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Chatter Analysis of a Parallel Mechanism-based Universal Machining Center

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Extensive researches have been carried out on machine tool chatter to obtain assessment procedure and improvement measures. In this study, chatter limit is predicted on a newly fabricated universal machining center by the combination of structural dynamic characteristics and cutting mechanics. We showed the unstable cutting conditions, and from them we could plot the unstable borderlines. From the chatter simulations we could say that the newly built universal machining center can be well used in the finishing machining of steel as other common machine tools.

Key Words : Universal Machining Center, Chatter, Structural Dynamic Characteristics, Cutting Mechanics

1. Introduction

Extensive researches have been carried out on machine tool chatter to obtain assessment procedure and improvement measures (Weck and Teipel, 1978 ; Nigm, 1981; Rahman and Ito, 1981). The ISO committee TC 39/SC2 has already discussed general acceptance conditions on static and dynamic behavior of machine tools (Moriwaki and Iwata, 1976). However, the objective assessment of the dynamic performance of machine tools has not been established.

In this study, chatter limit is predicted on a newly fabricated universal machining center by the combination of structural dynamic characteristics and cutting mechanics (Lee et al., 1989). The structural dynamic characteristic was obtained by impulse test and the cutting dynamics were analyzed by using three-dimensional cutting dynamics (Sata et al., 1975) and the minimum energy theory for chip flow angle (Usui, 1971).

2. Universal Machining Center

Recently an universal machining center has been designed and built in Seoul National University. The CNC machine is based on the Eclipse, a fast parallel mechanism built as a second version after a prototype as shown in Fig. 1.

In order to achieve the minimum machining time of the Eclipse, the following two objectives were required.

(1) The Eclipse should be capable of per-

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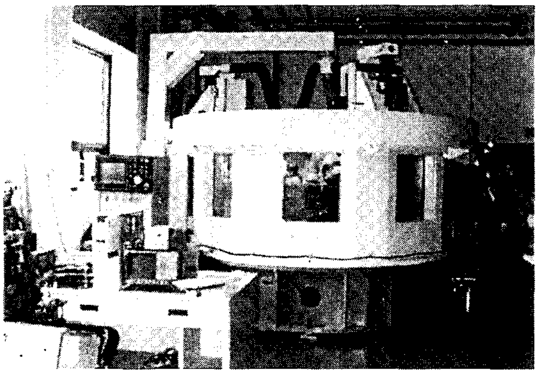


Fig. 1 An universal machining center : Eclipse

forming 5 faces machining.

(2) The Eclipse should be capable of performing complex such as milling, turning, and grinding.

The common CNC machining centers basically perform 1-face machining and they are divided into two groups : vertical and horizontal machining centers. Even though some machining centers are capable of 5-faces machining, they need to change the setup of a workpiece in order to fully machine 5-faces due to the limit of spindle axis movement. Therefore, these CNC machining centers have time lag of setup changes. The Eclipse was able to obtain the spindle tilting angles to a full 90 degrees and 5-faces machining in one setup of a workpiece.

The common machining centers are capable of performing particularly one machining process among milling, turning, and grinding. However, the Eclipse has an ability to perform milling, turning, and grinding. The tool spindle can be tilted to 90 degrees and the vertical workpiece spindle is rotating to perform a turning process. Also grinding process can be done by attaching a grinding tool to the tool spindle.

In order to achieve two objectives we mentioned above, we need a mechanism which has 6 degrees of freedom with the tilting angle of the spindle unit to full 90 degrees. Most parallel mechanism-based machining centers do not exceed the spindle tilting angles above 30 degrees. The Eclipse no longer has this shortcoming of common machining centers. Figure 2 shows the schematic drawing of a universal machining center.

