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CHARACTERISTICS OF CHATTER VIBRATION OF LATHE TOOLS

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Abstract

The elimination of chatter vibration is important to improve the cutting accuracy and to speed up the cutting operation. In this study, the characteristics of the primary and regenerative chatter vibration occuring in the spindle-workpiece system are investigated experimentally using six spindle-workpiece systems having different vibratory properties. The vibratory locus of the spindle-workpiece system is found. The phase lag between the cutting force and chatter displacement and the phase lag between the successive chatter marks are obtained quantitatively. These phase lags are closely related to the energy supply. The chatter vibration hardly grows up in the spindle-workpiece system of large dynamic rigidity.

1. Introcuction

Chatter vibration occurring in cutting operation impedes the improvement of the cutting accuracy, the high speed cutting and the unmanned operation of machine tools. In these points, it is very important to ascertain the cause of chatter vibration and to clarify the technique of chatter suppression.

Chatter vibration can be classified into two types, owing to the mechanism by which it occurs, that is, whether it is affected by the chatter marks made by the previous rotation of workpiece. The first type is called primary chatter vibration, which is caused by the falling cutting force characteristic[1], but mainly by the time lag of cutting force variation behind the cutting depth variation[2~3]. The second type of chatter vibration is the regenerative chatter vibration, in which

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exciting energy is supplied by the phase lag between successive chatter marks on the workpiece[4~8]. The latter type is more frequently caused than the former in the usual cutting operations. The analytical technique treating the chatter vibration is given by Merritt[8], and the effects of various system parameters are clarified. However, there has been insufficient discussion from the dynamic cutting point of view.

In this research project, the mechanism by which chatter vibration occurs in the spindle-workpiece system of a lathe is examined synthetically from the standpoint of dynamic cutting characteristics. First, in the present study, the primary and the regenerative chatter vibrations occurring in the various spindle-workpiece systems having different vibratory characteristics are observed in detail, and the effects of the vibratory characteristics of the system (i. e., equivalent mass, damping coefficient, spring constant, etc.) or cutting conditions on the chatter are experimentally examined to obtain fundamental knowledge for chatter elimination.

2. Experimental Apparatus and Experimental Procedure

Figure 1 gives an outline of the experimental apparatus used for chatter observation. The main spindle 2 is firmly attached to the lathe chuck. The workpiece 4 is attached on the other end of the spindle. Six spindle-workpiece systems of different vibratory characteristics are used in the experiment. The vibratory characteristics of the systems are varied by adding a weight 3 or changing the overhang length a. Tool 7 is the offset tool formed from the high speed steel, which is positioned on the tool post without top slide. The natural frequency of this cutting tool system is about 20000 Hz, while the rake and relief angles are both 10°.

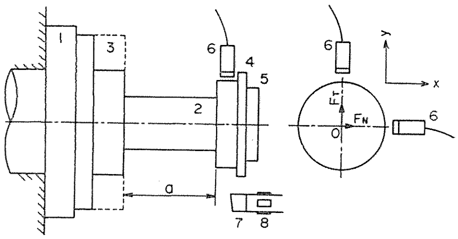

Fig. 1. Experimental apparatus.

The workpiece displacements in the horizontal and vertical directions are measured by displacement sensors 6 of eddy current type. The main and the thrust cutting force components F_T, F_N are detected by the semiconductor strain gauges 8 pasted on the tool shank. The revolution mark of the workpiece is also recorded on the chart by the tachometer mounted on the rear end of the spindle. Cutting speed is $V_0=16$ m/min in both primary and regenerative chatter experiments.

In the primary chatter experiment, a square thread of various widths is cut by feeding the cutting tool with a lead screw, and chatter vibration is observed. Next, in the regenerative chatter experiment, disc-type workpieces of various widths are continuously cut automatically by feeding the cutting tool in the lateral direction.

3. Experimental Results and Considerations

3. 1. Vibratory Characteristics of Spindle-Workpiece System

The vibratory characteristics of six spindle-workpiece systems are clarified here.

The natural frequency p and the damping coefficient n are obtained from the free damped vibration experiment. The values of these parameters p and n are identical in both the horizontal and vertical directions. The spring constant of the spindle-workpiece system is obtained from the static load test.

