# Monitoring Method of Cutting Force by Using Additional Spindle Sensors*

Ahmed Aly Diaa SARHAN**, Atsushi MATSUBARA***, Motoyuki SUGIHARA***, Hidenori SARAIE****, Soichi IBARAKI*** and Yoshiaki KAKINO†

This paper describes a monitoring method of cutting forces for end milling process by using displacement sensors. Four 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 in order to examine the thermal effect in the displacement sensing. The change in the spindle stiffness due to the spindle temperature and the speed is investigated as well. Finally, the estimation performance of cutting forces using the spindle displacement sensors is experimentally investigated by machining tests on carbon steel in end milling operations under different cutting conditions. It is found that the monitoring errors are attributable to the thermal displacement of the spindle, the time lag of the sensing system, and the modeling error of the spindle stiffness. It is also shown that the root mean square errors between estimated and measured amplitudes of cutting forces are reduced to be less than 20 N with proper selection of the linear stiffness.

***Key Words***: End Milling, Cutting Force, Machine Tool, Monitoring, Displacement, Spindle

## 1. Introduction

In order to realize high productive and flexible machining systems, intelligent machining functions have been developed for NC machine tools(1)–(4). Among those intelligent functions for machining centers, monitoring functions of cutting forces are important issues, as they could tell limits of cutting conditions, accuracy of the workpiece, tool wear, and other process information. In the researches on cutting force monitoring, there are two approaches: an internal sensor approach and an external sensor approach. Some researchers have succeeded in the cutting force monitoring by utilizing motor currents in CNC-Servo systems(5),(6). However, it is often difficult to estimate cutting forces in an accurate and stable manner by motor currents 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. 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),(8).

Among those external sensors, the authors have employed displacement sensors(9) in order to measure the spindle displacement due to cutting forces, as they are cheap and small enough to be built in the spindle structure. Displacement signals are translated into cutting force information by using spindle stiffness model. With respect to the sensing resolution and accuracy, the estimation of the cutting force as small as 10 N is possible. Typically, an important issue to be addressed in practical application is its long-term quality and reliability. In this research, we develop a spindle with displacement sensors and thermal sensors to monitor the spindle displacement and clarify

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** Department of Precision Engineering, Graduate School of Engineering, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606–8501, Japan. E-mail: ah_sarhan@prec.kyoto-u.ac.jp

*** Department of Micro Engineering, Graduate School of Engineering, Kyoto University. E-mail: matsubara@prec.kyoto-u.ac.jp; m.sugihara@t01.mbox.media.kyoto-u.ac.jp; ibaraki@prec.kyoto-u.ac.jp

**** Technology R&D, Mori Seiki, 201 Midai, Iga-cho, Ayama-gun, Mie 519–1414, Japan. E-mail: saraie@moriseiki.co.jp

† Kakino Research Institute, 342–1 Enpukujicho, Muromachi-oike-sagaru, Nakagyo-ku, Kyoto 604–8175, Japan. E-mail: kakino@crux.ocn.ne.jp

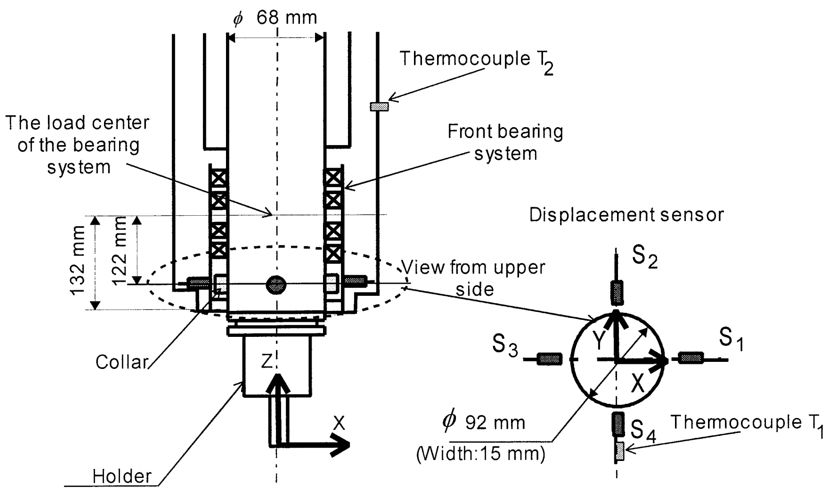



Fig. 1  Locations of the sensors

the resources of the monitoring errors. First, we investigate the behavior of the spindle displacement in the radial direction by using four displacement sensors. Second, the change in spindle stiffness due to the spindle speed and temperature is investigated. Finally, monitoring tests of cutting forces in end milling operations under different cutting conditions are carried out as a case study.

