ON THE CHATTER VIBRATIONS OF LATHE TOOLS

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(Received October 31, 1953)

General Introduction

"Chatter" is the vibration of cutting tool or workpiece set up frequently in machining metals when the rigidity of cutting tool or workpiece is not sufficient. It is detrimental to the tool life, to the surface finish and to the accuracy of the machined parts. It must also be avoided for the economical application of cemented carbide cutting tools, owing to the risk of fatigue fractures in this material. Some investigations have been done on the subject by Arnold,[1] Chisholm,[2] Hahn[3] and Eisele.[4] But the experimental and theoretical understanding of chatter is at present rather incomplete. Thus the cause of chatter and remedy for it is of much technological interest.

The vibrations that occur in machining metals are of two types: forced or self-excited. Those occur in lathe work are classified as follows: (1) Self-excited vibrations due to flexible cutting tools. (2) Self-excited vibrations due to the deflection of main spindle of lathe or workpiece supported between both centers. (3) Forced vibrations due to the headstock gears of inadequate accuracies. (4) Forced vibrations due to the out-of-balance of the machine or workpiece or dog. The purpose of present experiment is to ascertain the characters and the causes of the chatter vibrations of the types (1)-(3).

This article is compiled from several papers reported on the Transactions or Journals of the Japan Society of Mechanical Engineers by the author and his coworkers.

Part I. Chatter Vibrations Caused by the Flexible Cutting Tool

Experiment I. On the Characters of Chatter[5]

EXPERIMENTAL APPARATUS

The chatter referred to here is the vibrations of cutting edge of tool in machining metals. The author devised about twenty years ago a method[5] of measuring the cutting force or displacement of cutting edge according to the following principle. When the cutting force acts on the cutting edge of a tool, the tool is slightly deflected. The deflection angle of it is approximately proportional to the cutting force. So, if we can measure this small deflection angle of tool end in detail during cutting operation, the vibration and thus the cutting force will be ascertained. Now to ensure purely elastic deflection of the tool, a special tool post without upper slide was employed, and to secure rigid clamps of the tool, the upper and lower surfaces of the tool were ground.

The measuring apparatus is shown in Fig. 1. A small mirror was fitted to the lower nose of tool with glue as shown in the figure. The light from an arc lamp, passing through the slit 1 and the condensing lens 2 placed before the mirror, are reflected by it and focused on a rotating film. To measure the deflection of tool with accuracy, the displacement of light point on the film surface due to the deflection must be as large as possible. The distance between the mirror and the rotating film was set to 6.9 m in this experiment. The ratio of the displacement of the reflected light on the film and the deflection of tool end was about 160 in this case, where the size of tool was 16 mm square, length being 70 mm. To calibrate the recorded amount on the basis of dimension of true deflection or cutting force, the tool tip was statically loaded with gradually increasing weight. It was ascertained that there existed a linear relation between the load and the displacement of the reflected light.

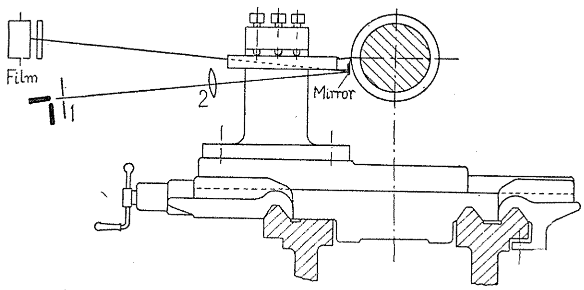


FIG. 1. Method of experiment.

Beside the vertical component of cutting force, there are generally two other components, a traversing and an axial component. The traversing component is proportional to the deflection angle of tool end in traversing direction and it can be measured with the deflection angle in that direction. The tool has a top rake angle on the tool end. Then in measuring the vertical component of cutting force with the vertical deflection angle, it is necessary to examine the effect of axial component of the force on the vertical deflection angle. According to some experiments, it was found that the vertical cutting force was measured less by about 2-3%, due to the effect of the axial component, with a roughing tool having the top rake angle of 20°. But this effect can be easily compensated by the proper assumption of horizontal cutting force. In the case of side lathe tool, it is not necessary to consider that effect.

The workpiece was the round bars of mild steel and cast iron initially of 9 cm diameter. Each bar was previously turned so as to leave a number of flanges, each of which was 1.5 mm in thickness and was separated by slots from others. The tool was always placed normally to the peripheries of the flanges and the tool was fed in its axial direction to the desired thickness of chip by the cross spindle of the lathe.

RESULTS OF EXPERIMENT

The cutting tests were carried out on a mild steel in feed 0.029 mm with a tool having the cutting angle of 70°. Figs. 2–5 show the vertical vibrations of the cutting edge at the cutting speeds, 14, 30, 45, 67 m/min. At low cutting speed the cutting force is nearly constant and the tool does not vibrate as shown in Fig. 2, chips in flow type being produced. The underlying horizontal line in the figure shows the stationary position of the cutting edge when no force is acting on it. When the cutting speed increases, the vibration of cutting edge occurs as shown in Figs. 3–5. It is seen that the frequencies of the vibrations are very regular and their amplitudes are fairly stable. The amplitude of vibration is nearly in proportion to the cutting speed and the frequency of vibration does not depend on the cutting speed.

During the chatter, the chip was scattered periodically in small pieces producing a high pitched sound. The chatter patterns corresponding to the frequency of vibration were produced on the workpiece.

As shown in Fig. 6, the natural vibration of the tool was also measured by the aid of a spring devise which was able to remove suddenly a weight previously loaded on the tool end. Its frequency is about 2,120/sec. The frequency of chatter is almost the same as that of natural frequency of the tool. It was ascertained by other experiments that this frequency was not affected by the thickness of chip or the cutting angle of tool. When the length of tool becomes longer, the frequency of chatter decreases corresponding to the natural frequency of the tool. Therefore, it is considered that the chatter is a kind of self-excited vibration.

Now, to ascertain the character of the chatter, tests were carried out under various cutting conditions, *i.e.*, feed 0.029–0.23 mm, cutting angle 80°–60° and various lengths of tools. Chatter is liable to occur in the case of cutting in small feed. As the feed increases the tendency for chatter to occur decreases, the chip in flow type being produced. In this case, a large built-up edge is formed on the cutting edge, causing an irregular fluctuation of cutting force. An increase in the cutting angle augments the tendency for chatter to occur. When the length of tool is large, the tendency is conspicuously heightened. It was ascertained that the occurrence of chatter is effectively prevented by the decrease in the length of tool, in the cutting speed, in the cutting angle and clearance angle of tool or by a brush resting lightly on the tool.

An increase in cutting angle of tool heightens the tendency to set up the other type of chatter. Fig. 7 shows the result of experiment with a tool having the cutting angle of 80°. As shown in the figure, besides the vibration above mentioned, another regular vibration with low frequency of about 123/sec occurred. According to the frequency and the mode of vibration, this vibration is considered as that due to the deflection of work, which will be dealt with in the next part.