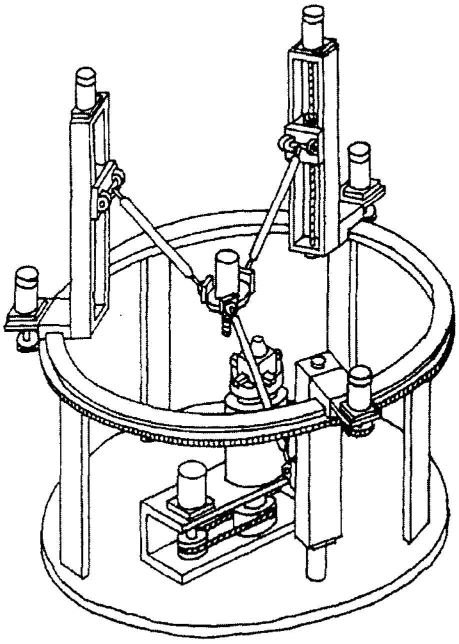


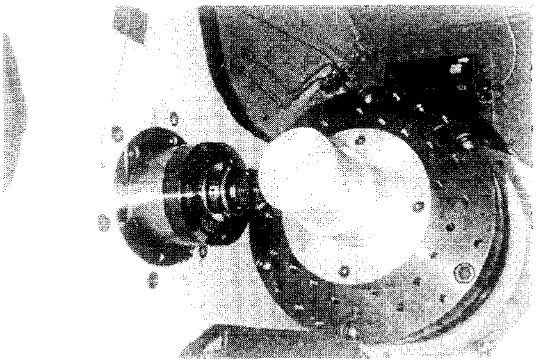
Fig. 2 Schematics of the Eclipse

The Eclipse has 6 kinematic degrees of freedom, and 8 independent actuated joints. It consists of three vertical columns, each of which slides independently on a circular guide. The movement of each column along the circular guide is achieved by a servomotor through a pinion and ring gear transmission. Each column has a carriage, which moves vertically along the linear slideway provided on the column. The carriage movement is achieved by a servomotor and a ball screw transmission. A fixed link is attached to each of the carriages through a pin joint. The other end of the fixed link is attached to the tool spindle plate via a ball-socket joint. The Eclipse achieves 6 degrees of freedom using the independent movements of 3 circular prismatic joints and 3 linear prismatic joints. The tool spindle unit can tilt from 0 to 90 degrees and can rotate 360 degrees around a workpiece. This is the key factor which let 5 faces machining possible.

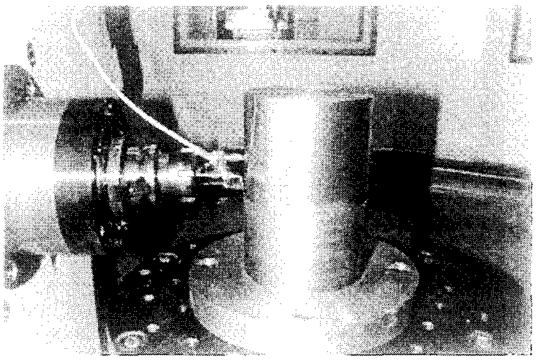
In addition to 3 linear prismatic joints and 3 circular prismatic joints, 2 complementary joints are necessary to overcome the actuator singularities. These 2 additional joints are actuated dependently with other 6 joints.

3. Structural Dynamics

The total performance of a machine tool is specified by the combination of the structural dynamics and the cutting dynamics of cutting process because cutting forces are generated and the cutting forces make some variations in the configuration of the workpiece and the tool when the cutting is performed by given cutting conditions (Doi and Kato, 1956 ; Merritt, 1965 ; Sata et al., 1975 ; Ssengonzi, 1982a, b ; Lee and Lee, 2000). Any external forces applied to the tool will cause some deflections in the links and joints ; if these deflections are significant they can seriously impact the overall accuracy of the mechanism. Hence a careful stiffness analysis of the mechanism is an integral part of the design process. Since the rods of the mechanism can be made arbitrarily stiff by increasing their diameters, for most purposes it is sufficient to consider only