The equivalent mass m and the viscous damping coefficient c are calculated by the following equations applying the above values of p, n and k.

$$m=\frac{k}{p^2},\quad c=2nm$$

The obtained vibratory characteristics are listed in Table 1. The spindle-workpiece system A is called as system A in the following, to simplify the description.

Table 1. Vibratory characteristics of spindle-workpiece system.

	a mm	Weight	f Hz	p 1/S	n 1/S	m kg	k 10^7 N/m	c N·S/m
A	200	×	130	816	42.7	17.2	1.15	1470
B	200	○	118	738	36.1	20.0	1.09	1440
C	100	×	155	973	46.6	20.7	1.96	1930
D	100	○	136	857	53.5	25.1	1.84	2690
E	150	×	142	892	46.8	19.5	1.55	1820
F	150	○	128	804	44.9	23.4	1.51	2100

3. 2. Properties of Primary Chatter Vibration

Figures 2 and 3 show the vibratory locus of the workpiece and the relation between the cutting force and the vibration displacement, when a square thread workpiece of 4 mm width is cut with the cutting depth d_s=0.01 mm, and the primary chatter vibration occurs according to system A.

Figure 2 shows the vibratory locus of the workpiece viewed from the workpiece side. The workpiece vibrates along the slender elliptical loop in the vertical direction, which rotates clockwise. Figure 3 shows the relations between the thrust and main cutting force components F_N, F_T and the horizontal displacement of workpiece. These relations describe the clockwise loop as seen in the figure, because the phases of both cutting force components lag behind the phase of the horizontal vibration displacement x. As a result, the thrust cutting force acting in the recess period of the workpiece is larger than that acting in the approaching period, although the cutting depths in both periods are identical. Thus, exciting energy is supplied to the system owing to the horizontal vibration.

Next, Fig. 4 shows the phase lag of the thrust cutting force behind the cutting

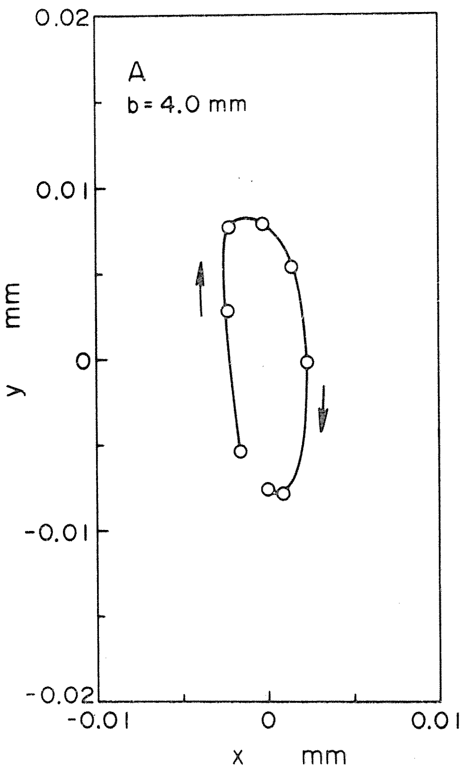

Fig. 2. Vibratory locus.

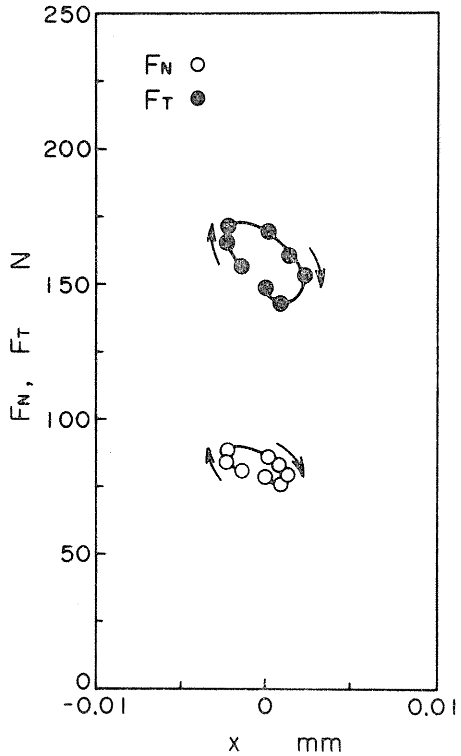

Fig. 3. Relations between thrust and main cutting forces and horizontal displacement.

depth variation. These phase lags are considered to be affected not only by the dynamic cutting depth variation but also slightly by the dynamic variations of cutting velocity and rake angle.

