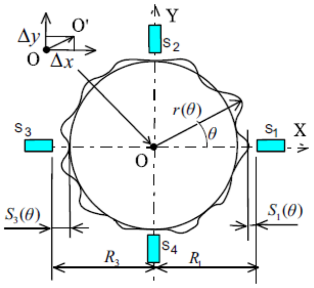

Fig. 2. The concept of the displacement measurement.

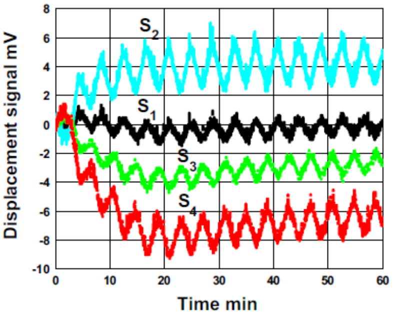

Fig. 3. Displacement signals.

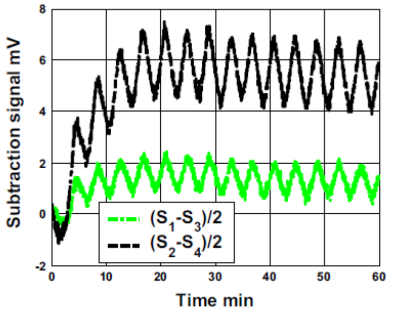

Fig. 4. Subtraction signals.

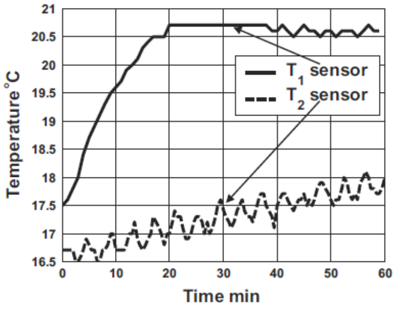

Fig. 5. Spindle temperature.

2.3. *Experimental result*

For the measurement of the spindle displacement due to the cutting forces, the sensor signals should be stable for any other disturbance. To check the stability of the sensing, the spindle displacement and temperature are measured during the spindle rotation without cutting. The spindle is started at 3000 rpm and kept rotating for 1 h. After that the spindle speed is increased to 6000 and 9000 rpm for every hour. Fig. 3 shows an example of measured displacement signals at the spindle speed of 6000 rpm. Fig. 4 shows the subtraction signals of the opposite sensors. As shown in Fig. 3, all the sensor signals involve two types of fluctuation: a transient response type and a periodic type. These fluctuations appear in the spindle displacement, and they are remaining in the subtraction signals shown in Fig. 4. Fig. 5 shows the measured spindle temperature.

The transient response can be seen in the temperature measured by sensor T_1, and the periodic fluctuation can be seen in sensor T_2. The same fluctuations are also observed in the measurement results at other spindle speeds, but the periodicity and range are different for each spindle speed. The transient fluctuation type is related to the thermal expansion of the spindle, while the periodic fluctuation type is related to the cooling control of the oil, which is circulating inside the spindle body.

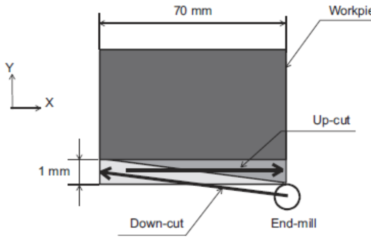

Fig. 6. Workpice and tool paths.

Table 1
Cutting conditions.

Spindle speed (rpm)	3000, 6000, 9000
Feed per tooth (mm/tooth)	0.167
Axial depth of cut (mm)	10
Cutting tool	Coated carbide end mill, diameter: 10 mm, number of flute: 4
Coolant	Air
Workpiece material	Carbon steel, S50C (0.5%C steel).

3. Measurement of the spindle stiffness

3.1. *Experimental procedure*

In the previous section, it can be seen that the fluctuation of the spindle displacement depends on the spindle temperature. Therefore, we can compensate the fluctuation by monitoring the spindle temperature. For the monitoring of cutting forces, however, the spindle stiffness should be constant in the cutting process. For this reason, characterization of the spindle stiffness in radial direction

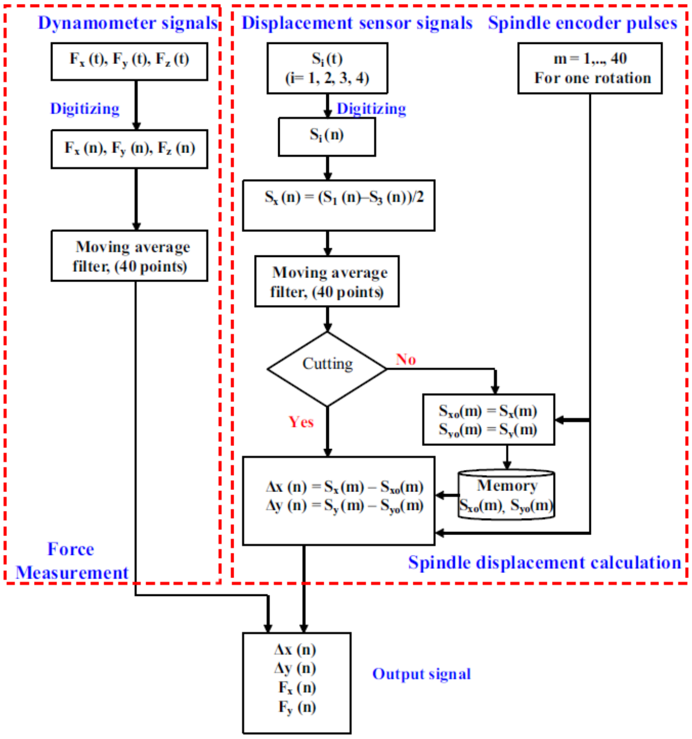

Fig. 7. The signal processing algorithm for the identification of spindle stiffness.