## 2. Measurement of the Spindle Displacement

### 2.1 Experimental set-up

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 Co., LTD.). The spindle has constant position preloaded bearings with oil-air lubrication, and the maximum rotational speed is 20 000 $\mathrm{min}^{-1}$. Four eddy-current displacement sensors are installed on the housing in front of the bearings to detect the radial motion of the rotating spindle. The specifications of the sensor are as follows: the diameter is $\phi$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; linearity is ±1% of full scale. 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, $S_2$ 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. The thermocouple $T_1$ is installed in the same hole where the displacement sensor $S_4$ is installed, 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 spindle displacement measurement

Figure 2 shows the concept of the spindle displacement measurement. When the spindle axis shifts by $\Delta x$ 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.

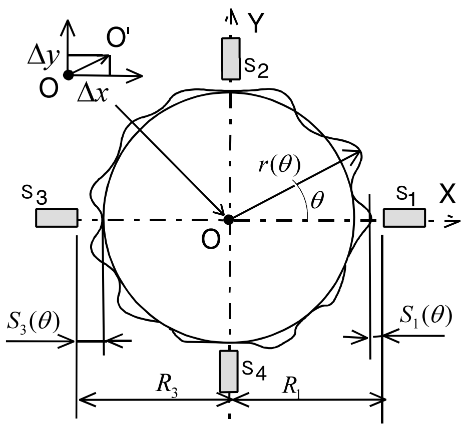



Fig. 2  The concept of the spindle displacement measurement

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

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

Where $G$: sensor sensitivity [mV/μm], $R_i$: the distance between the spindle center and detection surface of the sensor $S_i$ [μm] ($i = 1,\ldots,4$), $\theta$: 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

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

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

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

Then we obtain the axis shift $\Delta x$ as follows.

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

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

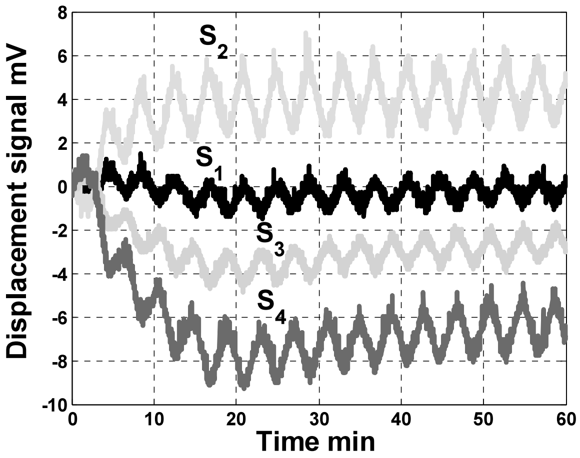



Fig. 3 Displacement signals (Spindle speed: 6 000 min$^{-1}$)

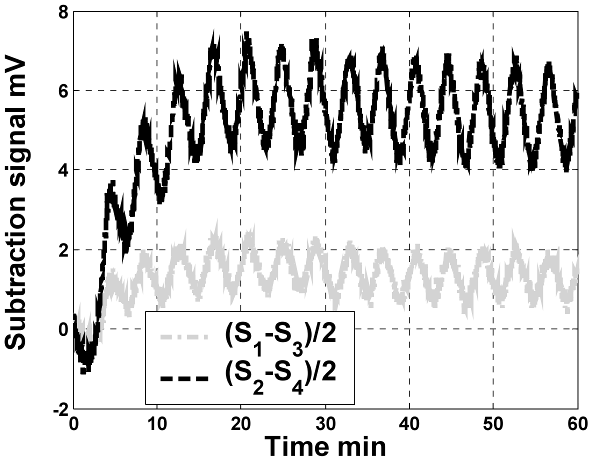



Fig. 4 Subtraction signals of two opposite-direction sensors

## 2. 3 Experimental investigation of thermal effect on spindle displacement measurement

For the measurement of the spindle displacement caused by the cutting forces, the effect of other disturbance on sensor signals must be investigated in advance. 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 3 000 min$^{-1}$ and kept rotating for 1 hour. After that the spindle speed is increased to 6 000 and 9 000 min$^{-1}$ for every hour. Figure 3 shows an example of measured displacement signals at the spindle speed of 6 000 min$^{-1}$. Figure 4 shows the subtracted signals of the opposite sensors. As shown in Fig. 3, all the sensor signals involve two components of fluctuations: the transient component and the periodic component. These fluctuations appear in the spindle displacement, and they are remaining in the subtraction signals shown in Fig. 4. Figure 5 shows the measured spindle temperature by the thermocouples $T_1$ and $T_2$. The transient fluctuation component can be seen in the temperature measured by the sensor $T_1$, and the periodic fluctuation component can be seen in the 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 component is related to the thermal extension of the spindle, while the periodic fluctuation component is related to the cooling control of the oil, which is circulating inside the spindle housing.