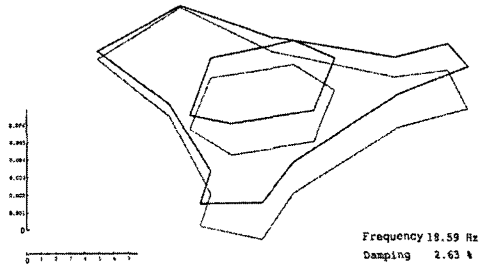


(a) Accelerometer

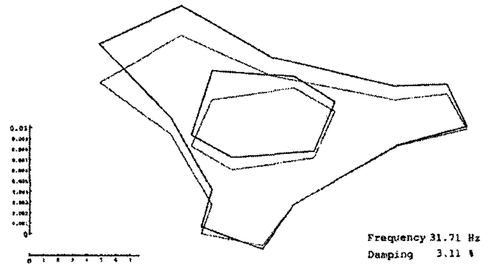


(b) Displacement meter

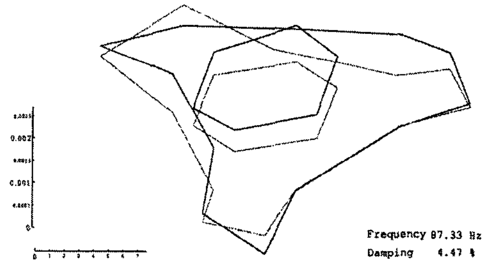
Fig. 3 Workpiece, tool and sensor in experiment



