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CHARACTERISTICS OF DYNAMIC CUTTING FORCE AND MECHANISM OF CHATTER VIBRATION

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Abstract

The cutting force acting in the dynamic state of a lathe spindle-workpiece system is affected by the dynamic variations of cutting depth, cutting velocity and rake angle. In this study, the influences of these parameters on the dynamic cutting force are measured by unique experiments. The phase lag between the dynamic cutting force and vibration displacement is clarified under various cutting conditions. The dynamic cutting force when the cutting velocity and the rake angle are dynamically changed is measured, and the results are represented as the cutting velocity coefficients and the rake angle coefficients. Based on these results, the energy supplied by the dynamic cutting force is obtained and the mechanism by which the chatter vibration occurs is discussed.

1. Introduction

In the previous report[1)], the primary and the regenerative chatter vibrations occurring in a spindle-workpiece system were observed, and the effects of the vibratory characteristics of the system and cutting conditions on the chatter vibration are clarified.

It is quite natural that the cutting force acting on the workpiece in the dynamic state is affected by the dynamic variations of cutting depth, cutting velocity and

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rake angle. There are many reports on the dynamic cutting force characteristics[2~7]. The dynamic cutting force responses to the cutting depth variation or cutting velocity variation are treated in these studies. The present authors measured the dynamic cutting force when the workpiece is forced to displace in the cutting depth direction[8~9]. The dynamic variation of rake angle is an important factor influencing the dynamic cutting force characteristics[10].

Then in the present study, the dynamic variation effects of the cutting depth, cutting velocity and rake angle on the cutting force characteristics are systematically investigated, when the spindle-workpiece system vibrates. Using the experimental results on dynamic cutting force, the exciting energy of chatter vibration is also discussed.

2. Representation of Dynamic Cutting Force

In this section, equations representing the dynamic cutting force are given, when the workpiece vibrates and is cut orthogonally.

Figure 1 shows the workpiece position while vibration. Point O″ is the workpiece center before cutting. Point O is the workpiece center during steady state cutting; it is x_s apart from O″ in the horizontal direction and y_s in the vertical direction. Point O′ is the workpiece center during vibration. Displacements of O′ from O are x and y in both horizontal and vertical directions.

Putting the steady state cutting depth as d_s, the cutting depth during vibration is as follows:

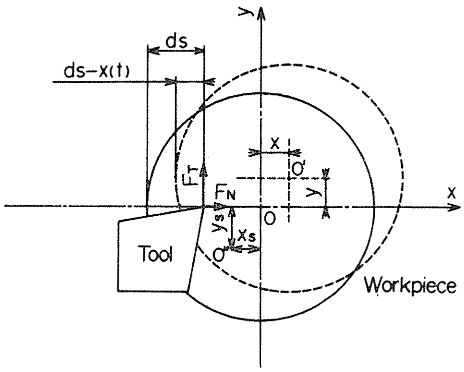

Fig. 1. Coordinate system of workpiece during vibration.

$$d=d_s-x(t) \tag{1}$$

Cutting force is assumed to be proportional to the cutting depth during vibration. The proportional constants in both directions are $K_N b$, $K_T b$, respectively. The cutting force acts on the workpiece slightly behind the cutting depth variation. The time lag of te thrust cutting force is H and that of the main cutting force is h. If the chatter frequency is β, then these time lags correspond to the phase lags of $\Theta=\beta H$ and $\theta=\beta h$. Therefore, the two components of the cutting force can be written as follows:

$$\left.\begin{aligned} F_N&=K_N b\left\{d_s-x\left(t-\frac{\Theta}{\beta}\right)\right\} \\ F_T&=K_T b\left\{d_s-x\left(t-\frac{\theta}{\beta}\right)\right\} \end{aligned}\right\} \tag{2}$$

where specific cutting resistances K_N and K_T may be influenced by the dynamic variations of the cutting velocity and rake angle. They are assumed as follows:

$$\left.\begin{aligned} K_N &= K_{N0} + \Delta K_{Nv} + \Delta K_{N\alpha} \\ K_T &= K_{T0} + \Delta K_{Tv} + \Delta K_{T\alpha} \end{aligned}\right\} \quad (3)$$

In equation (3), K_{N0} and K_{T0} are the specific cutting resistances in steady state cutting. The chages ΔK_{Nv} and ΔK_{Tv} are induced by the cutting velocity variation and $\Delta K_{N\alpha}$, $\Delta K_{T\alpha}$ are by the rake angle variation, respectively.