Therefore, there are frequently cases in which the cause of the chatter cannot be easily distinguished in practice.

Instead of steel, cast iron was used as the workpiece. Tests were done under the same conditions as in the case of steel, and the chatter occurred with the same frequency as in the case of steel. The tendency for chatter to occur was also nearly equal to the case of steel. The amplitude of it increased nearly in proportion to the cutting speed. But the amplitude fluctuated rapidly in each cycle of vibration as shown in Fig. 8. This fluctuation of amplitude is considered to be caused by the irregular formation of chip due to the lack of uniformity of this material.

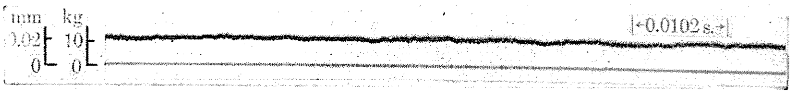


FIG. 2. Cutting speed 14 m/min.

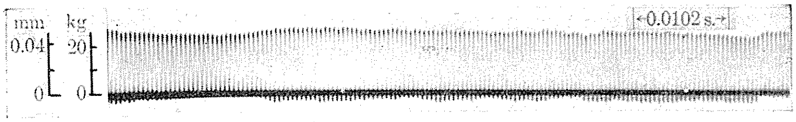


FIG. 3. Cutting speed 30 m/min.

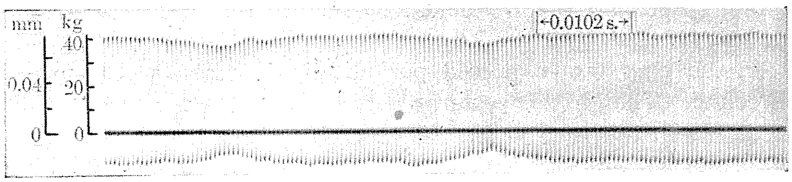


FIG. 4. Cutting speed 45 m/min.

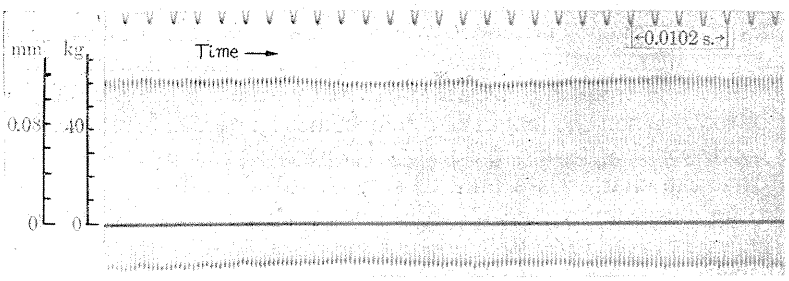


FIG. 5. Cutting speed 67 m/min.

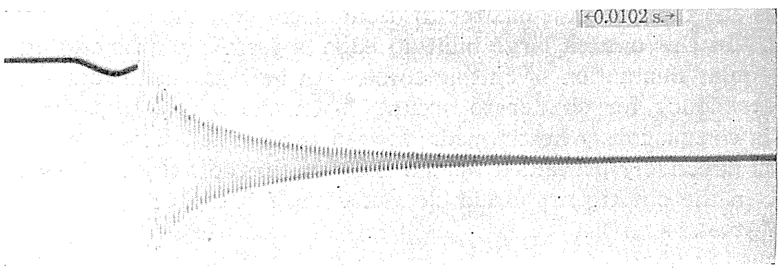


FIG. 6. Natural vibration of tool.

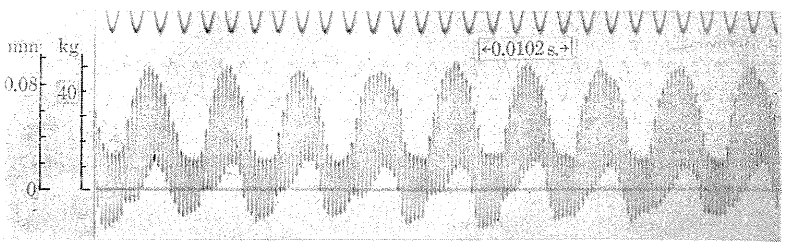


FIG. 7. Cutting speed 67 m/min, cutting angle 80°.

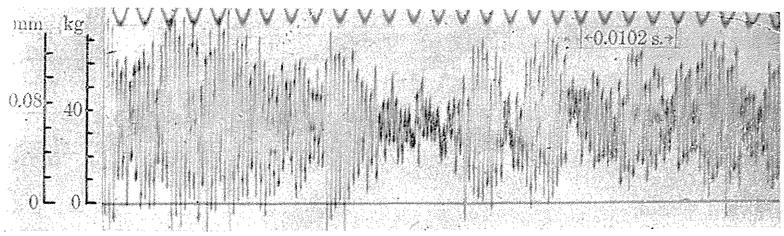


FIG. 8. Work: Cast iron.

Experiment II. On the Causes of Chatter Vibration[6]

INTRODUCTION

According to the recent investigations on the chatter vibration due to flexible tools, it has been believed[1][2] that the chatter is a self-excited vibration caused by the variation in cutting force with cutting speed, as in the frictional vibration caused by frictional force.

Now, in the first place of the present investigation, experiments were done on the self-excited frictional vibration of a flexible rubbing tool fitted into the tool post. Next, experiments were carried out on the chatter vibration in actual machining operation and the characters and the causes of it were investigated in comparison with the frictional vibration.

METHOD OF EXPERIMENT

A rubbing tool from high speed steel was fitted into the tool post of the lathe. The rubbing tool was a rod 12.5 mm square and 250 mm long. A flange was machined previously from a mild steel bar which was held by the chuck of the lathe. The side surface of the rubbing tool was placed in contact with the periphery of the flange, as shown in Fig. 9, so as the tool rubs the flange according as the flange rotates. The outside diameter of the flange was 120 mm, the thickness of it being 1 mm. The desired contact pressure was obtained by adjusting the position of the tool post against the flange by the cross spindle of the lathe and its magnitude was measured by the horizontal deflection of the tool end. The vertical vibration of the tool end was measured by means of the vertical deflection angle of it as mentioned in the above experiment.

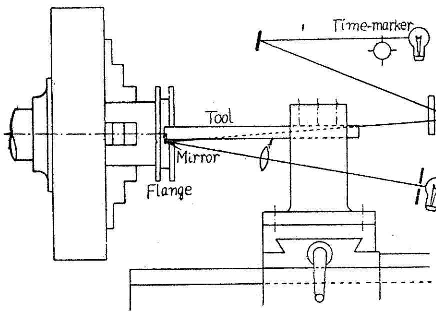


FIG. 9. Method of experiment.