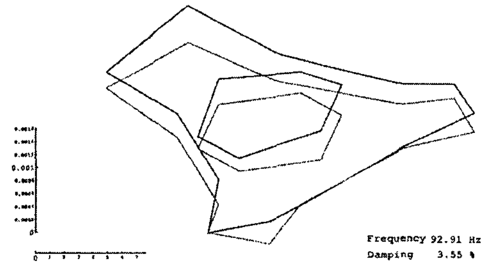
(a) Mode shape at 18.6 Hz



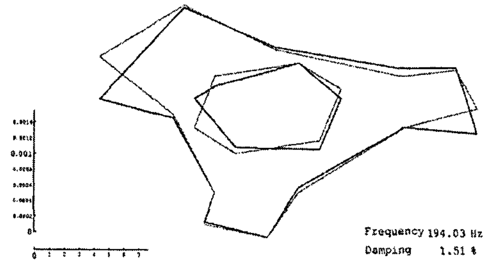
(b) Mode shape at 31.7 Hz



(c) Mode shape at 87.3 Hz



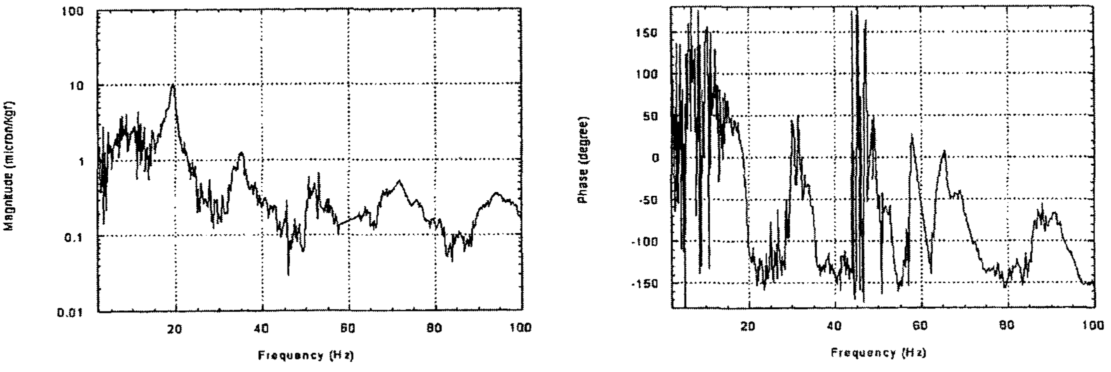
(d) Mode shape at 92.9 Hz



(e) Mode shape at 194 Hz

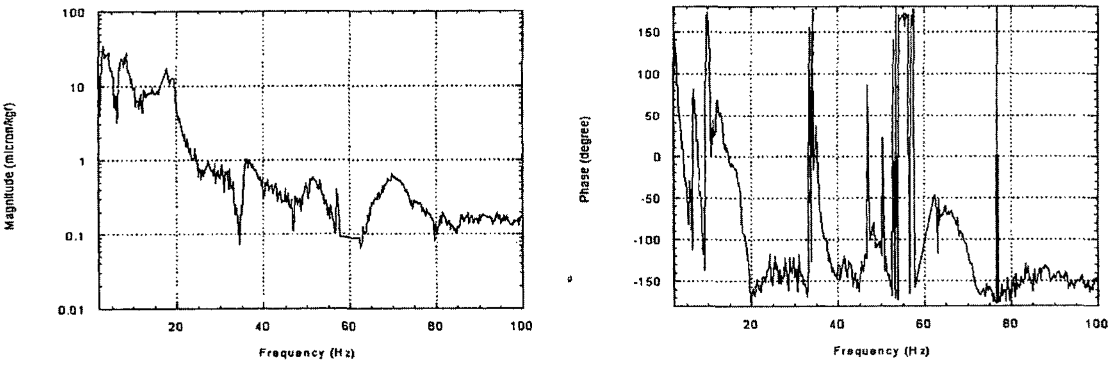
Fig. 4 Mode shapes of the tool spindle plate the stiffness of the joints. In this study in order to obtain the structural dynamics of the total system modal testing (Ewins, 1984; Nagamatsu, 1993; McConnell, 1996; Blake and Mitchell, 1972) was done by an impact hammer, accelerometers, and noncontact displacement meters as shown in Fig. 3.

Figure 4 shows the mode shape of the tool spindle plate. In Figs. 5~7 the frequency response functions between the tool mounted on the



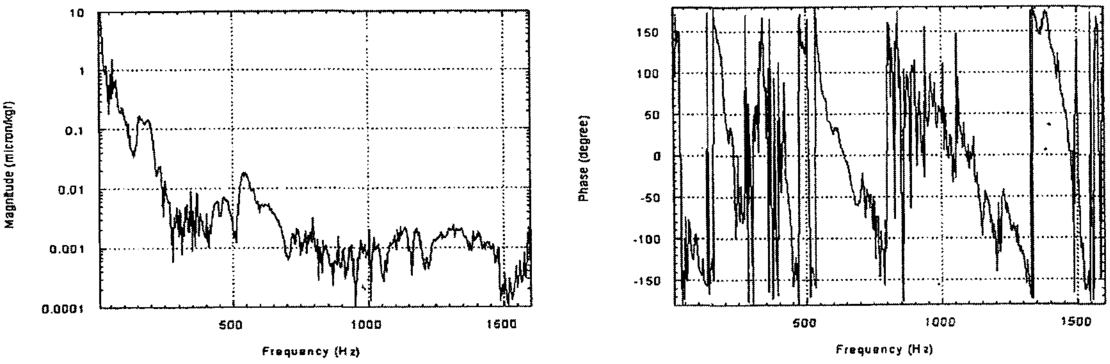
(a) Magnitude (b) Phase

Fig. 5 Frequency response functions between a tool and an aluminium workpiece



(a) Magnitude (b) Phase

Fig. 6 Frequency response functions between a tool and a steel workpiece



(a) Magnitude (b) Phase

Fig. 7 Frequency response functions between a tool and a steel workpiece shown in broad frequency range tool spindle and the workpiece mounted on the work table is shown. From Figs. 5~7 it is shown that the dynamic characteristics of this universal machining center is somewhat different from other types of machine tools in that the magnitudes of the area in lower frequency is bigger than those of common machine tools.

4. Chatter Prediction

The relative vibration between the tool and the workpiece is complex because it is dependent on frequency. It gives bad effects to precision such as the geometry and surface roughness of machined surfaces. So the forced vibration or chatter vibration should be lessened or avoided (Doi and Kato, 1956 ; Merritt, 1965 ; Arnold, 1946). Chatter vibration is known as the results of machine tool structure and cutting process, and many researches (for example Sata et al., 1975 ; Ssengonzi, 1982) have performed on the dynamic orthogonal cutting. Let the cutting stiffness coefficients be K, the overlap coefficient μ, the time lag between the inner modulation and the outer modulation in cutting ε. Also we indicate the index for the outer modulation as a superscript (o), the index for the inner modulation as a superscript (i) and structural stiffness coefficients of the machine tool-workpiece system as P. Figure 8 shows the block diagram of the three dimensional cutting system (Merritt, 1965). $T(s)$ is $\mu \cdot e^{-j\varepsilon}$. From the block diagram and some assumptions, we can obtain the formulas that gives the chatter borderline for a given cutting condition. If the structural dynamic characteristics are given by vibrational test or analysis, and cutting dynamics are obtained, chatter stability can be analyzed by the combination of the structural dynamics and the cutting dynamics of the machine tool-workpiece system. We used the cutting conditions and tool geometry as shown at Table 1 in the chatter simulation.