In Fig. 2, the cutting situation of the tool edge during vibration is shown. The cutting velocity during vibration is obtainable from the figure as follows:

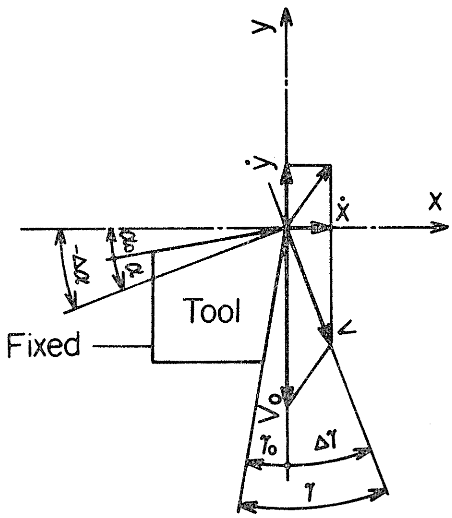

Fig. 2. Cutting edge during vibration.

$$v = V_0 - \dot{y} \quad (4)$$

The rake angle during vibration is,

$$\alpha = \alpha_0 - \Delta\alpha$$

$$= \alpha_0 - \tan^{-1}\left(\frac{\dot{x}}{V_0 - \dot{y}}\right) \quad (5)$$

The cutting force, of course, is affected by the relief angle variation. In the practical cutting tool. The relief angle is varied following the rake angle variation. Accordingly, the effect of the relief angle variation can be included in the estimate of the rake angle variation.

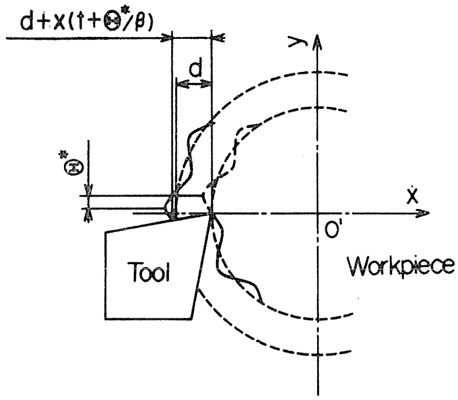

Fig. 3. Cutting operation under regenerative effect.

Here, let the changes of specific cutting resistances be proportional to the cutting velocity or rake angle variations. Then,

$$\left.\begin{aligned} K_N &= K_{N0} - a_{Nv}\cdot\dot{y} - a_{N\alpha}\cdot\tan^{-1}\left(\frac{\dot{x}}{V_0 - \dot{y}}\right) \\ K_T &= K_{T0} - a_{Tv}\cdot\dot{y} - a_{T\alpha}\cdot\tan^{-1}\left(\frac{\dot{x}}{V_0 - \dot{y}}\right) \end{aligned}\right\} \quad (6)$$

where, a_{Nv}, a_{Tv}; $a_{N\alpha}$, $a_{T\alpha}$ are the proportional constants.

The cutting situation under regenerative effect is shown in Fig. 3. The phase of the chatter mark in the successive cutting lags behind that in the previous cutting by the angle Θ^*. Then the cutting depth in the regenerative state is written as follows:

$$d' = d_s - x(t) + \mu \cdot x\left(t + \frac{\theta^*}{\beta}\right) \qquad (1)'$$

In the equation, μ is the overlap factor. Putting $\mu=0$, then this equation represents the primary state.

The dynamic cutting force components F_N and F_T are obtained by equations (1)', (2), (6). It is clear in the above consideration that the dynamic cutting state can be described by cutting velocity coefficients a_{Nv}, a_{Tv}, rake angle coefficients $a_{N\alpha}$, $a_{T\alpha}$, phase lags of cutting force Θ, θ, and the phase lag of chatter marks Θ^*.

3. Experimental Apparatus and Experimental Procedure

Figures 4 and 5 show the outline of the experimental apparatus used to estimate the dynamic cutting state.

The dynamic variation effects of the cutting depth and the cutting velocity are measured by the apparatus shown in Fig. 4. The spindle 1 is directly attached to the nose cone of the lathe main spindle. The diameter of the spindle 1 is 50 mm. The distance from the nose cone to the workpiece 5 is 370 mm. The natural frequency of the spindle is about 150 Hz. The spindle is in contact with two eccentric cams 3 through a roller bearing 2. The eccentric cams are located 70 mm from the workpiece, and installed at the horizontal and vertical positions of the spindle 1. The arbitrary forced displacement of various amplitudes and phases can be input by changing the eccentricities and phases of both cams. The workpiece is a disc of carbon steel. The cutting tool is set on a tool post without top slide. The rake and relief angles of the cutting edge are both 10°.

