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Real-Time Estimation of Machining Error Caused by Vibrations of End Mill

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Abstract

The purpose of this study is to establish a method of estimating, in real time, the machining error caused by vibrations of the cutting point of an end mill. The vibration displacement at the shank of the end mill and the dynamic cutting force were measured during cutting tests while spindle speed was increased from medium to high. It was found that the vibration displacement at the cutting point at the moment when the radial direction of the cutting edge is normal to the feed direction showed a good agreement with the height of the machined surface at a spindle speed of 4500 rpm or less.

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Keywords: End milling; Machining error; Stiffness; Cutting force; Compensation

Nomenclature

Fx	Cutting force
|G|	Gain
$\angle G$	Phase angle
K	Equivalent stiffness
X	Vibration displacement
λ	Frequency ratio
ζ	Damping ratio
ω	Frequency
Ω	Natural frequency

1. Introduction

In recent years, machining centers have been widely used for metal mold manufacturing processes because high-speed machining, using small-diameter end mills, has become practical. Unfortunately, the use of a long, small-diameter end mill degrades the machining accuracy of the metal mold, because the cutting forces cause the cutting point to deflect considerably at the cutting point. In peripheral milling, which is often used in mold processing, machining error due to tool deflection is a serious obstacle to processing the precision machining parts [1]. Therefore, many researchers have proposed preliminary methods of predicting machining error in end-milling with square end-mills [2, 3]. In addition, a compensation system that minimizes the machining error by compensating for the deflection of the end mill at the cutting point was proposed [4].

It is pointed out that the static stiffness of end mill systems greatly influences the machining error in slab milling with square end mills [5, 6]. In our previous studies, we found that the machining error caused by the deflection of the tool at the cutting point in end-milling processes at a spindle speed of 1000 rpm could be closely estimated from the static stiffness of the end mill system and the quasi-static cutting force [7]. However, end-milling processes are generally carried out at a spindle speed of 5000 rpm or more.

The purpose of this study is to propose a means of compensating for machining errors caused by the vibration of an end mill at the cutting point. To this end, the vibration displacement at the shank of the end mill and the dynamic cutting force were measured during cutting tests while spindle

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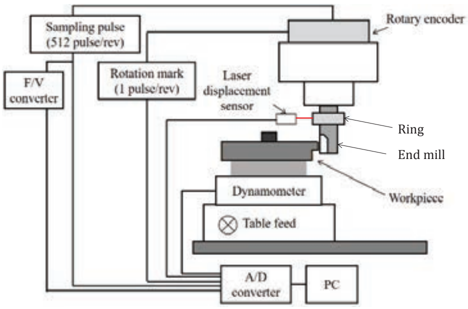

Fig. 1. Experimental apparatus.

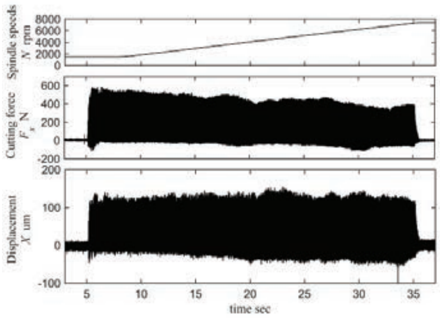

Fig. 2. Experimental results.

Table 1. Cutting conditions.

	Material	Brass(JIS C3713)
Tool	Type	Straight fluted end-mill
	Diameter mm	12
	Number of teeth	1
	Overhang mm	53
Spindle speed N rpm		1500-7450
Feed rate *f* mm/rev		0.1
Axial depth of cut mm		2
Radial depth of cut mm		3
Type of cut		Down cut

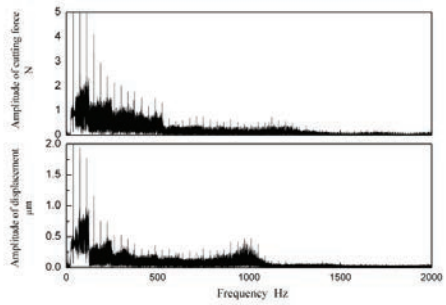

Fig. 3. Spectra of cutting force and displacement.

speed was increased from medium to high. Furthermore, the machining error was estimated from the cutting force and vibration displacement using the frequency-response function obtained from impact testing.

2. Experimental Apparatus

Cutting tests were carried out on a vertical machining center. The experimental apparatus used in this study is shown in Fig. 1; cutting conditions are shown in Table 1. The workpieces were made from free-cutting brass plate, and were fixed on the table horizontally, as shown in Fig. 1. In all cutting tests, spindle speed was gradually increased. The dynamic cutting force, Fx, normal to the feed direction, was measured with a dynamometer, which is a piezoelectric quartz force transducer. The vibration displacement at the ring fixed on the shank of the end mill was measured with a laser displacement sensor. Laser displacement sensor was fixed on the spindle head column through a bracket with soft support. The dynamic cutting force and the vibration displacement were measured while spindle speeds were increased from 1500 to 7450 rpm. In order to determine the angular position of the cutting edge precisely, two kinds of pulses were used in this study and are shown in Fig. 1. The first, at 512 pulses per revolution, was used in conjunction with the experimental data for cutting force and displacement, and was generated by an optical rotary encoder fixed on the end of the spindle. Furthermore, the spindle speeds were measured with an F/V converter using the obtained pulses. The second, at one pulse per revolution, was used for determining the angular position of the cutting edge during end-milling processes, and was generated by a position transducer and a bump on the cylindrical surface of the spindle. Signals for the cutting force, the vibration displacement and the rotation pulse were transmitted to a personal computer through an A/D converter. After each cutting test, the height of the machined surface was measured with a contact displacement sensor fixed on the spindle head through a bracket.

3. Experimental Results

3.1. Cutting force and vibration displacement

Figure 2 shows the cutting force and the vibration displacement of the tool at the ring. The spindle speed was increased at a constant rate and the displacement of the tool at the ring gradually increased while milling progressed. On the other hand, the cutting force gradually decreased.

3.2. Frequency-response function of end mill at cutting point

Figure 3 shows the spectra of the cutting force and vibration displacement shown in Fig. 2. Figure 4 shows the frequency-response function obtained from the cutting force and vibration displacement shown in Fig. 2. The amplitude ratio of the vibration displacement of the tool relative to the excitation force is shown in the upper figure, and the phase angle is shown in the lower figure. The phase angle at the natural frequency shown as a dashed line is -90 degrees. However, the result of the frequency-response function shown in Fig. 4 includes the vibration characteristic of the dynamometer. Figure 5 shows the frequency-response