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Investigation on Direction Dependency of Tool-Workpiece Compliance of Machine Tool

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Abstract

The direction dependency of tool-workpiece compliance of machine tool was investigated in three dimensions. The tool-workpiece compliance is defined as the frequency response of the relative displacement between the tool and the workpiece to the cutting force. The tool-workpiece compliance of a vertical type machining center was measured. The direction dependency of the compliance magnitude was discussed using the polar plot. The compliance in the Z (vertical) direction was smaller than that in the XY (horizontal) directions. The maximum value of the compliance in the X direction was almost twice as large as those in the Y and Z directions. The influence of the frequency on the direction dependency was also discussed. The direction dependency in the XY plane was small in the frequency range higher than 250 Hz. This can be explained by the symmetry of the spindle about the X and Y directions because the tool-workpiece relative displacement was dominated by the tool displacement in the high frequency range.
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Keywords: Machine tool; Vibration; Evaluation; Tool-workpiece compliance; Direction dependency

1. Introduction

Vibration caused by cutting force is one of important issues of machine tool because it limits the productivity. In machining of the workpiece with complicated shapes, the direction of cutting force changes greatly. In addition, vibration reduction in larger workspace is required because several workpieces are often machined on one work table with single setup for higher productivity. Consequently, the dependencies of vibration characteristic on direction and position must be evaluated to design machine tools and cutting process.

The vibration characteristic against the cutting force can be evaluated by tool-workpiece compliance. The tool-workpiece compliance is defined as the frequency response of relative displacement between the tool and the workpiece to the cutting force. The tool-workpiece compliance has been obtained by the traditional impact test using an impulse hammer. Several noncontact type shakers have been developed to impose an artificial cutting force on machine tools [1-3]. The developed shakers are used to obtain the frequency response of spindles. Several methods have been also proposed to identify the frequency response of machine tools in milling process [4-6]. Although studies such as forementioned literatures are useful to obtain the frequency response of machine tools, the position and the direction dependencies of the tool-workpiece compliance have not been focused on.

Law et.al. and Zulaika et.al. evaluated the position and the direction dependencies of the tool-workpiece compliance to optimize the machine tool structure [7, 8]. However, their evaluation is limited in two dimensions. Moreover, the influence of the cutting force frequency is not clearly evaluated because they focused on the critical depth of cut in regenerative chatter vibrations.

The final goal of this study is to propose a comprehensive evaluation method of the tool-workpiece compliance in the three dimensions. For this purpose, a map of the frequency

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Table 1. Specification of machine tool

Size	W×L×H:1.2 m× 2.4 m× 2.6 m
Travel	X: 600 mm, Y: 530 mm, Z: 510 mm
Total mass	5500 kg
Drive	Ball screw
Guideway	Rolling (Ball)
Spindle taper	BT No.40
Control type	Semi closed

response is used. In this paper, the direction dependency of the tool-workpiece compliance is evaluated on a vertical machining center prototype. An experiment was conducted to investigate the influence of the frequency on the direction dependency.

2. Concept of compliance evaluation

In this paper, a method is introduced to evaluate the tool-workpiece compliance against a cutting force in a certain three dimensional direction. When the tool and the workpiece are excited in a certain direction, the resultant relative displacement consists of three components, which are one principle component in the excitation direction and two perpendicular (cross talk) components. In this paper, the principle component in the excitation direction is focused on because the cross talk effect is small in many cases.

The principle tool-workpiece compliance must be obtained in various directions to evaluate its direction dependency. For this purpose, the tool-workpiece compliance is measured with excitations in the X, Y and Z directions. Then, the compliances in other directions are calculated from the measured compliances. In this paper, the compliance is assumed to be a second order tensor similarly to stress. Therefore, the compliance in an arbitrary direction is calculated using the following equation:

$$G_{\phi\theta} = (G_x \cos^2\phi + G_y \sin^2\phi)\times\sin^2\theta + G_z \cos^2\theta \quad (1)$$

where ϕ and θ are longitude and colatitude in the spherical polar coordinates system, respectively, G represents the compliance, subscripts x, y, and z indicates the direction. The influence of cross talk component is neglected in Eq.(1).

3. Experiment

3.1. Machine tool used in experiment

The direction dependency of the tool-workpiece compliance is evaluated according to the concept mentioned in section 2. A machining center prototype is used in the experiment. The machine is a typical vertical type machine. Its drive system consists of a spindle head driven by vertical Z axis and a table driven by X and Y axes. Major specification of the machine is summarized in Table 1.

