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Indirect cutting force measurement in the micro end-milling process based on frequency analysis of sensor signals†

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Abstract

In this study, a useful indirect cutting force measurement method using an acceleration sensor and current hall sensors is proposed. A series of experiments was performed on a precise micro machining stage with a high-speed spindle. A three-axis acceleration sensor was installed on the spindle head, and current hall sensors were connected to the motor current inlet cables. From the results obtained, the correlations of the tool teeth rotation and current amplitude showed a linearity of 92.0% precision for hall sensor signals, and 98.0% precision for acceleration sensor signals. Even though the results using the acceleration sensor showed better linearity than those of the current hall sensors, the signals can be easily affected by chattering, spindle vibration, and other external disturbances. From this perspective, the current hall sensor can provide more robust results.

Keywords: Micro end-milling; Indirect cutting force measurement; Frequency analysis; Sensor system

1. Introduction

Recently, with the increasing demands for precise micro component production, the importance of micro machining processes has been increasing in a number of fields, such as in the medical instrumentation, aerospace engineering, and computer industries. However, it is very difficult to observe the machining process as compared to the macro machining process due to its low material removal rate (MRR), very small tool size, high spindle speed, and low sensor signal levels, among others. While a micro tool dynamometer can solve these problems, its application is limited due to cost concerns and issues related to sensititivity, robustness, and workpiece size. To overcome such problems, several studies using multi-sensors (e.g., AE, acceleration, displacement, and vision sensors) [1-3] and sensors for the main spindle and/or measurement of the feed motor currents have been reported [4-5]. The present study proposes a useful indirect cutting force measurement method based on a frequency domain analysis using an acceleration sensor and current hall sensors. A series of experiments was performed on a precise micro machining stage. Measured signals were analyzed at the frequency domain after FFT (Fast Fourier Transform), and the results were compared with the cutting force components measured using a micro tool dynamometer. The calculated correlations between the sensor signals and the measured cutting forces showed a linearity of 98.0% and 94.5% precision for the acceleration sensor and hall sensors, respectively. It could thus be verified that the proposed indirect cutting force measurement method provides a useful method to monitor micro end-milling processes.

2. Measurement method

An internal permanent magnet is connected with a rotational axis in a three-phase AC induction motor or Surface Permanent Magnet Motor (SPMM). It rotates by synchronizing with the supplied alternative currents. In the case of SPMM, the internal permanent magnet corresponds to the rotation frequency of the motor. The number of rotations of a three-phase AC servo motor (n) is related to the frequency (f) of the supplied current and the number of poles of the motor (p) according to the following equations:

$$n = \frac{120f}{p}[rpm] \tag{1}$$

$$T_m = k\Phi I_r \tag{2}$$

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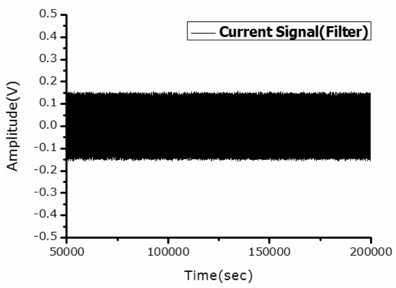
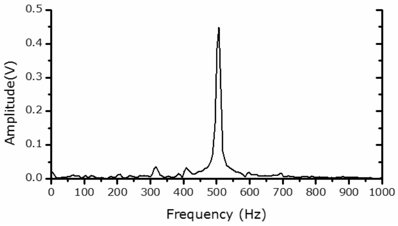


(a) Time domain



(b) FFT domain

Fig. 1. FFT analysis of a motor current (30,000 rpm).

Thus, if the number of poles of an AC servo motor is fixed, the feeding speed can be controlled by changing the frequency of the supplied current. The torque of a three-phase induction motor can be obtained by the magnetic flux (Φ) and current (I_r). The magnetic flux increases with an increase in current, and magnetization occurs in a specific range of the magnetic flux. Therefore, the motor torque is related to the current (I_r). However, the voltage and current in the rotator of the induction motor are very difficult to measure because the rotator part is assembled in a set with an electric circuit. Therefore, indirect measurement of the current (I_r) is possible by measuring the current (I_s) in the stator of the induction motor using hall sensors.

The measured signals were analyzed at the frequency domain after a Fast Fourier Transform, as shown in Fig. 1. For the measurement of induced vibrations in the machining process, an acceleration sensor was installed on the spindle housing. As shown in Fig. 2, the rotation (500 Hz) and the tooth frequency (1,000 Hz) were analyzed at a frequency domain of 30,000 rpm. The cutting force was correlated with the rotation frequency of the current signal and the tooth rotation frequency of the acceleration signal.