Figures 9~15 show the results of the chatter analysis for some cutting conditions. Figure 9 shows the unstable cutting conditions, and from it we could plot the unstable borderline as in Fig. 10. The borderlines depended on the cutting conditions such as cutting speeds, feedrates, nose radius of the tool, and so on. As the nose radius of a tool decreased, the stable depth of cut increased. As the feedrate increased, so did the stable depth of cut to some extent. On the other hand as the cutting speed increased the stability was varied because the structure dynamics depends on the frequency. From the chatter sim-

Table 1 Cutting conditions used in chatter simulation

Item	Unit	Values
Spindle speed	m/min	50~150
Feedrate	mm/rev	0.1, 0.2, 0.4
Depth of cut	mm	0.1~4.0
Nose radius	mm	0.4, 0.8
Side cutting edge angle	degree	45
End cutting edge angle	degree	45
Side rake angle	degree	0
Back rake angle	degree	−7

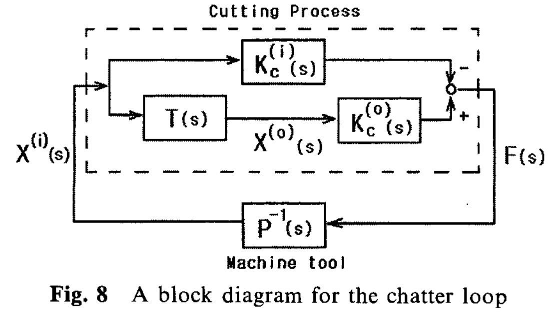


Fig. 8 A block diagram for the chatter loop

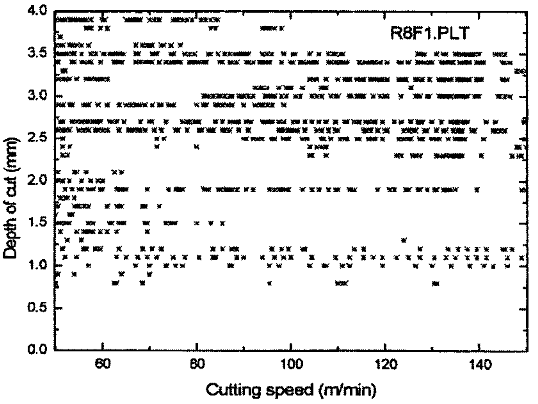


Fig. 9 Unstable cutting conditions for nose radius 0.8 mm, feed 0.1 mm/rev

ulations we can say that the newly built universal machining center can be well used in the finishing machining of steel as other common machine tools.