The workpiece coincides with the vibration center of the eccentric cams, and finished before the experiment. Then, cutting tool is fed into the workpiece by a prescribed cutting depth d_s. The forced displacement of the workpiece and the corresponding cutting force variation are measured within one revolution of the workpiece. The cutting velocities adopted are $v=4.5$, 6.0, 7.5 m/min. These velocities are a little lower than the cutting velocity adopted in the self-excited chatter experiments of the previous study[1], for convenience' sake. The displacements of the workpiece are measured by the eddy current-type displacement meters,

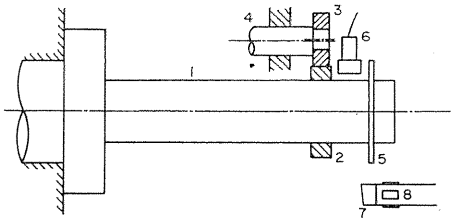

Fig. 4. Experimental apparatus for cutting depth and cutting velocity variations.

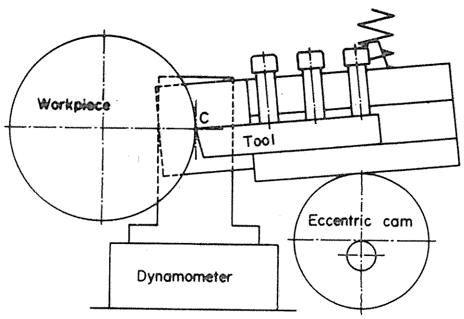

Fig. 5. Experimental apparatus for rake angle variation.

and the cutting forces are measured by the semi-conductor strain gauges pasted on the tool shank.

The dynamic variation effect of the rake angle is observed by the apparatus shown in Fig. 5. The cutting tool is oscillated around the cutting edge C by the eccentric cam, while varying the rake angle continuously. The oscillating axis of the cutting tool coincides with the cutting edge, not so as to change the cutting depth or cutting velocity, accompanying the oscillation. The variation of the rake angle is measured by the rotary encoder mounted on the same axis of the cutting edge. The cutting force is measured by the piezo-electric type dynamometer which is supporting the tool holder. The rake and relief angles of the high speed steel tool are both 10°. The cutting conditions are as follows: cutting width $b=2$ mm, cutting depth $d_s=0.12$ mm, cutting velocity $v=10.1$ m/min.

4. Experimental Results and Considerations

4. 1. Dynamic Variation Effect of Cutting Depth

The workpiece is displaced only in the horizontal direction, to ascertain the dynamic variation effect of cutting depth. The eccentricity of the horizontal cam is $x=0.06$ mm, and the frequency of the horizontal displacement is within the range of 10~20 Hz due to the convenience of the experiment. The cutting conditions are as follows: cutting velocity $v=6$ m/min, cutting width $b=2$ mm, cutting depth $d_s=0.06$ mm.

Figure 6 shows the phase lags Θ, θ of the thrust and the main cutting force components behind the cutting depth variation. It is seen in the figure that the phase lags of the cutting force are almost constant regardless of the displacement frequency, and the phase lag of the thrust force is larger than that of the main cutting force. Since the phase lags are irrelevant to the displacement frequency, this result can be applied to the discussion on the chatter vibration of higher frequency.

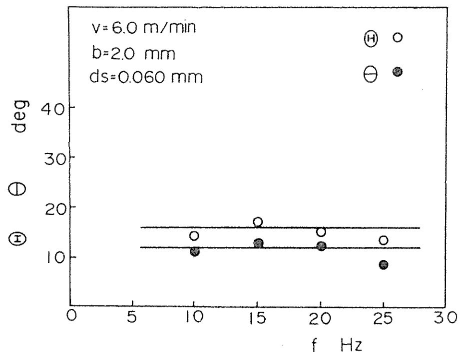

Fig. 6. Phase lag of cutting force.

4. 2. Dynamic Variation Effect of Cutting Velocity

The workpiece is displaced only in the vertical direction by the vertical cam, to examine the dynamic variation effect of cutting velocity. The eccentricity of the vertical cam is $y=0.3$ mm, and the displacement frequency is $f=25$ Hz. The mean cutting velocity is changed within the range of 3~9 m/min. The cutting depth is $d_s=0.06$ mm.

Figure 7 shows the relations between the thrust or the main cutting force components F_N, F_T and the dynamically varying cutting velocity. Although the cutting force variation describes a small clockwise hysteresis loop against the cutting velocity variation, it decreases linearly with the increase of cutting velocity.