RESULTS OF EXPERIMENT

(*A*) *Frictional Vibration*

Tests were first done on the contact pressure 19.2 kg. In various rubbing speeds, regular vibrations of the tool occurred in the vertical direction. Figs. 10–13 show these vibrations set up at the rubbing speeds 10, 24, 42, 57 m/min. The underlying horizontal lines in the figures show the stationary positions of the tool end. The amplitude of vibration is somewhat unstable at the rubbing speed 10 m/min. It increases and becomes stable as the rubbing speed increases. But the vibration becomes unstable and the amplitude decreases suddenly at the rubbing speed 57 m/min. The frequencies of these vibrations are about 149/sec, which is nearly equal to that of natural vibration shown in Fig. 14. The same tests were done on the contact pressures 5.4 and 12.4 kg. Fig. 15 shows the results of these experiments together. The curves *A*, *B*, *C* in the figure show the amplitudes in the cases of the contact pressures 5.4, 12.4, 19.2 kg respectively. The amplitude of

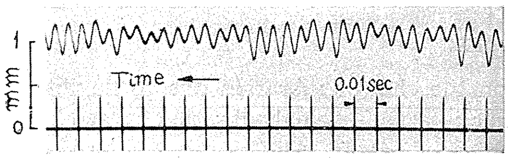


FIG. 10. Rubbing speed 10 m/min.

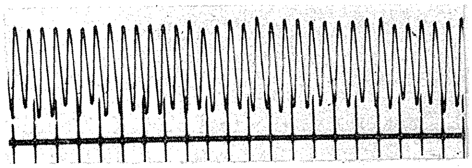


FIG. 11. Rubbing speed 24 m/min.

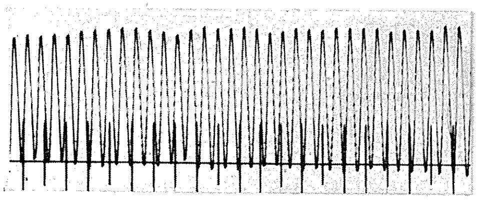


FIG. 12. Rubbing speed 42 m/min.

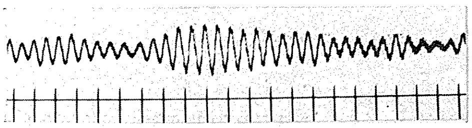


FIG. 13. Rubbing speed 57 m/min.

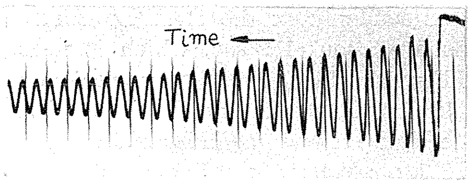


FIG. 14. Natural vibration of rubbing tool, size 12.5 mm square, length 250 mm.

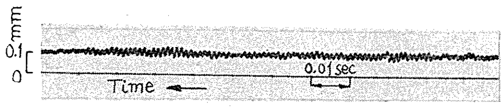


FIG. 18. Cutting speed 10 m/min.

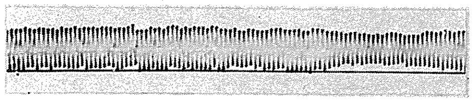


FIG. 19. Cutting speed 20 m/min.

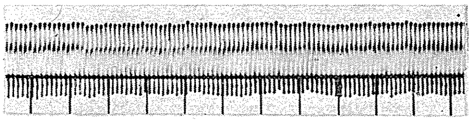


FIG. 20. Cutting speed 34 m/min.

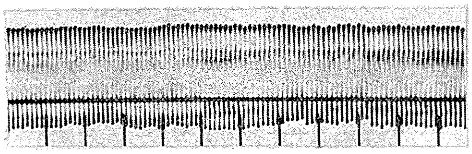


FIG. 21. Cutting speed 48 m/min.

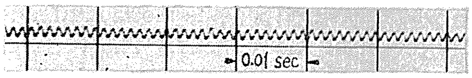


FIG. 23. Horizontal vibration of tool.

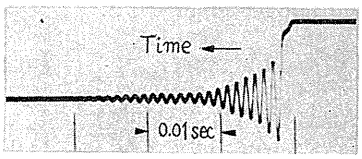


FIG. 25. Natural vibration of cutting tool, size 18 mm square, length 120 mm.

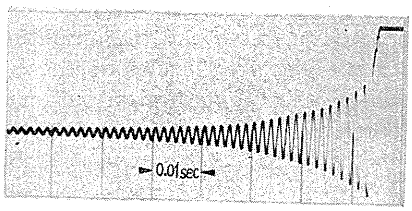


FIG. 26. Natural vibration of cutting tool, size 12.5 mm square, length 120 mm.

vibration increases proportionally to the rubbing speed and it suddenly decreases at a certain speed. This character of vibration coincides well with the experimental results of chatter vibration obtained by Chisholm.[2]

To ascertain the effects of rubbing speed on frictional force, the frictional forces in the cases of the contact pressures 5.4, 12.4, 19.2 kg respectively were measured by means of the vertical deflection angles of the rubbing tool end. Now, to avoid the occurrence of vibration, the length of the tool was shortened to 6 cm. Fig. 16 shows the results of these experiments. As shown in the figure, the frictional

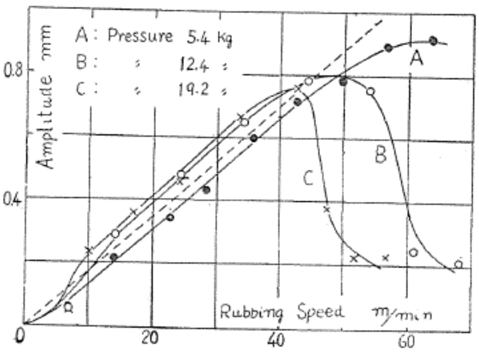


FIG. 15. Effect of rubbing speed on frictional vibration.