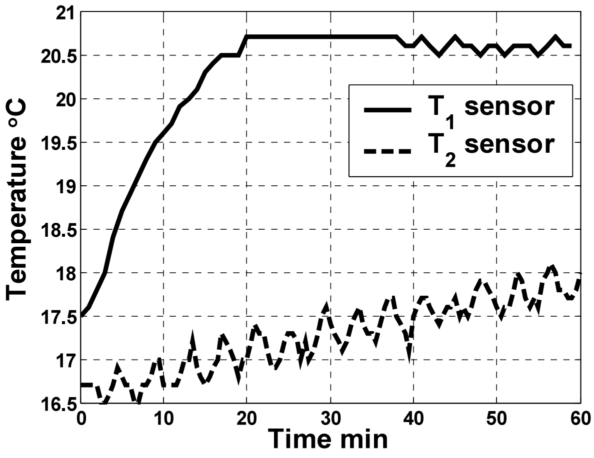



Fig. 5 Spindle temperature

## 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 should be investigated as well as the factors that affect the spindle stiffness. It is well known that the spindle speed and the temperature change the state of ball contact and the preload of the bearing systems. Therefore, it is likely that the spindle speed and temperature influence the spindle stiffness. For this reason we investigate the effect of these parameters on 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). Figure 6 shows the tool paths for cutting tests. The tool moves in the −X direction and then +X direction with the radial

Table 1 Cutting conditions

| | |
|---|---|
| Spindle speed ($min^{-1}$) | 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). |

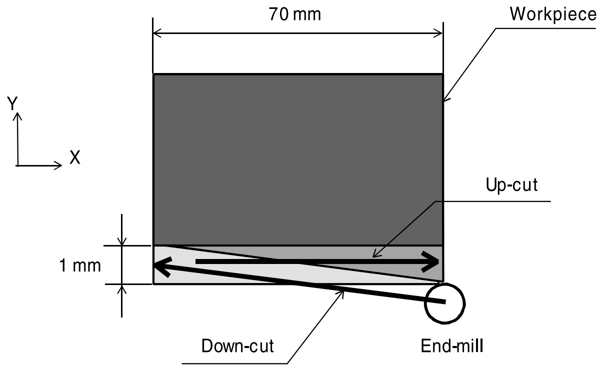



Fig. 6 Workpice and tool paths

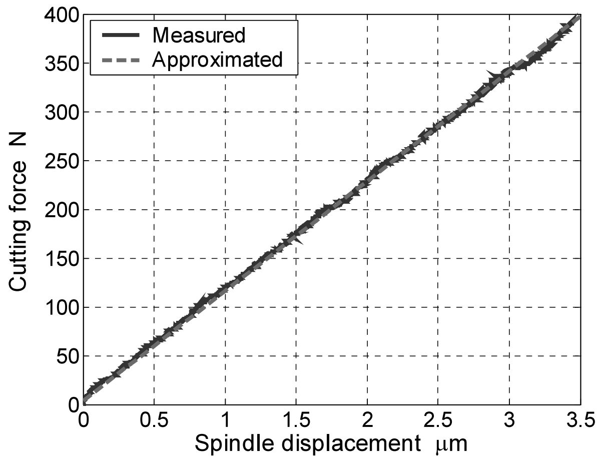



Fig. 7 An example of the relationships between the spindle displacement and the cutting force (direction: X-axis, spindle speed: 3 000 $min^{-1}$, cutting mode: up-cut, spindle temperature: 19.8°C)

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 seconds, which is short enough to avoid the thermal disturbances on displacement signals. Table 1 shows the cutting conditions. First the spindle is rotated at 3 000 $min^{-1}$ 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 6 000 $min^{-1}$ for 30 min without cutting. The same cutting test (the 2nd cut) is repeated, and followed by the spindle warm-up operation at the speed of 9 000 $min^{-1}$ for 30 min. Finally the 3rd cut is carried out.