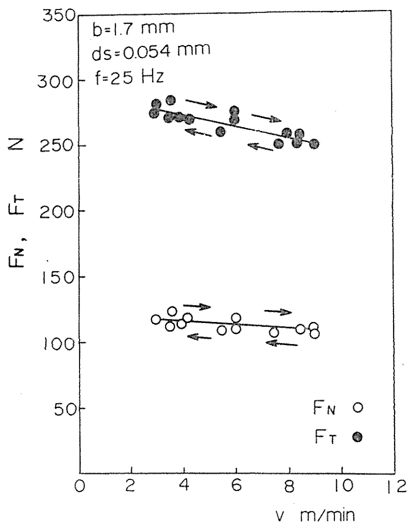

Fig. 7. Relation between cutting force and cutting velocity variation.

The cutting velocity coefficients a_{Nv} and a_{Tv}, which represent the influencing degree of the cutting velocity variation, can be obtained from the slopes of the straight lines in figure. The results are as follows:

$$a_{Nv} = -0.64 \times 10^9 \ (\mathrm{N \cdot s/m^3})$$

$$a_{Tv} = -2.75 \times 10^9 \ (\mathrm{N \cdot s/m^3})$$

The values are important as the basic data to estimate the effect of dynamic cutting conditions on the initiation of chatter vibration in spindle-workpiece system.

4. 3. *Dynamic Variation Effect of Rake Angle*

Figure 8 shows the relations between the thrust or main cutting force F_N and F_T and the dynamic variation of rake angle. This result is obtained for the conditions in which the frequency of rake angle variation is $f=20$ Hz, cutting velocity is $v=10.1$ m/min, cutting width is $b=2$ mm and cutting depth is $d_s=0.12$ mm. The results of two cycles are plotted in the figure. The thrust and the main cutting force components decrease almost linearly with the dynamic increase of rake angle, describing slender hysteresis curves.

Next, in Fig. 9, as the representative values of cutting force components F_N and F_T at the rake angle $\alpha=10°$ in dynamic variation of rake angle are plotted against the frequency. It is seen in the figure that the cutting force components are approximately independent of the fre-

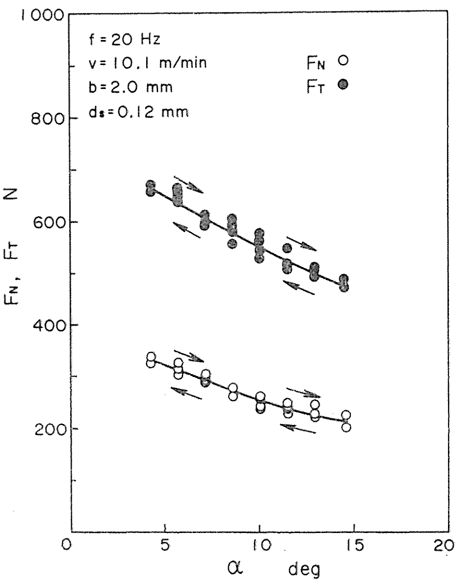

Fig. 8. Relation between cutting force and rake angle variation.

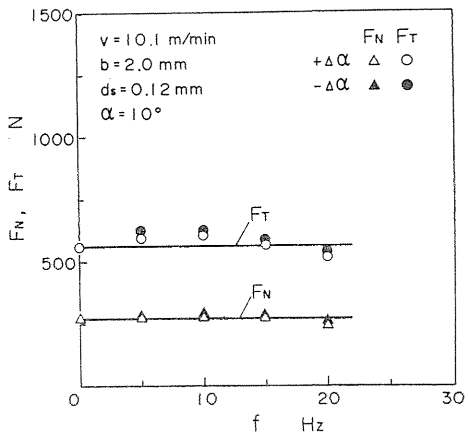

Fig. 9. Relation between cutting force and variation frequency.

quency.

From Fig. 8, the rake angle coefficients $a_{N\alpha}$ and $a_{T\alpha}$, which represent the influencing degree of the rake angle variation, can be obtained. The results are as follows:

$$a_{N\alpha}=-1.7\times10^{9}\ (\mathrm{N/m^2})$$

$$a_{T\alpha}=-1.1\times10^{9}\ (\mathrm{N/m^2})$$

5. Concluding Remarks

The experimental investigations are carried out on the dynamic cutting force characteristics in the chatter vibration state of spindle-workpiece system. As a result, it becomes clear that the cutting force when the cutting depth changes continuously, lags a little behind the cutting depth variation. This is one of the important properties of the dynamic cutting process. Next, the effect of the dynamically varying cutting velocity and rake angle on the cutting process is clarified too, in the experiment.

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