3. 3. *Stability Boundary of Primary Chatter Vibration*

Chatter vibration is observed when square thread workpieces of various width b are cut, keeping the cutting depth d_s constant ($d_s=0.01$ mm). The boundary width, that is, the stability boundary, where chatter vibration initiates is obtained for each system. The obtained boundary width is converted into the thrust or main cutting force components K_{IN} and K_{IT}, which correspond to the cutting force components in the case of unit cutting depth. To utilize these data efficiently for chatter elimination in lathes, it is important that the relation between the stability boundary of chatter initiation and

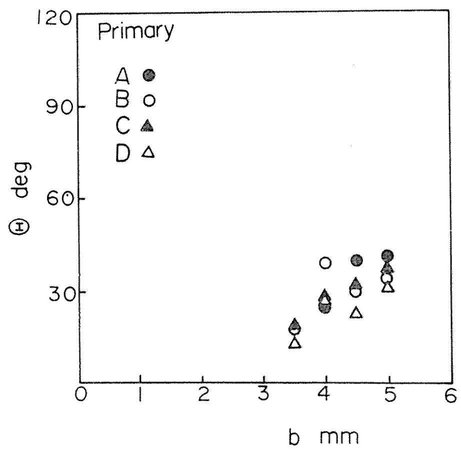

Fig. 4. Phase lag of cutting force.

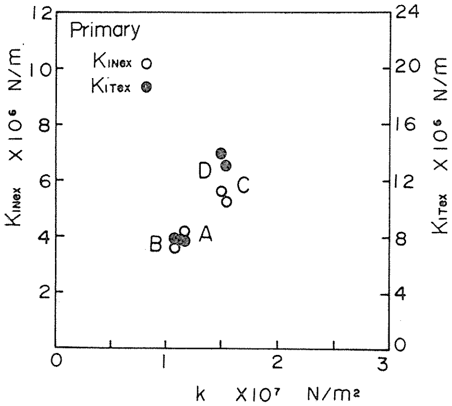

Fig. 5. Relation between stability boundary and spring constant.

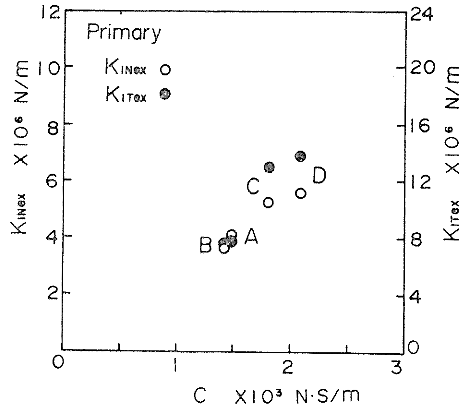

Fig. 6. Relation between stability boundary and damping coefficient.

the vibratory characteristics of the system is examined.

Figures 5 and 6 show the relations between the stability boundary K_{IN} or K_{IT} and the spring constant, the damping coefficient. It is clear from the figures that chatter vibration can hardly occur when the spring constant and the damping coefficient are large. However, no correlation between the stability boundary and the equivalent mass can be recognized in this experiment.

From the above experimental results, the effects of the spring constant and the damping coefficient on the stability boundary are remarkable. Chatter vibration can effectively be eliminated by improving the dynamic rigidity of the spindle-workpiece system.

3. 4. *Properties of Regenerative Chatter Vibration*

In this section, the experimental results for regenerative chatter vibration are given. Figure 7 shows the vibratory locus of the workpiece (system A) in which the square thread workpiece is repeatedly cut and the regenerative chatter vibration occurs. The cutting width is $b=3$ mm. In the figure, the loci on the same part of the workpiece for the fourth, fifth and sixth cuttings are described. The workpiece vibrates along the slender clockwise elliptical loop in the vertical direction in the regenerative chatter case, too. The regenerative effect on the chatter growth is very remarkable.