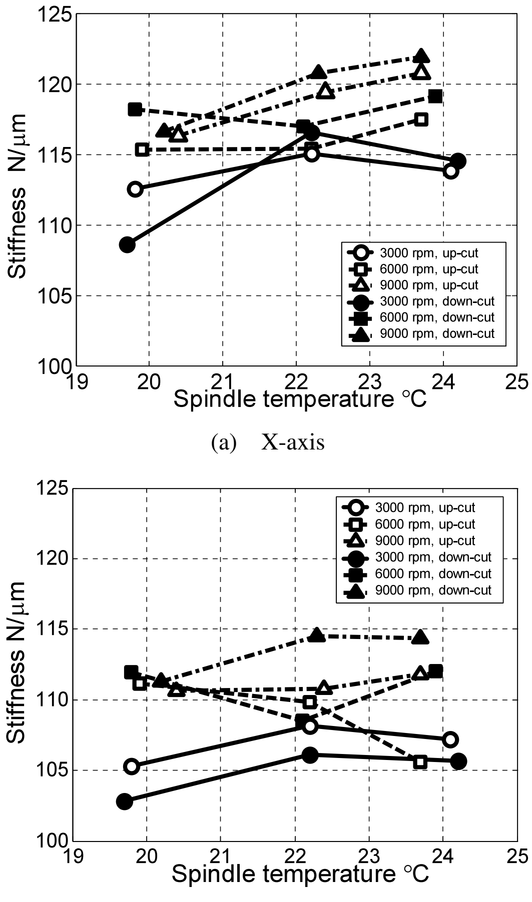
### 3.2 Signal processing for the identification of spindle stiffness

The spindle displacement signals are digitized with a 16-bit A/D board, and the cutting force signals (X, Y, and Z direction) from the dynamometer are digitized with a 12-bit A/D board. For the measurement of rotational angle of the spindle, A, B, and Z pulses of the rotary encoder, which is originally used for the spindle speed control, are counted with a 32 bit-counter board. The sampling frequency is set so that 40 points per one spindle revolution can be obtained. The subtraction of the digitized signals of the opposite sensors in one rotation, $S_{j0}(m)$ ($m = 1,\ldots,40$, $j = x,y$), are recorded in the PC memory prior to the cutting. When the cutting is started and the subtraction signal for one revolution, $S_j(m)$, are obtained, $S_{j0}(m)$ are subtracted from $S_j(m)$ for each index $m$. The subtraction data are filtered by a moving average filter. Then the spindle displacements in the X and Y directions are obtained and compared with measured cutting forces.

### 3.3 Experimental results

After the 1st warm-up term, the spindle temperature was around 19°C. The increase of the spindle temperature was 2°C in the 2nd and 3rd warm-up terms, respectively. Figure 7 shows an example of the relationships between the spindle displacement and the cutting force. As shown in Fig. 7, the relation can be approximated linearly, but the y-section of the line is not exactly zero because of the nonlinearity around the origin. As other relationships obtained in the different conditions show the same tendency, the spindle stiffness is identified by using linear approximation.

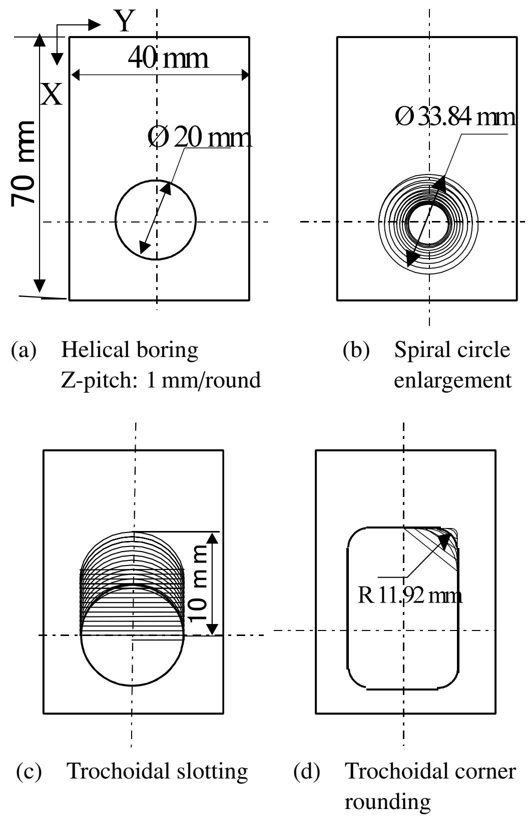
Figure 8 shows the identified spindle stiffness in different cutting conditions. The spindle stiffness indicates slight correlation with the spindle temperature and speed. As for the stiffness data at the spindle speed of 3 000 $min^{-1}$ in down cut, the estimated stiffness is smaller than that of other conditions. Checking the force range of the data, we found that the air-cut term is not long enough to get the same force range as other ones. This indicates the existence of the nonlinearity in the force-displacement relationship, but we assume that the spindle stiffness is constant. By taking the average of the estimated stiffness for




(a) X-axis

(b) Y-axis

Fig. 8 Identified spindle stiffness in different cutting conditions




(a) Helical boring Z-pitch: 1 mm/round

(b) Spiral circle enlargement

(c) Trochoidal slotting

(d) Trochoidal corner rounding

Fig. 9 Workpiece and tool paths used in each process

the cutting force range 0 – 400 N, we concluded that the estimated spindle stiffness is 117 N/μm in the X direction, and 110 N/μm in the Y direction. The slight difference in the stiffness between X and Y-axis might come from the sensitivity difference of each sensor, as we use the nominal sensitivity value for each sensor.