should be investigated as well as the factors that affect the spindle stiffness. For the measurement of the spindle stiffness in the radial direction, the load in this direction is necessary to deflect the spindle and to be measured precisely. The static loading test is widely used to evaluate the overall stiffness of machine tools. The stiffness obtained by the static test, however, typically shows hysterics characteristics, because the contact area of the bearing changes as the load direction changes. More importantly, the static stiffness is different from the stiffness of the rotating spindle. Therefore, we carry out cutting tests to provide dynamic load and measure cutting forces with a table type tool dynamometer (Model 9257B made by Kistler).

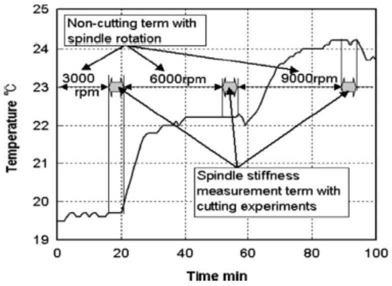

Fig. 8. The measured spindle temperature by thermocouple T_1.

Fig. 6 shows the tool paths for cutting tests. The tool moves in the –*X* direction and then +*X* direction with the radial depth of cut varied from 0 to 1 mm. In the −*X* direction the cutting mode is down-cut, while in the +*X* direction it is up-cut. To remove residual stock, each path is repeated. The cutting time for one operation is about 4 s, which is short enough to avoid the thermal disturbances on displacement signals. Table 1 shows the cutting conditions.

First the spindle is rotated at 3000 rpm without cutting for 20 min for the first warm-up. Then, the 1st cutting test is carried out at three spindle speeds. Then the spindle is warmed up again at the speed of 6000 rpm for 30 min without cutting. The same cutting test (the 2nd cut) is repeated, and followed by the spindle warm-up

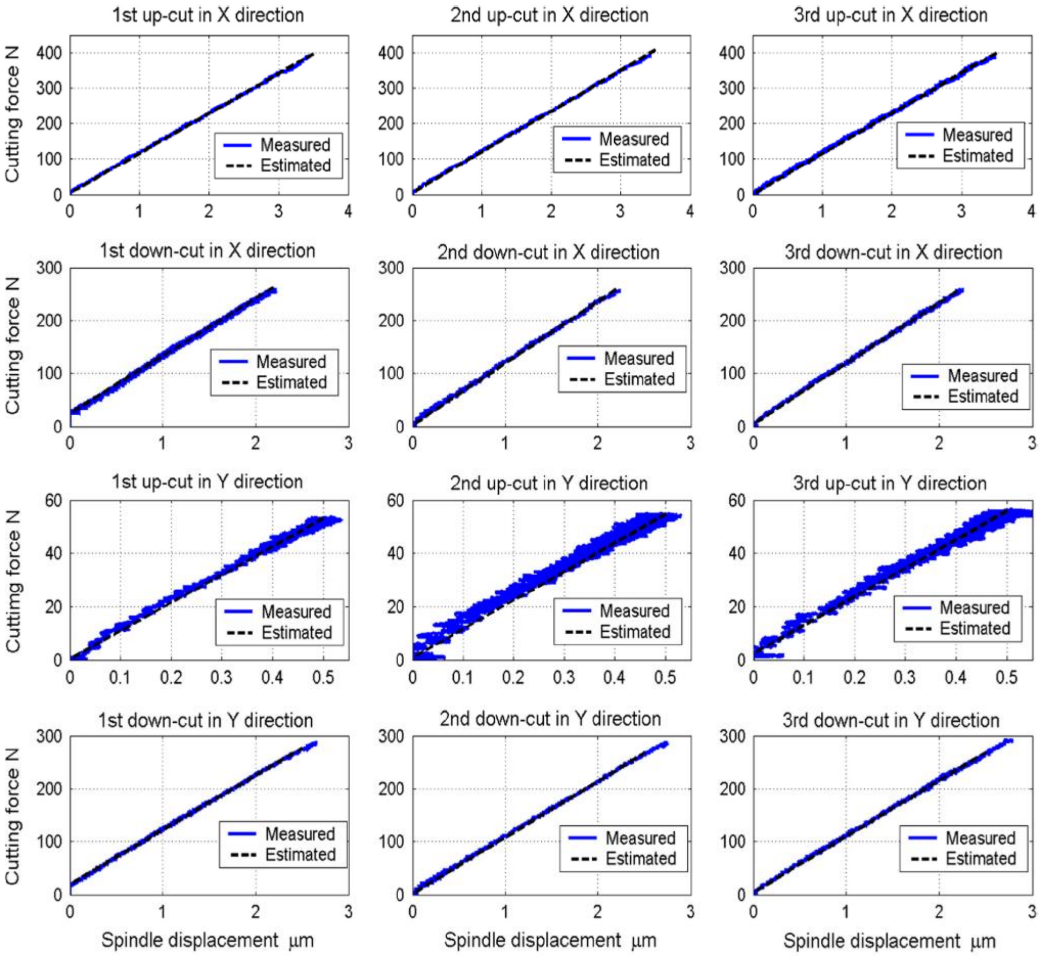

Fig. 9. The relationship between the spindle displacement and the cutting force (spindle speed: 3000 rpm).

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