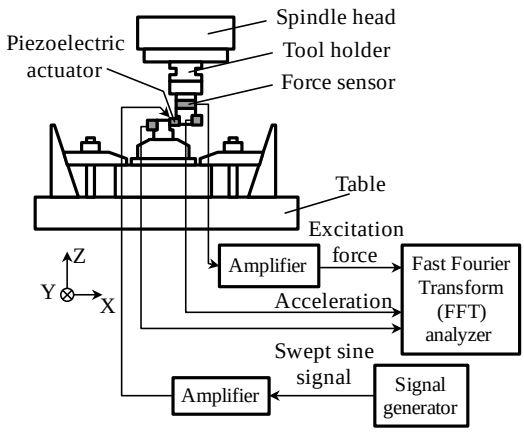

Fig.1 Experimental setup.

3.2. Experimental method

Figure 1 shows the schematic drawing of the experimental setup. A dummy tool and a dummy workpiece are attached to the spindle and the table, respectively. A piezoelectric actuator is used to excite the tool and the workpiece simultaneously. The excitation force is measured using a three axis force sensor (Kistler) installed in the tool. The relative acceleration between the tool and the workpiece is measured using three axis accelerometers (PCB piezotronics). The frequency response of the relative acceleration to the excitation force is calculated using a fast Fourier transform (FFT) analyzer (Ono sokki). Then, the tool-workpiece compliance is obtained by integration. The accelerometer sensitivity is 50 mV/m/s^2. The force sensor sensitivity is 7.8 pC/N in the X and Y directions and 3.8 pC/N in the Z direction.

The 50 N preload is given to the piezoelectric actuator in excitation. Then, the swept sine signal is input to the actuator for 60 s. To obtain higher coherence of the measurement, the excitation is conducted three times with different frequency ranges of the swept sine signal: 1-250 Hz, 1-500 Hz and 1-1600 Hz.

3.3. Experimental result

Figure 2 shows the polar plot of the magnitude of the tool-workpiece compliance. The magnitude is represented in color scale. The excitation direction is represented by the argument. The radius shows the frequency. To show the excitation direction in three dimensions, the directions in the XY, the YZ and the ZX planes are shown in the first, the second and the third quadrants, respectively.

The direction dependency of the compliance can be evaluated comprehensively by Fig.2. Figure 2 (a) and (b) show that the compliance is small around the Z direction for entire frequency range.

Depending on the excitation direction, circular lines in sky blue are observed at different frequencies in the XY plane in Fig.2 (b). It indicates that the direction dependency of the compliance magnitude is relatively large for frequencies less

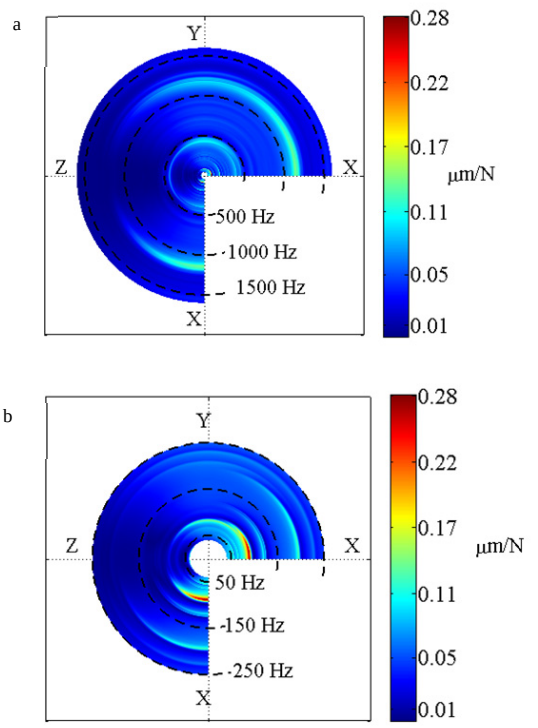

Fig.2 Polar plot of compliance magnitude for (a) frequencies up to 1600 Hz; (b) frequencies up to 250 Hz.

than 250 Hz. The magnitude is especially large around the X direction at about 90 Hz. From the result of an experimental modal analysis, we concluded that this magnitude peak was caused by the torsion vibration of the column. In Fig.2 (a), the direction dependency of the compliance magnitude is small in the XY plane for frequencies larger than 250 Hz. This can be explained by the symmetry of the spindle about the X and Y directions because the tool-workpiece relative displacement was dominated by the tool displacement in the high frequency range as described in the later discussion.