## 4. Case Study on Monitoring of Cutting Forces

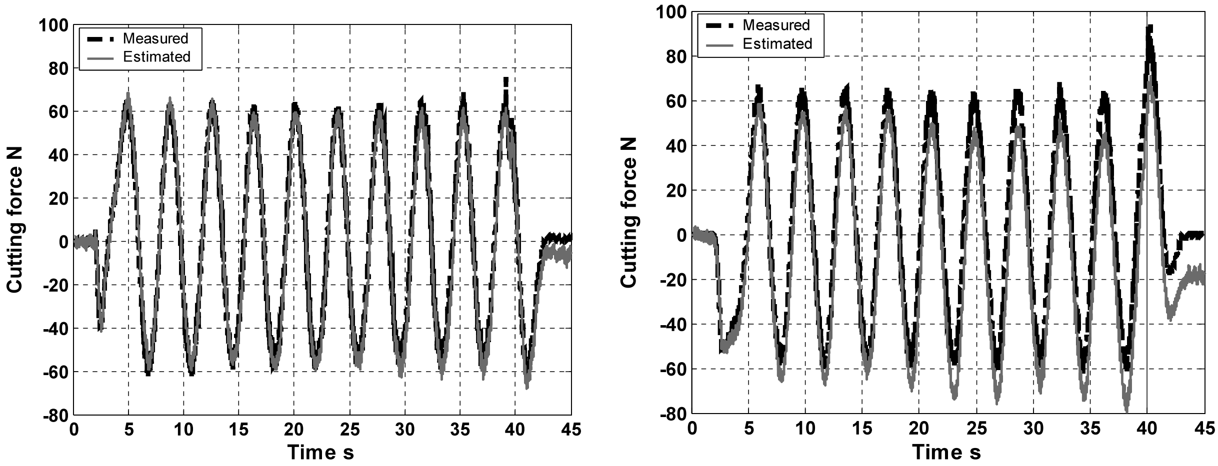
### 4.1 Experimental procedure

In this section, a cutting test is carried out to validate the monitoring performance. A cutting process of a rectangular pocket feature is selected as a case study, as several sub-features are involved in the entire cutting process. The entire process consists of the following sub-processes: (a) boring with helical cycles, (b) circle enlargement with spiral cycles, (c) slotting with trochoidal cycles, and (d) corner rounding with trochoidal cycles. Figure 9 shows the workpiece and the tool paths used in each process. We use the same cutting tool as the one shown in Table 1. The spindle speed is 3 000 min$^{-1}$, and the axial depth of cut is 10 mm. As each process has different feed rates and radial depths of cut, the entire process monitoring is a difficult subject. Spindle displacements in the X and Y-axis are monitored by using the measurement system presented in section 3.2. Cutting forces are estimated by multiplying measured spindle displacements and the stiffness identified in section 3.3. The results are compared with cutting forces measured by using the dynamometer. The spindle temperature $T_1$ and $T_2$ are monitored simultaneously to check the effect of the spindle thermal displacement on the estimated cutting forces.

### 4.2 Experimental results

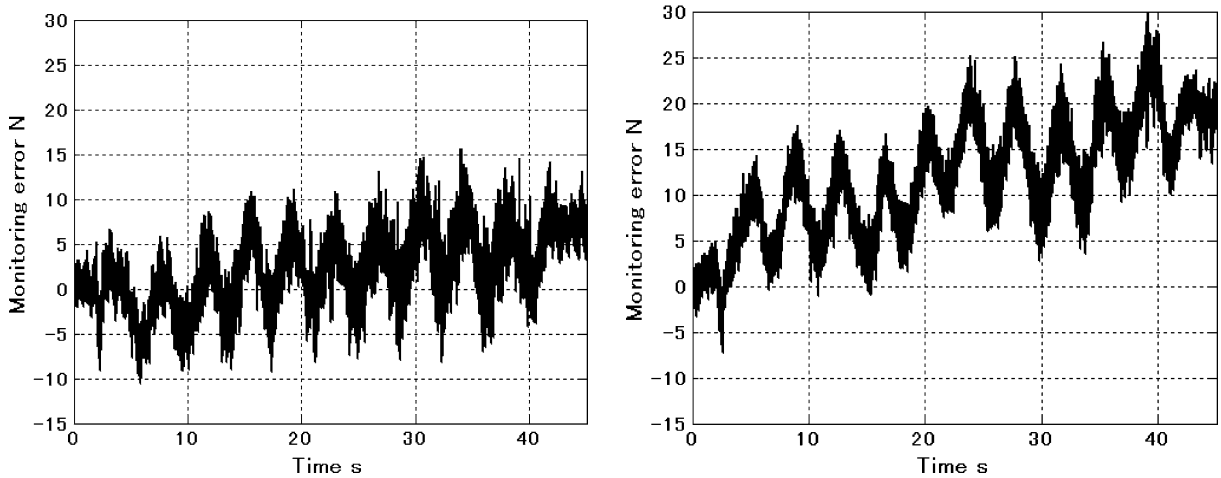
By comparing estimated and measured cutting forces in each process, monitoring errors (measured minus estimated cutting forces) are calculated. Figure 10 shows the comparison of estimated and measured cutting forces in the helical boring process; Fig. 11 shows the monitoring errors. In the helical boring process, the monitoring error profile contains both periodic and drift components. The spindle temperature $T_1$ has a small range of fluctuation in the entire term, but the spindle temperature $T_2$ has the periodic fluctuation. The periodic temperature fluctuation corresponds to the drift error in Fig. 11.