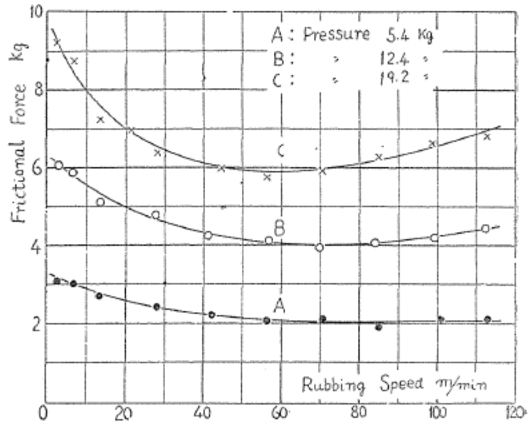


FIG. 16. Effect of rubbing speed on frictional force.

force at first decreases as the rubbing speed increases, and beyond the certain speed it increases again. The larger the contact pressure is, the more remarkable is this tendency. If the tool vibrates at its own frequency, the relative velocity between the tool end and the flange will fluctuate. If it is assumed that the vibration of tool end is harmonic and its amplitude is given, the frictional force corresponding to the relative velocity at any phase of one cycle of vibration can be obtained from Fig. 16. The net energy available per cycle for maintaining vibration can be obtained diagrammatically. The energies thus estimated for the rubbing speeds 20, 40, 60, 80 m/min and the contact pressures 5.4, 12.4, 19.2 kg are illustrated in Fig. 17. As shown in the figure, the energy increases rapidly as the amplitude increases in each frictional speed. However, a limit to the amplitude exists for each rubbing speed where the maximum vibratory velocity of the tool end becomes slightly greater than the surface velocity of the workpiece. If the amplitude exceeds the limit, there occur powerful positive damping effects on the vibrations, which prevent any appreciable increase in their amplitudes, beyond the value

$$x_0 = V/2\pi f$$

where x_0 = amplitude of vibration, V = rubbing speed and f = frequency of vibration.

As shown in Fig. 17, the powerful dampings start at the amplitudes 0.36, 0.75, 1.08, 1.44 mm corresponding to the frictional speeds 20, 40, 60, 80 m/min respectively. These amplitudes are plotted with the broken line in Fig. 15. It is seen in this figure that the amplitude of vibration increases nearly in proportion with the rubbing speed along this line.

On the other hand, the energy consumed per cycle for damping the vibration of the rubbing tool can be estimated from the natural vibration of the tool shown in Fig. 14. The broken line in Fig. 17 shows this energy. The intersections of the line with ordinates drawn from the limiting amplitudes, shown in the figure with X, Y, Z indicate the energies of vibrations when the available energy balances with the amount of energy lost due to damping and the tool vibrates with stable amplitude. In addition, the available energy per cycle depends on the contact pressure and the rubbing speed as shown in the figure. So it is seen that the amplitude of vibration must have a tendency to decrease beyond the speeds about 74, 63, 58 m/min for the contact pressures 5.4, 12.4, 19,2 kg respectively. Therefore, the sudden decrease of the amplitude at a certain high speed shown in Fig. 15 is well explained.

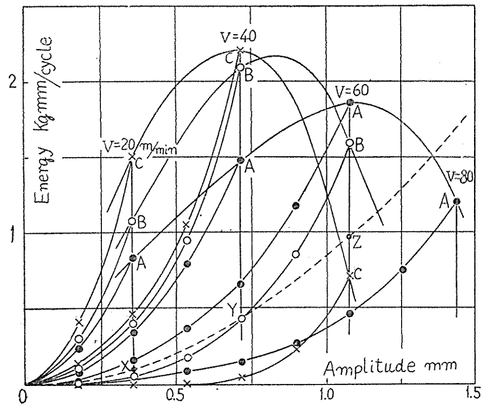
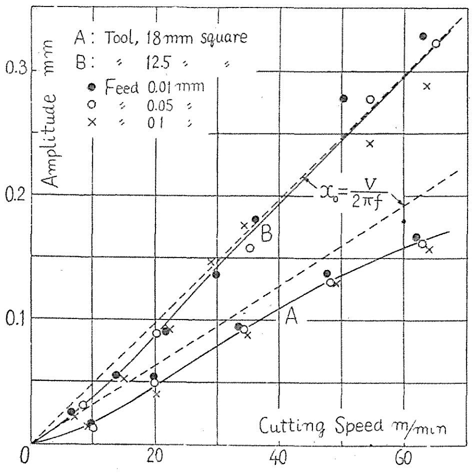


FIG. 17. Available energy for maintaining vibration.

(*B*) *Chatter Vibration*

Now, experiments were carried out on the chatter vibration which occurred in machining. The same flanged bar of mild steel as in the above experiment was machined with a tool 18 mm or 12.5 mm square and 120 mm long. Figs. 18–21 show the vertical vibrations of cutting edge where the cutting conditions are as follows; tool 18 mm square, cutting angle 70°, feed 0.01 mm and cutting speeds 10, 20, 34, 48 m/min. The manner of vertical vibration of the cutting tool is almost the same as the frictional vibration shown in Figs. 10-13. The same tests were carried out in the feeds 0.05 and 0.1 mm. The curves A and B in Fig. 22 show the results of these tests in each case of tools 18 mm and 12.5 mm square. The amplitude of chatter is not nearly affected by the amount of feed. The broken lines show the amplitude expressed by the equation $X_0 = V/2\pi f$. As shown in the figure the amplitude of chatter increases nearly along these broken lines in proportion to the cutting speed. This character coincides well with that of the frictional vibration above mentioned. The amplitude of chatter has no decreasing tendency in this range of cutting speed yet.

Fig. 23 shows the horizontal vibration of cutting edge obtained by means of the horizontal deflection angle of tool end. This frequency of vibration is exactly the same with that of vertical vibration. Therefore, the tool end vibrates in somewhat elliptic orbit. The frequency of chatter is shown in Fig. 24. The natural frequencies obtained from the natural vibrations shown in Figs. 25, 26 are 806/sec and 556/sec corresponding to the sizes of tools 18 mm and 12.5 mm square. As seen in Fig. 24, the frequencies of chatter are nearly equal to these natural frequencies of tools and not nearly affected by cutting speed or feed, but depend merely



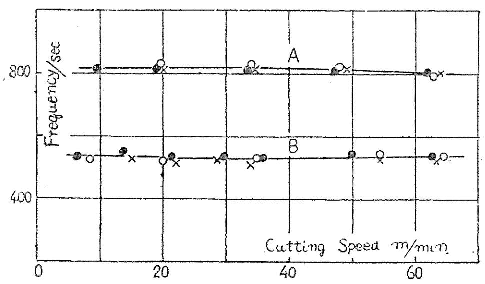


FIG. 22 (*left*). Effect of cutting speed on chatter vibration.

FIG. 24 (*right*). Effect of cutting speed on frequency of chatter.

upon the size of tool. Therefore, the chatter vibration is considered as a kind of self-excited vibration.

Now, to ascertain the cause of chatter, the cutting force was measured under the same conditions as those of above experiment, except that the length of tool was shortened so as not to set up the vibration. The results of this experiment are shown in Fig. 27. As shown in the figure the vertical cutting forces in the feeds 0.01–0.1 mm are nearly independent of the cutting speed.