3. Experimental setup

3.1 Monitoring system

Fig. 3 shows the micro cutting and monitoring systems used for the experiments. The micro cutting system has the same structure as a three-axis machine tool, and consists of three-axis linear stages (X, Y, and Z-axis) and a high-speed spindle

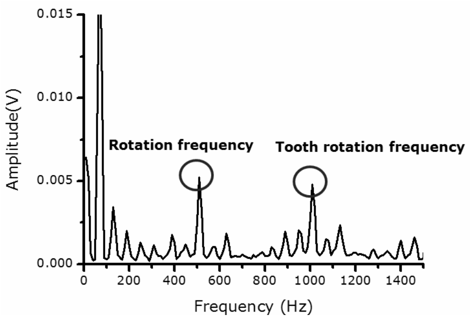


Fig. 2. FFT analysis of acceleration (30,000 rpm).

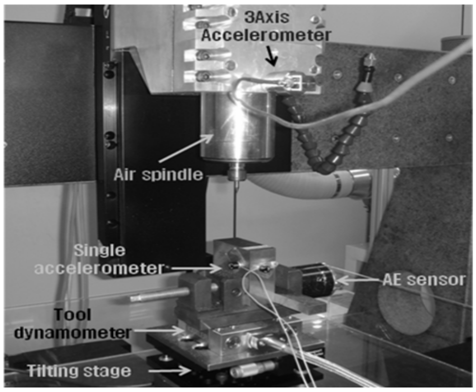


Fig. 3. Micro monitoring system.

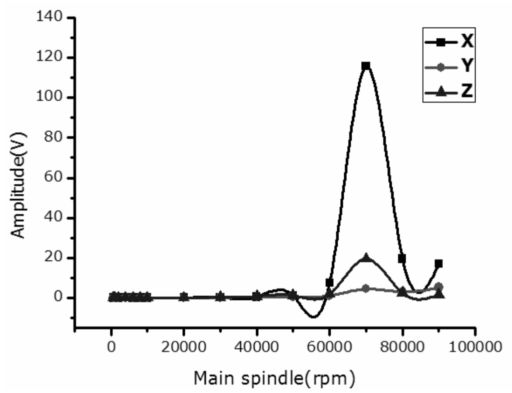
that can rotate at a maximum speed of 100,000 rpm. The cutting force monitoring system is composed of a micro tool dynamometer, an acceleration sensor, and current hall sensors. A three-axis micro tool dynamometer (Kistler) is used to obtain the reference cutting force components in comparison with the signals obtained using the acceleration sensor and current hall sensors during the experiments. The three-axis acceleration sensor (SA12ZSC-TI) was attached to the main spindle housing, and the current hall sensors were connected to the motor inlet cables (*U* and *V* lines). In this research, all sensor signals were obtained through 10 kHz low pass filters to remove high-frequency noise. The filtered sensor signals are acquired simultaneously through an A/D conversion board (PCI-NI 9133).

3.2 Cutting conditions

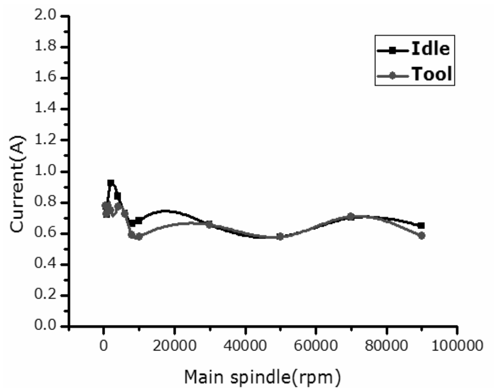
A two-fluted Ø500 µm end-mill and SM45C plates were used for the cutting tests. Feedrate and cutting speed levels were chosen according to the tool manufacturer's recommendations. The depth of cut was increased by 100 µm for each step. The cutting conditions used for this experiment are listed in Table 1.

Table. 1. Cutting conditions for the experiment.

Micro tool	500 µm
Cutting speed	30,000 rpm
Feedrate	100 mm/min
Depth of cut	100 ~ 500 µm



(a) Acceleration sensor signals



(b) Hall sensor signals

Fig. 4. Variation in sensor signals according to spindle rpm.

4. Experimental results

4.1 Micro machining condition measurement

The required preliminary cutting experiments were first performed in order to investigate the machine tool performance and sensitivity of the sensors with increasing cutting speed, as shown in Fig. 4. From the results, the maximum amplitude of rotation frequency was generated at 70,000 rpm (1.166 Hz). This range can be regarded as the natural frequency of the main spindle. If the natural frequency approaches the rotation frequency, resonance can occur. Since the performance of a machine tool can be easily affected by the natural frequency, the reliability of the acceleration signal can deteriorate. The hall sensor signals become stable from 10,000 rpm. From the results of the preliminary cutting tests, it is recognized that the natural frequency range should be avoided in the cutting conditions for precise signal acquisition and a stable cutting process with micro machine tools.