Figures 12 and 13 show results in the trochoidal slotting process. Figure 14 shows the estimated and measured cutting forces in the one cycle. As can be seen in Fig. 14, the time lag is observed between the estimated and measured profiles. Moreover, the measured profile does not reach the estimated one at the bottom. This observation implies that the spindle stiffness is a little larger than the true value when the cutting force is over 400 N. As the



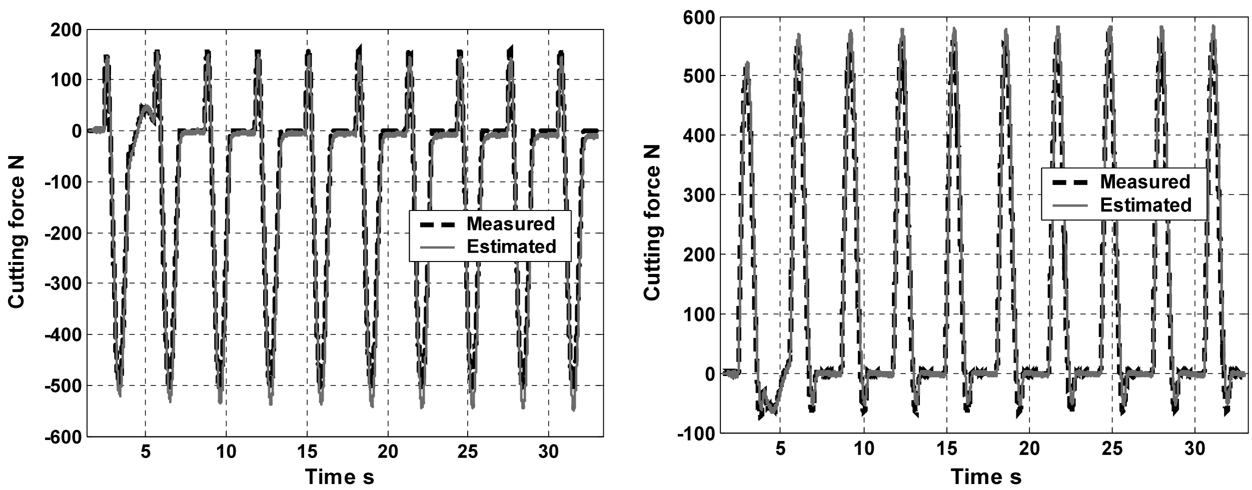

(a) X-axis (b) Y-axis

Fig. 10 Comparison of estimated and measured cutting forces in helical-cut