Hitherto, many experiments were carried out on the cutting force. Formerly, Schlesinger[7] and others reported that the cutting force does not depend upon the cutting speed. But it has recently been reported[8] that when high speed cutting is done in large feed with tungsten carbide tool, the cutting force decreases a little as the cutting speed increases. In the present experiment also, it was ascertained that, when the feed is large, the cutting force decreases slightly as the cutting speed increases. But as for the small feeds, *i.e.*, 0.01–0.1 mm, the cutting force seems to be scarcely affected by the cutting speed. According to Arnold's experiment[1] the cutting force in case of large feed, decreases remarkably corresponding to the increase of cutting speed, whereas it, in the case of small feed, is nearly constant. On the contrary, the chatter in practice is more liable to occur in the range of small feed than of the large feed. In the case of large feed, this chatter does not occur usually. This character of chatter does not justify the prevailing opinion that the chatter is caused by the variation in cutting force with the cutting speed.

In addition, the chatter in machining is more liable to occur than the frictional vibration in the present experiment. For instance, though the frictional vibration is examined with a rubbing tool 12.5 mm spuare and 250 mm long, it does not occur in the case where the tool length is shortened to 120 mm. Whereas, the chatter occurs not only with a tool 120 mm long but with a tool 18 mm square and 120 mm long as shown in Figs. 18-23, and it occurs also even with tools shorter than 120 mm. Therefore, if the chatter is caused by the variation in cutting force with cutting speed, the variation in cutting force must be more remarkable than that in the frictional force shown in Fig. 15. Then, to what degree must the cutting speed have influence on the cutting force? The amount of energy lost from the vibration system per cycle due to damping can be estimated from the natural vibration shown in Figs. 25, 26. For simplicity, provided a linear relation between the cutting force and cutting speed exists, the cutting force must decrease linearly about 6.5 kg in the interval of cutting speeds from 10 m/min to 60 m/min with a tool 18 mm square, and with a tool 12.5 mm square it must decrease 1.5 kg in the same interval. The relations, for example, are shown with the broken lines M and N, referring to the cutting force in the feed 0.05 mm in Fig. 27. These large decreases of cutting force with increase in cutting speed cannot actually exist, especially in the cutting force in the small feed as 0.01 mm. Therefore, it seems that the chatter vibration is set up by another cause which will be investigated in the next part.

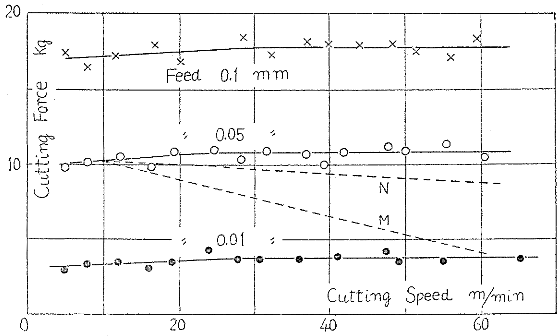


FIG. 27. Effect of cutting speed on cutting force.

CONCLUSION

The chatter vibration due to the flexible tool is a kind of self-excited vibration, and in its mode resembles the self-excited vibration caused by the frictional force, but its cause cannot be explained by the effects of cutting speed on the cutting force as is the case in the frictional vibration.

In the frictional vibration, the end of rubbing tool vibrates only in the direction of frictional force, but in the chatter vibration of cutting tool, the cutting edge vibrates also in horizontal direction, as shown in Fig. 23, with the same period of the vertical vibration, and chatter patterns are produced on the work surface corresponding to the frequency of it. The undulations of chatter patterns have the lag in phase relative to that of the previous passage (on this subject more precise investigation will be described in the next part). These characters of the cutting tool are the same as those of the chatter due to the deflection of work or main spindle of the lathe of which the cause will be investigated in the next part. Therefore, it is considered that the cause of the chatter due to a flexible tool is the same as that due to the deflection of work or main spindle of the lathe.

Part II. Chatter Vibrations due to the Deflection of Work and Main Spindle of Lathe [9]

Experiment III. On the Characters of Chatter Vibration

INTRODUCTION

Once this chatter is present, the rotating work and the tool vibrate laterally in large amplitude producing a sharp sound. Among the chatter vibrations set up in lathe work, this chatter is most liable to occur and to have a large amplitude.

Therefore, this chatter is most troublesome for the lathe turner. The purpose of this experiment are to ascertain the characters of this chatter. The cause of it will be investigated in the next experiment.

EXPERIMENTAL APPARATUS

The vibration of cutting edge and the fluctuation of cutting force are measured by the same method as that in the previous experiment. To measure the lateral vibration of work which is rotating, the author devised an optical method sixteen years ago, and since that time this method has been frequently[10) 11)] used.

The principle of this method is shown in Fig. 28. A ring of mild steel was fitted on the workpiece near the part at which the work was cut and on that ring the mirror A was pasted with glue and its surface was sooted. Rotating the work by hand, the soot was scribed with a sharp razor blade so as to draw precisely a circular arc in fine line. Then, if a small segment of the circle stationed in the uppermost position is lighted by the vertical illuminator and magnified by microscope, a horizontal bright line in the black matrix can be observed. The center of circle drawn on the mirror coincides exactly with the axis of rotation of the work, so the horizontal line segment is stationary not affected any way by the rotation of the work. It moves in the vertical direction only due to the vertical vibration of work independent of horizontal vibration. When this horizontal line segment is illuminated, the reflected light forms an image point on the rotating film through the microscope and the cylindrical lens. The magnifitude of microscope used in this experiment was about 25–100 times.

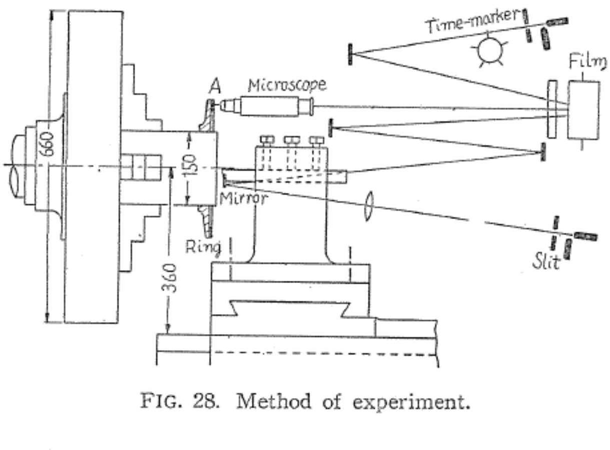


FIG. 28. Method of experiment.

The microscope was mounted on the heavy angle plate situated on the concrete foundation separated from that of the lathe, so as to keep stationary not affected anyway by the vibration of the lathe. For measuring the horizontal vibration of work, the line segment of the scribed circle stationed in the position most laterally situated was magnified by the microscope and the horizontal displacement of that line segment was recorded on the rotating film.

The lathe which was used in this experiment was of a heavy type having the swing 720 mm, the diameter of main spindle 127 mm and 26″ chuck. A mild steel bar of diameter 150 mm, length 220 mm was held by the chuck of the lathe. The size of tool was 25 mm square and 90 mm long.