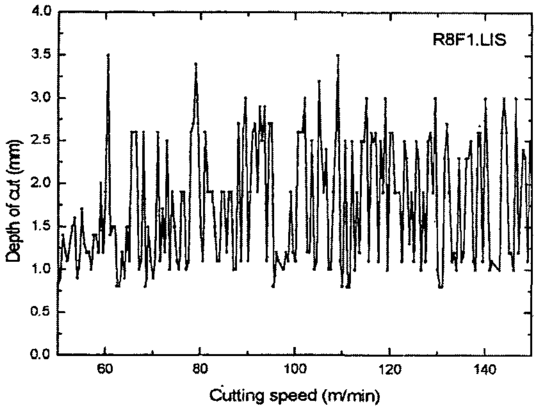


Fig. 10 Unstable borderline for nose radius 0.8 mm, feed 0.1 mm/rev

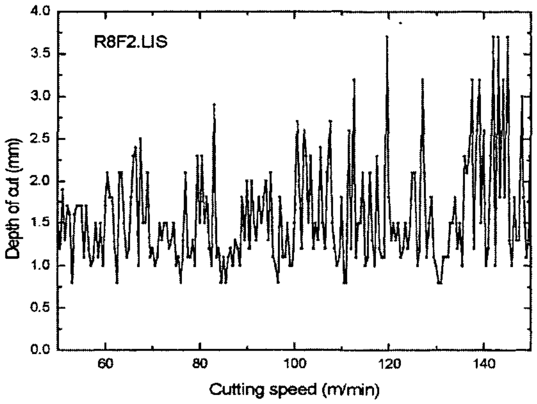


Fig. 11 Unstable borderline for nose radius 0.8 mm, feed 0.2 mm/rev

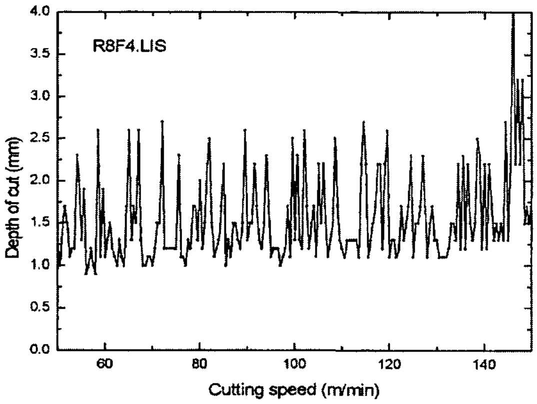


Fig. 12 Unstable borderline for nose radius 0.8 mm, feed 0.4 mm/rev

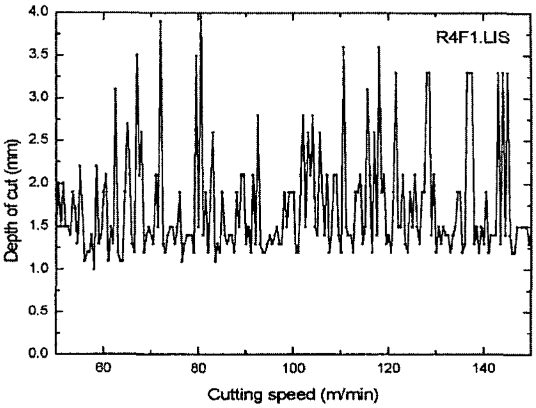


Fig. 13 Unstable borderline for nose radius 0.4 mm, feed 0.1 mm/rev

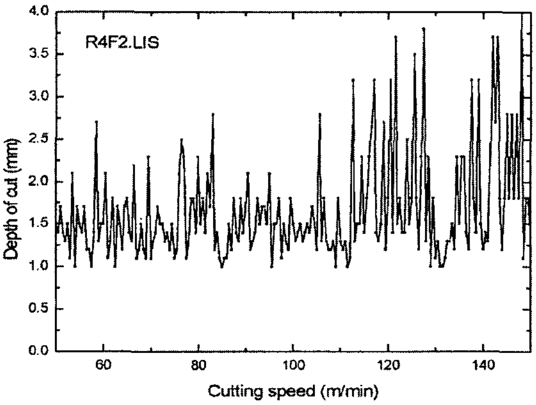


Fig. 14 Unstable borderline for nose radius 0.4 mm, feed 0.2 mm/rev

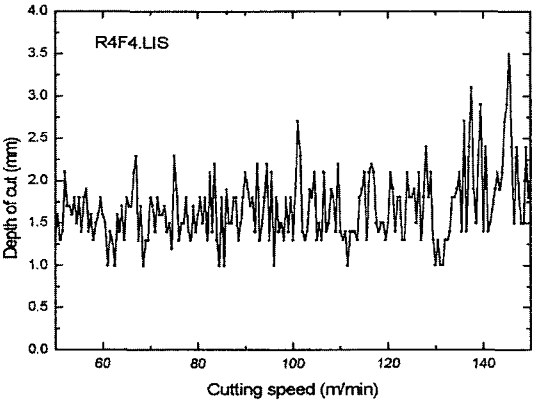


Fig. 15 Unstable borderline for nose radius 0.4 mm, feed 0.4 mm/rev

5. Concluding Remarks

The total performance of a machine tool is specified by the combination of the structural dynamics and the cutting dynamics of cutting process because when the cutting is done by cutting conditions cutting forces are generated and the cutting forces make some variations in the configuration of the workpiece and the tool. We examined the structural dynamics of the universal machining center and other machine tools by experimental modal analysis. Also, in order to estimate the total performance we used the chatter analysis by using the structural dynamics data and the cutting dynamics data. We showed the unstable cutting conditions, and from them we could plot the unstable borderlines. From the chatter simulations we could say that the newly built universal machining center can be well used in the finishing machining of steel as other common machine tools.

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