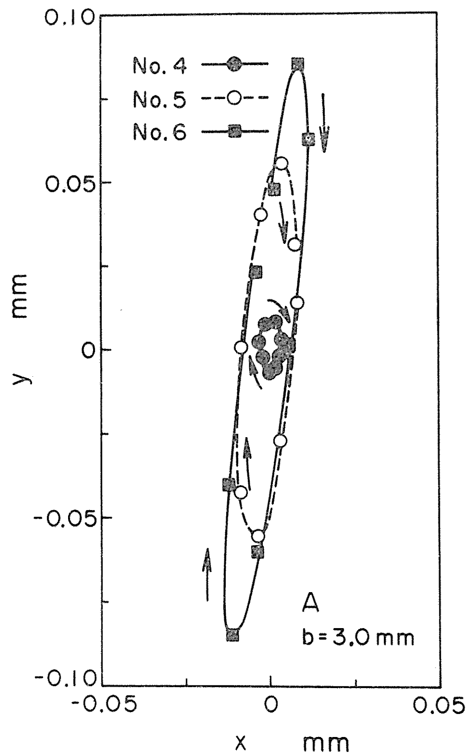

Fig. 7. Vibratory locus.

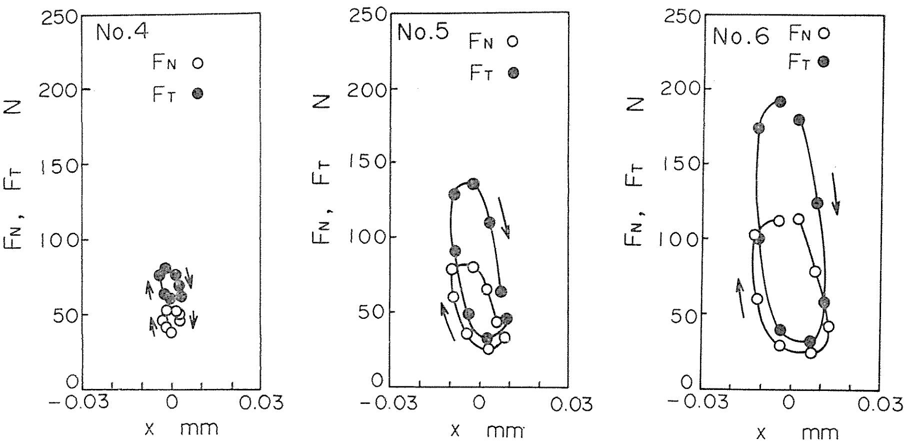

Fig. 8. Relation between thrust and main cutting forces and horizontal displacement.

Next, Fig. 8 gives the relation between the thrust or main cutting force components and the horizontal vibration displacement. The loci described by the cutting force components and the displacement are also clockwise, because the cutting force lags behind the horizontal vibration as in the primary chatter vibration. This cutting force lag in the regenerative chatter vibration is related to the lag behind the cutting depth variation and the phase lag of chatter marks in successive cuttings. The exciting energy corresponding to the area of closed loop is supplied to the vibratory system. The magnitude of the exciting energy supplied in the regenerative chatter vibration is greater than in the primary chatter vibration.

From the above considerations, it may be concluded that the primary chatter vibration of small amplitude initiates owing to the phase lag of the cutting force in the spindle-workpiece system, then the exciting energy can be supplied by the regenerative effect and the chatter vibration of large amplitude may maintain.

Hence, it can be understood that the chatter vibration which becomes a serious problem in the usual cutting operation is the regenerative chatter type.

The magnitude of the exciting energy by this regenerative effect is related to the phase lags of the cutting force and chatter marks. In the following discussion, this point is highlighted.

Figure 9 shows the phase lag of the thrust cutting force behind the cutting depth variation. This phase lag in regenerative chatter vibration is affected not only by the present vibration displacement of the workpiece (inner modulation) but also by the chatter marks made by the previous cutting (outer modulation). The phase lag distributes in the neighborhood of $\Theta=60°$. This value of Θ is fairly greater than the phase lag of cutting force in the primary chatter vibration. The phase lag of the main cutting force behind the vibration displacement has the same tendency, too.

In Fig. 10, the phase lag Θ^* of the present chatter mark behind the previous chatter mark is plotted for each system. It is seen in the figure that the phase lag of chatter marks is always about $\Theta^*=90°$, regardless of the vibratory characteristics or cutting width. In the regenerative chatter vibration, the cutting area

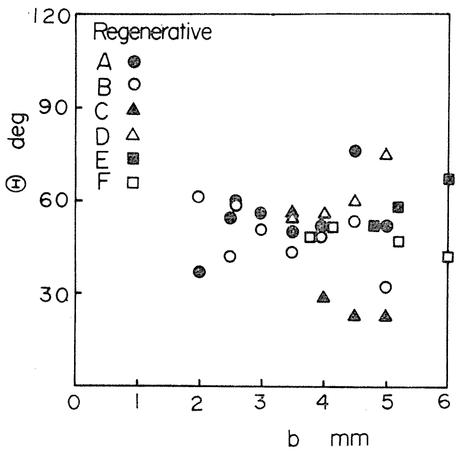

Fig. 9. Phase lag of thrust force.