Results of Experiment

At first, the work was cut in facing with a roughing tool. The operation was done from center to outside of the work, the cutting speed being increased automatically. Fig. 29 shows the effects of cutting speed on the occurrence of chatter. The feed was 0.3 mm and the depth of cut was 3 mm. It is seen that cutting is started at the point A in the figure, the work being deflected upward. The vibration of the work is suddenly set up at the cutting speed about 45 m/min. Such a sudden occurrence of vibration is the characteristic of this chatter. Once the chatter occurs, it maintains almost constant amplitude. In this figure, cutting was stopped at the point B. Fig. 30 shows the vertical vibration of work which appeared in the outside turning operation.

As shown in the figure, the period of vibration is very regular and its frequency is about 39 cycles per revolution of the work.

Next, the vertical cutting force and the vibration of work in chatter were measured simultaneously as shown in Fig. 31. In this figure, (*a*) shows the vertical vibration of work and (*b*) shows the vertical cutting force. The line X-X is the zero line of force and line Y-Y shows the stationary position of work. The cutting force fluctuates largely and it retains zero over a part of each cycle of vibration. The phase of cutting force precedes about 90° relative to that of vibration.

It was ascertained that the frequency of this vibration was scarcely affected by the cutting speed, the feed, and the cutting angle of the tool.

Fig. 32 shows the horizontal cutting force and the horizontal vibration of work in the feed 0.3 mm. The upward displacement in the figure corresponds to the displacement of work toward the cutting edge. The horizontal cutting force increases at the beginning of this movement and it decreases when the work moves far from the cutting edge. The frequency of horizontal vibration is the same with that of vertical vibration. Therefore, in this chatter, the work vibrates laterally making a somewhat elliptical orbit.

In use of roughing tool, the longitudinal component of cutting force exists. Hence, it is expected that the work vibrates in that direction. To measure this vibration of work, a part of the work was turned precisely and a fine line was drawn along the circumference with a sharp knife edge. A part of this circle was magnified by a microscope without being affected by the rotation of work. Thus the longitudinal vibration of work was recorded together with the horizontal cutting force as shown in Fig. 33. In the figure, (*a*) shows the longitudinal vibration of work and (*b*) shows the horizotal cutting force. It was ascertained that the work vibrates in longitudinal direction with the same frequency as that of vertical vibration. So, the rigidity of work in longitudinal direction seems to have also some effect on the occurrence of chatter.

During the chatter, cracks were usually set up in chip corresponding to the frequency of the vibration. Fig. 34 shows the cracks in chip pared on the top rake surface of the tool.

Fig. 35 shows the vertical natural vibration of the work including the chuck and main spindle of the lathe. It was ascertained that the frequency of chatter is

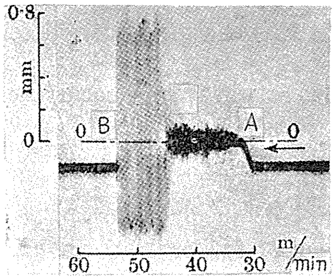


FIG. 29. Effect of cutting. speed on vibration.

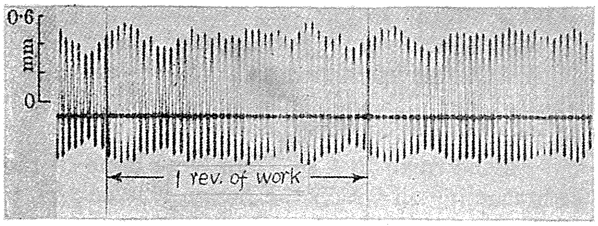


FIG. 30. Vibration of work.

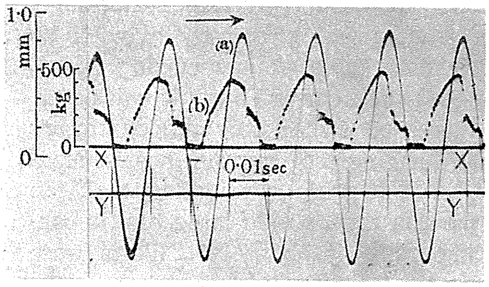


FIG. 31. Vertical vibration (*a*) and vertical cutting force (*b*).

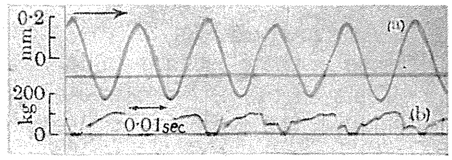


FIG. 32. Horizontal vibration (*a*) and horizontal cutting force (*b*).

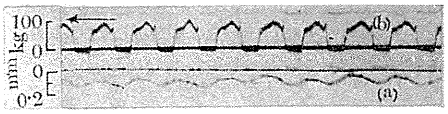


FIG. 33. Longitudinal vibration (*a*) and horizontal cutting force (*b*).

FIG. 34. Crack in chip pared on cutting edge.

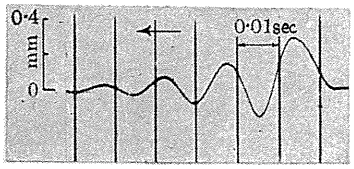


FIG. 35. Natural vibration of work.

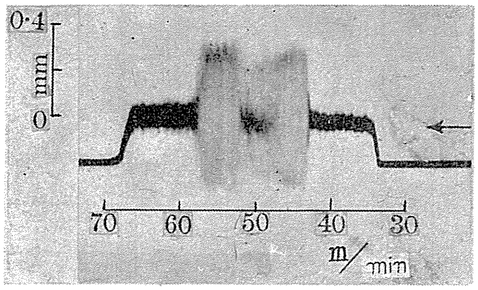


FIG. 39. Effect of cutting speed on vibration.

almost the same with this natural frequency of work. If the size of work, chuck or main spindle of the lathe is changed, the frequency of chatter changes correspondingly to the natural frequency of it. Therefore, this chatter is considered to be a kind of self-excited vibration.

Experiments were made under the cutting conditions relating to the occurrence of this chatter as follows:

(*a*) *On the Shape of Tool*

As shown in Fig. 36, tests were done in the various cutting angles 80°, 70°, 60° in machining in which the flange was cut by the side tool fed crossly. In each case, the chatter occurred suddenly at the thickness of flanges 2.5, 3.1, 4.2 mm respectively. The larger the cutting angle was, the greater was the tendency for chatter to occur.

The clearance angle of tool is in a close connection with the occurrence of chatter. Tests were done on the clearance angle of tool having the cutting angle 70°. As shown in Fig. 37, the occurrence of chatter was effectively avoided by decrease in the clearance angle. This is more remarkable at low cutting speed.