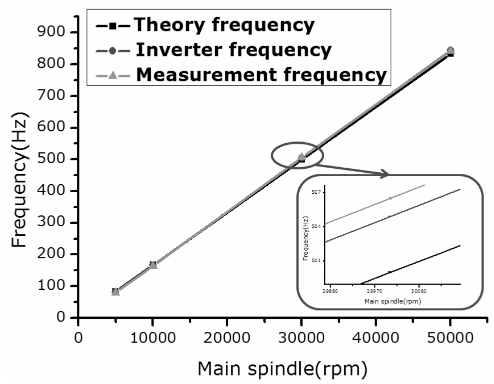


Fig. 5. Relationship of spindle rpm and acceleration.

4.2 Indirect cutting force measurement

For the experimental purpose, the main spindle speed (rpm) was changed from 5,000 rpm to 50,000 rpm, and the frequency of the signals was measured using hall sensors and an acceleration sensor. From the results of the experiments, it could be confirmed that the supplied current frequency, rotation frequency, and rpm have a linear relation as shown in Fig. 5. Thus, indirect measurement of the main spindle speed (rpm) can be performed using the hall sensors and acceleration sensor.

The amplitudes of the rotation frequency and tool teeth rotation frequency, and those of the hall sensor signals and acceleration sensor signals were correlated with the measured cutting force components using a micro tool dynamometer.

Correlations between the amplitudes and the measured cutting forces using the dynamometer tool were calculated. From the results, the correlation of the tool teeth rotation and current amplitude showed linearity of 92.0% precision for the hall sensor signals, and 98.0% precision for the acceleration sensor signals (Fig. 6 and Fig. 7). Even though the results obtained using the acceleration sensor showed better linearity than those of the current hall sensors, the signals from the latter can be easily affected by chattering, spindle vibration, and external disturbances. From this perspective, the current hall sensor can provide more robust results.

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5. Conclusions

In this study, an indirect cutting force measurement method based on frequency analysis is suggested for micro end-milling process monitoring. Two types of sensor systems, an acceleration sensor and current hall sensors, were used. The measured signals were compared with the cutting force com-

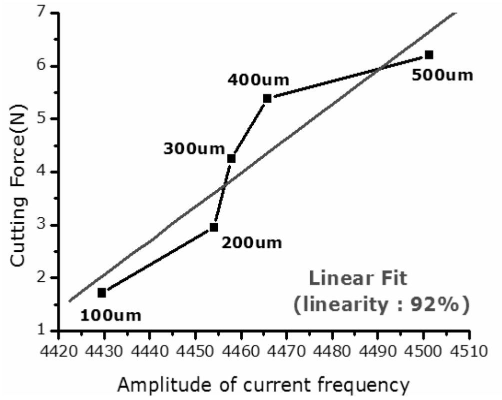

Fig. 6. Spindle current vs. cutting force at various depths of cut.

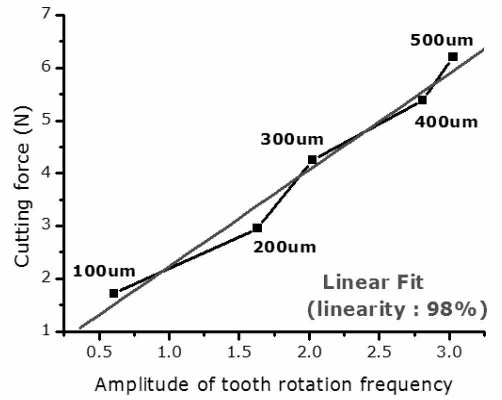

Fig. 7. Acceleration sensor vs. cutting force at various depths of cut.

ponents obtained using a micro tool dynamometer at the frequency domain. The calculated correlations showed linearity of 98.0% and 94.5% precision with the use of an acceleration sensor and current hall sensors, respectively. The results of this research are summarized as follows:

(1) The developed monitoring system using current hall sensors and an acceleration sensor can be used to investigate the required characteristics of a micro machining system and to determine the optimum cutting conditions.

(2) For the purpose of indirect cutting force measurement, the motor currents and acceleration signal can be measured by amplitude variation via frequency analysis.

(3) Analysis using multi-sensors in the micro machining process is a very useful means of obtaining precise results.

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