For further quantitative evaluation, Fig.3 shows the comparison of the maximum value of the compliance magnitude. The excitation direction is represented by the argument. The radius represents the maximum value of the compliance magnitude. The magnitude in the X direction is about twice as large as the one in the Y direction in the frequency range of 40-250 Hz. The magnitude difference is decreased to less than 30 % in the frequency range of 250-1600 Hz. This result also shows the small direction dependency in the XY plane in the high frequency range.

The contribution of the tool and the workpiece displacements to the tool-workpiece relative displacement is discussed in the following. Figure 4 shows the comparison of the measured compliance in the X direction. In the frequency range of 150-1600 Hz, the compliance about the relative displacement is almost dominated by the one about the tool displacement because they are similar. In the frequency range less than 150 Hz, the compliance about the relative displacement differs from the one about the tool displacement.

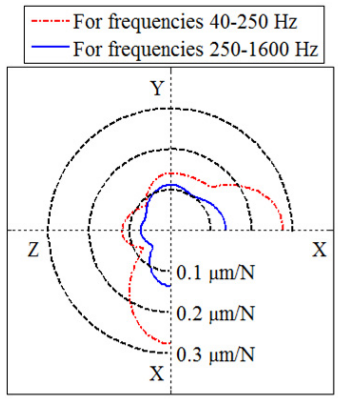

Fig.3 Maximum value of compliance magnitude.

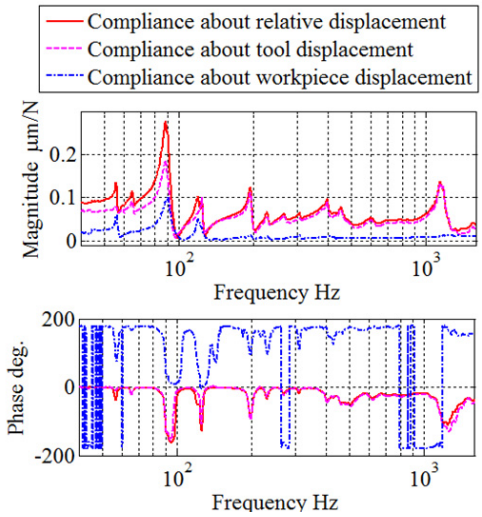

Fig.4 Comparison of compliances in X direction.

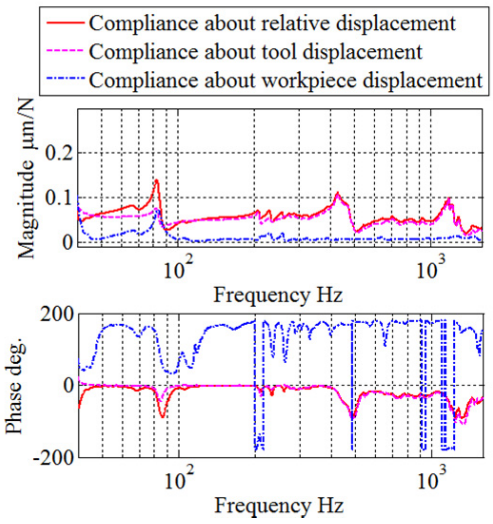

Fig.5 Comparison of compliances in Y direction.

The contribution of the wopkpiece displacement is 30-40% to the relative displacement at resonance peaks. Figure 5 shows the comparison of the compliance in the Y direction. The contribution of the tool displacement is also dominant in the frequency range larger than 100 Hz.

4. Conclusions

The tool-workpiece compliance of a vertical type machining center was evaluated in the three dimensions. The direction dependency of the compliance magnitude was discussed using the polar plot. The compliance in the Z (vertical) direction was smaller than that in the XY (horizontal) directions. The maximum value of the compliance in the X direction was almost twice as large as those in the Y and Z directions. The influence of the frequency on the direction dependency was also discussed. The direction dependency in the XY plane was small in the frequency range higher than 250 Hz. This can be explained by the symmetry of the spindle about the X and Y directions because the tool-workpiece relative displacement was dominated by the tool displacement in the high frequency range.

Acknowledgements

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