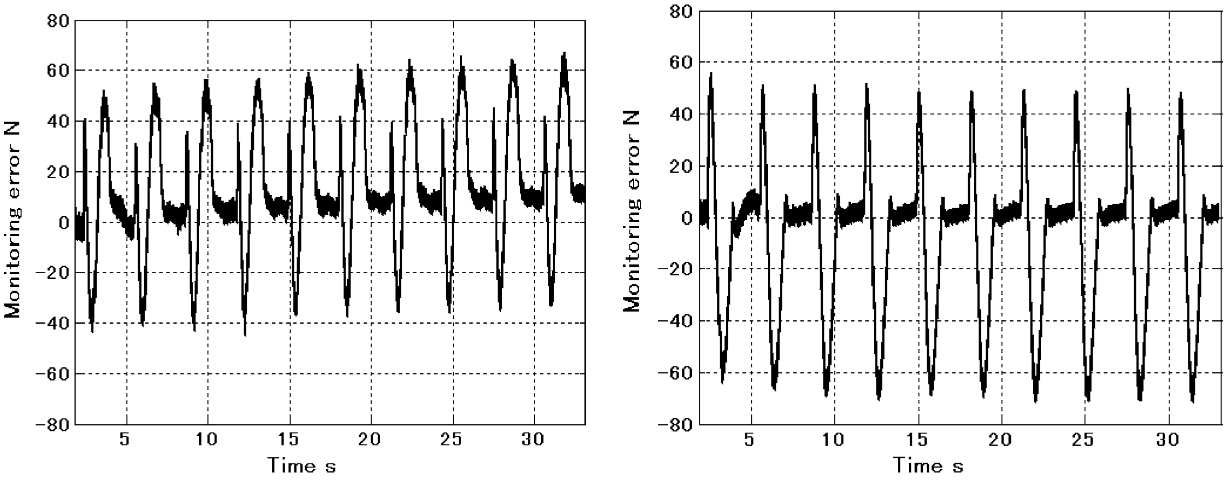

(a) X-axis (b) Y-axis

Fig. 11 Monitoring errors (measured minus estimated cutting forces) in helical-cut




(a) X-axis (b) Y-axis

Fig. 12 Comparison of estimated and measured cutting forces in trochoidal-cut




(a) X-axis (b) Y-axis

Fig. 13 Monitoring errors (measured minus estimated cutting forces) in trochoidal-cut

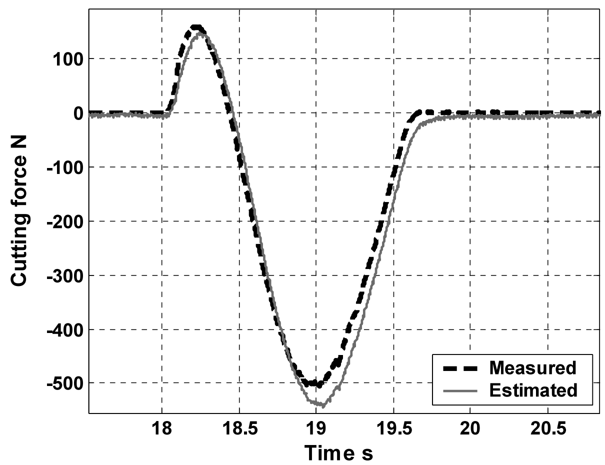



Fig. 14 Cutting forces in one cycle (enlargement of Fig. 12 (a))

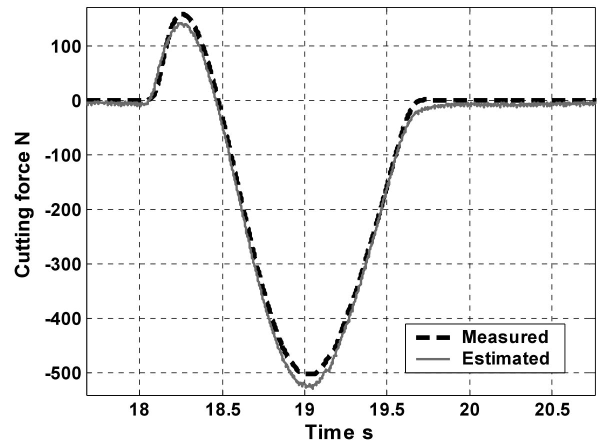



Fig. 15 Estimated and measured cutting forces in one cycle of trochoidal slotting process after the modification