Tests on the setting angle of a roughing tool were carried out. It was ascertained that the decrease in a setting angle increased remarkably the chattering tendency. In practice, it is well known that the finishing tool has the most tendency to vibrate. Considering a finishing tool as if it were a roughing tool, the setting angle of it will be almost zero. On the contrary, a side lathe tool is considered as a roughing tool in which the setting angle is about 90°. Tests were done on this latter tool. As shown in Fig. 38, the chatter did not occur to the large depth of cut. Although the horizontal vibration of work is excited when this tool is used, the fluctuation of the area of cut is smaller than in the case of other tools.

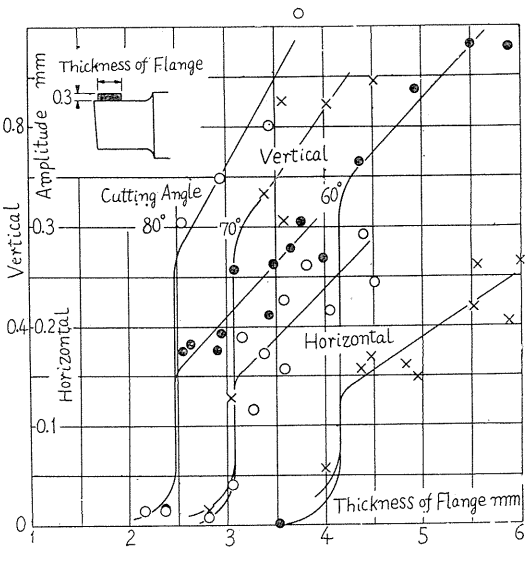


FIG. 36. Effect of cutting angle on vibration.

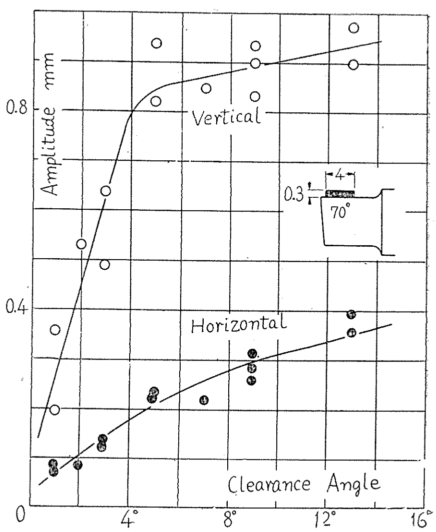


FIG. 37. Effect of clearance angle on vibration.

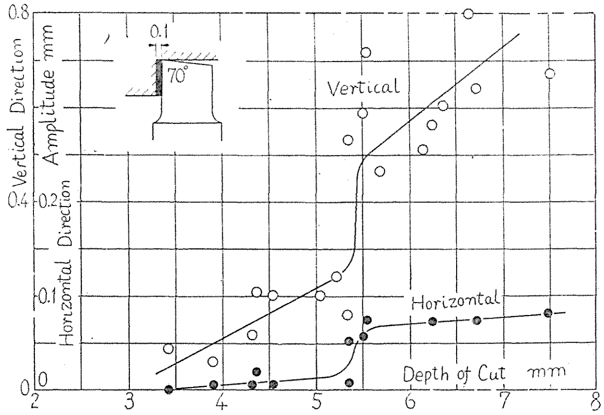


FIG. 38. Test of side tool.

(*b*) *Cutting Conditions*

There exists a certain cutting speed at which the chatter is most liable to occur, because at low cutting speed the rate of fluctuation in cutting force is too slow to excite the vibration of work and on the other hand at the extreme high cutting speed at which the built-up edge is lost, the fluctuation of cutting force decreases. Fig. 39 shows the experiment of facing operation from inside to outside in which the feed is 0.2 mm, and the depth of cut is 2 mm. In this figure, the chatter is set up suddenly at the cutting speed 43 m/min, and it comes to stop at the speed 58 m/min. Therefore, the occurrence of chatter can be avoided somewhat by the increasing or lowering the cutting speed. But, once the chatter is set up, there is a remarkable tendency to maintain the vibration according to the undulations of chatter patterns produced on the work surface by the previous passage (this subject will be investigated more fully in the next experiment).

Next, tests were done in various feeds. *i.e.,* 0.1, 0.2, 0.4, 0.5 mm in machining when the flange was cut by the side tool fed crossly. As shown in Fig. 40, the amplitude of chatter increases suddenly at the thickness of flange 2.5, 2.6, 3.1, 3.0 mm respectively. Then in this range of feed the occurrence of chatter is not so

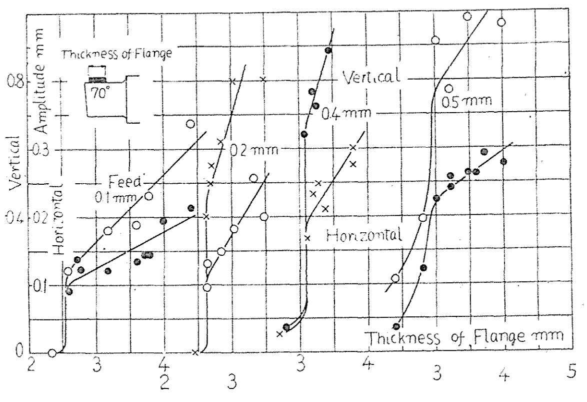


FIG. 40. Effect of feed on vibration.

much affected by the feed. As seen in the cases of the feeds 0.4, 0.5 mm, the vibration of a small amplitude is induced in the neighbourhood of the thickness of flange at which the sudden increase of amplitude occurs. In the facing operation with a roughing tool, tests were done on the feed in the depth of cut 2.5 mm. Fig. 41 shows the results of this test. The amplitude of chatter increases proportionally to the feeds in range 0.1–0.3 mm, and it maintains almost constant value in the feeds 0.4–1.2 mm and finally the chatter comes suddenly to stop. As the feed increases, the part over one cycle of vibration in which the cutting force retains zero decreases and the cutting force does not fluctuate to zero in a feed more than 0.6 mm and the amplitude becomes unstable. Therefore, it is considered that the chatter is liable to occur in range of small feed.

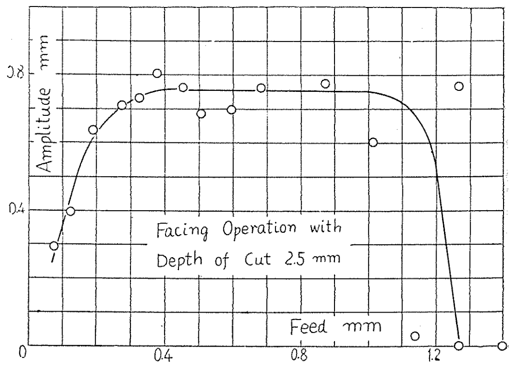


FIG. 41. Effect of feed on vibration.