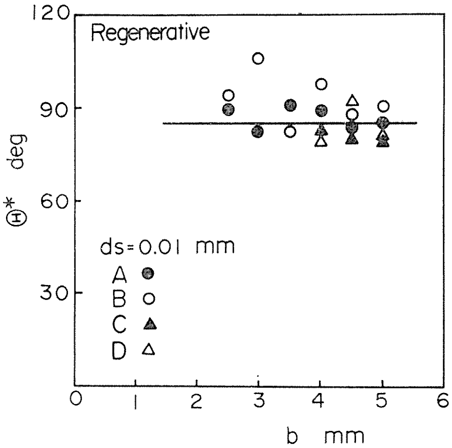

Fig. 10. Phase lag of chatter marks.

variation during vibration describes a hysteresis curve against the workpiece displacement, owing to the phase lag of chatter marks. Hence, the apparent phase lag of the cutting force increases as shown in Fig. 9. Corresponding to this fact, the exciting energy supply increases in regenerative chatter vibration.

The configuration of the vibratory locus is in harmony with the magnitudes of the phase lags Θ, θ, Θ^* of the cutting force and successive chatter marks in the practical cutting operation, and the regenerative chatter vibration initiates.

3. 5. Stability Boundary of Regenerative Chatter Vibration

Flange-type workpieces of various cutting width are successively cut under the cutting depth of $d_s=0.025$ mm and the boundary cutting width where the regenerative chatter vibration initiates is experimentally obtained. This boundary width is converted into the cutting force components K_{INex} or K_{ITex} (stability boundary) which are the thrust or main cutting force corresponding to unit cutting depth. The effect of the vibratory characteristics on the stability boundary is examined.

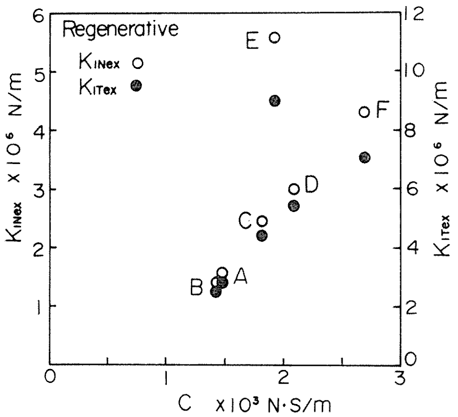

Fig. 11. Relation between stability boundary and damping coefficient.

Figures 11 shows the relations between the stability boundary of the regenerative chatter vibration and the damping coefficient. From the figure, it is clear that the stability boundary increases with the increase of damping coefficient. However, it is not affected by the equivalent mass within this experiment. These are the same as the primary chatter vibration. Hence, the regenerative chatter vibration can effectively be eliminated also by increasing the dynamic rigidity of the system as much as possible.

4. Concluding Remarks

In this study, the effects of the vibratory characteristics and cutting conditions on the initiation of the primary or regenerative chatter vibrations are experimentally discussed, to examine thoroughly the mechanism by which chatter vibration occurs in a lathe spindle-workpiece system.

As a result, it is ascertained that the cutting force lags slightly behind the cutting depth variation and also that the phase of the present chatter mark lags behind that of the previous cut in the regenerative chatter vibration. The apparent lag of cutting force in the regenerative chatter vibration is greater than that in the primary chatter vibration because of the chatter marks phase lag. The exciting energy which is determined by this phase lag and the vibratory locus of the workpiece is supplied to the system, and the stable chatter vibration is maintained. In the practical cutting operations, first, the primary chatter vibration may initiate owing to the phase lag of the cutting force. After that, chatter vibration may be amplified by the regenerative effect.

The stability boundary where chatter vibration initiates can be obtained. It is clarified that chatter vibration can effectively be eliminated in the system having large dynamic rigidity, for both primary and regenerative types.

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