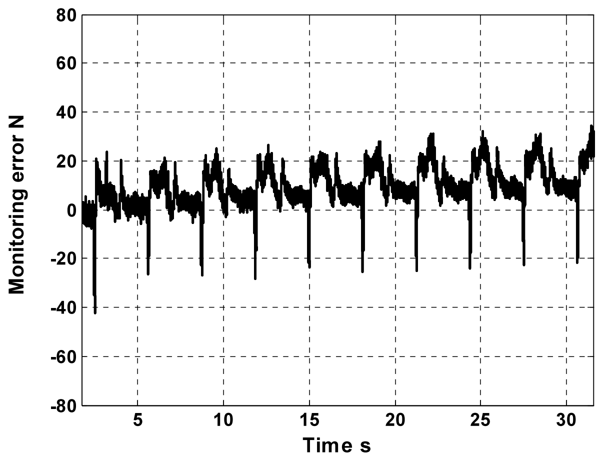
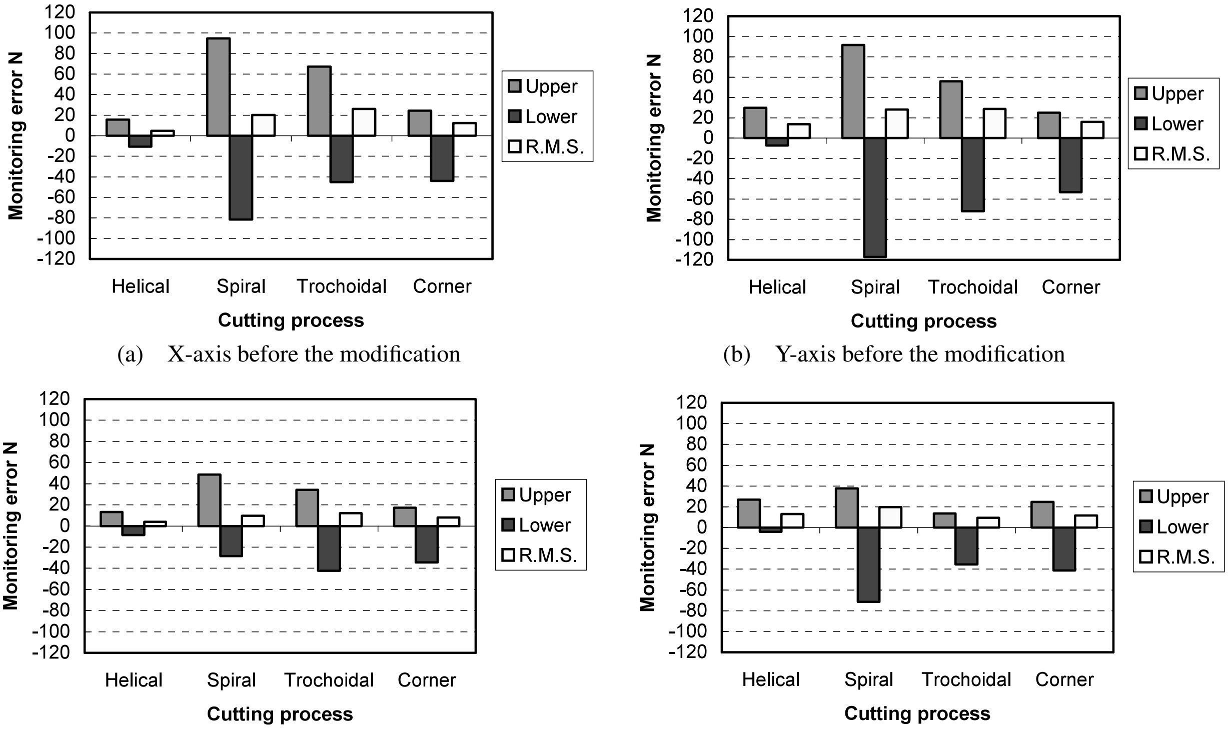



Fig. 16 Monitoring errors in the X-axis direction of trochoidal slotting process after the modification

experimental data set that is used for the identification of the spindle stiffness ranges from 0 to 400 N, the spindle stiffness are to be re-modeled for the monitoring of lager cutting forces. First, the measured cutting forces are filtered by a second order low-pass filter to match dynamic responses of the force and displacement signals. After that, the spindle stiffness is re-identified so that it can minimize the root mean square of the monitoring errors (R.M.S.) for all cutting processes in the case study. The re-identified spindle stiffness is 114 N/μm in the X direction, and 107 N/μm in the Y direction. Figure 15 shows estimated and measured cutting forces in one cycle of trochoidal slotting process after this modification of the stiffness, and Fig. 16 shows the monitoring errors. The estimate without the stiffness modification is subject to root mean square of monitoring error of about 26.2 N. By performing the modification, it is reduced significantly to about 12.2 N. Similar results were obtained by performing the modification of the other sub-cutting processes in the case study. The upper, lower and R.M.S. of the monitoring errors in each process before and after the modification in the X and Y directions are shown in Fig. 17. From these figures, it is found that the maximum root mean square




(a) X-axis before the modification

(b) Y-axis before the modification

(c) X-axis after the modification

(d) Y-axis after the modification

Fig. 17 The upper, lower and R.M.S. of the monitoring errors in each process before and after the modification

of monitoring errors are reduced significantly to less than 20 N. The remaining error after the modification is attributable to the spindle displacement drift caused by the thermal deformation of the spindle, which can be potentially compensated by utilizing temperature information.

## 5. Conclusion

Displacement sensors and thermocouples are installed in the spindle structure of a machining center for the monitoring of cutting forces. The error sources in cutting force estimation are investigated by several cutting tests. The obtained results are summarized as follows:

( 1 ) The estimation error of cutting forces are attributable to the time lag of the sensing system, the modeling error of the spindle stiffness, and the thermal displacement drift of the spindle.

( 2 ) The linear model for spindle stiffness is used to relate force signals with displacement signals. The identified spindle stiffness is stable in the cutting with spindle rotation speed from 3 000 to 9 000 $\mathrm{min}^{-1}$.

( 3 ) Due to the nonlinearity of the stiffness, the force range for identification of the stiffness is important. It is shown that the root mean square errors of measured and estimated amplitudes of cutting forces are reduced to less than 20 N with proper selection of the linear stiffness model.

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