The method of preventing chatter in which the rotation of work is reversed and the tool is fitted downward into the tool post, is familiar to those who experienced in machining metals. In this cutting method, the vertical cutting force acts downward on the work. This increases the rigidity of work in both vertical and horizontal directions. The chatter did not occur until the thickness of flange 7 mm under the cutting conditions corresponding to the case of the cutting angle 70° in Fig. 36. This preventing method is most effective in the case, in which the rigidity of main bearing is less stiff, especially when the housing of a main bearing is separated in two pieces. But this method is scarcely effective in the case in which the work is supported by both centers, because in this case the rigidity of work is scarcely increased by the downward cutting force.

Instead of steel, a cast iron and a brass were experimented on. The specific cutting force in these materials is smaller than that in steel. Then the chatter occurs at the larger depth of cut compared to that of mild steel. In cutting cast iron, the cutting force has the tendency to fluctuate rapidly due to the lack of uniformity of material, and then there is a tendency to set up the chatter due to the deflection of tool which has the high natural frequency of vibration.

(*c*) *On the Construction of Lathe*

The condition of the main bearing of a headstock has a close relation with the occurrence of chatter. Long ago, Taylor[12] recommended the proper adjustment of a main bearing for preventing chatter. In the present experiment, it was seen that the occurrence of chatter was effectively avoided by an increase of the length of the main bearing and a close fitting of the bearing metal to the journal. When a large clearance exists in the bearing, the frequency of chatter becomes irregular in a small amplitude of vibration. It was ascertained that the chatter was effectively prevented by increasing the size of a main spindle and holding the work securely by the chuck. When a small chuck is used, the chatter occurs in comparatively small depth of cut. But, once the chatter occurs in using a large chuck, the amplitude of vibration is large.

Usually in machining a long shaft, a steady rest or a follow rest has been used for preventing chatter or deflection of the work. According to the tests on the steady rest, the chatter can be well prevented. But, when the cutting force acts on the work supported by the usual steady rest, a little displacement of top jaw cannot be avoided due to the elastic yielding of the clamping device of the jaw and some clearance is made between the lower jaws and the work, and the horizontal vibration of work cannot be prevented sufficiently. Then the effect of the steady rest will be largely reduced. It was ascertained that the chatter can be prevented effectively by the follow rest having a horizontal jaw for preventing the horizontal vibration of work. It was observed that in such a case the natural frequency of work differed in vertical and horizontal directions and the work vibrated also in the vertical direction with the natural frequency of horizontal vibration.

Conclusion

It was observed from the above experiments that the cccurrence of chatter can be avoided chiefly on the following conditions:

(1) The rigidity of work, especially in the horizontal direction, must be secured as well as possible in the machining of metals or in the construction of a headstock.

(2) The shape of the cutting tool or the relative position of the cutting edge to the work must be attended to so carefully that the cutting edge and the work should not be apart from each other even though the horizontal vibration of work is excited.

Therefore, it is considered that the chatter is set up by the horizontal vibration of work.

Experiment IV. On the Causes of the Chatter Vibrations [13]

Purpose of Experiment

It is considered from the previous experiments that the cause of this chatter is in close connection with the horizontal vibration of the work. If the horizontal vibration is initially started in the workpiece at its own natural frequency, the area of cut and thus the vertical cutting force will fluctuate with that frequency setting up the vertical vibration of work. Therefore, in order to ascertain the cause of this chatter, the relation between the horizontal cutting force and the horizontal vibration in chatter must be investigated.

Method of Experiment

A lathe having a swing of 400 mm is employed in this experiment. Fig. 42 shows the method of experiment. The horizontal cutting force and the vibration of work during chatter were recorded simultaneously on a rotating film by the same principle as that in Experiment III. The workpiece was a round bar of mild steel, 73 mm in diameter and 300 mm in length, which was held by a 16″ chuck. In order to simplify the cutting manner, a flange cut out from the bar was provided and it was cut with a side lathe tool shown in Fig. 42. The tool was fed by the cross spindle to the desired thickness of chip. The tool was made from a 16 mm square rod of high speed steel, having a top rake angle of 5°, a clearance angle of 7°. It was mounted on the tool post so as to overhang the length 70 mm.

As shown in the figure, the workpiece was cut at the point A and the horizontal vibration at the point B was recorded on the film. On the point A of workpiece was statically loaded with 28 kg and 108 kg weights, and the horizontal deflections of each part of workpiece were determined as shown by the curves 1, 2 in the figure respectively.

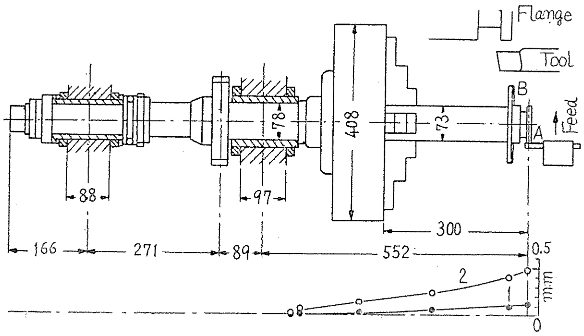


FIG. 42. Method of experiment.

RESULTS OF EXPERIMENT

At first, the cutting tests were done with various cutting speeds, *i.e.*, 2.2, 4.4, 8.4, 12.0, 18.0 m/min and the horizontal cutting force and horizontal vibration of work were recorded as shown in Figs. 43-47. The feed was 0.025 mm and the thickness of the flange was 6 mm. In these figures, the upper curve shows the horizontal cutting force and the lower one the horizontal vibration of work. The chatter does not occur at the cutting speed 2.2 m/min. At the cutting speed 4.4 m/min the chatter was set up and the work vibrated nearly harmonically. At the cutting speeds 12.0, 18.0 m/min the vibration were deviated a little from a harmonic type of motion.

Figs. 48-52 show the experimental results in various feeds, *i.e.* 0.052, 0.092, 0.151, 0.197, 0.296 mm; the cutting speed is 18 m/min, and thickness of flange is 3 mm. According to these figures, as the feed increases, the fluctuation of cutting force decreases, and the period of vibration becomes irregular and finally the chatter almost stops. Therefore, chatter is liable to occur in the range of small feed. The frequency of these chatter vibrations is about 70/sec which is nearly equal to that of the natural vibration of the workpiece shown in Fig. 53.

As to the horizontal displacement of work, the upward movement in the records shown in Figs. 43-52 corresponds to approaching of the work to the cutting edge of tool. As shown in the figures, the horizontal cutting force remains constant over a part of one cycle of vibration while the work moves away from the cutting edge. The work in this period is considered to be completely apart from the cutting edge and the horizontal cutting force is zero.

In vibration the work deflects horizontally against the cutting edge and the cutting edge should also deflect in the same direction. According to the load-

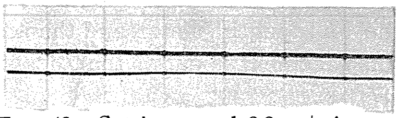


FIG. 43. Cutting speed 2.2 m/min.

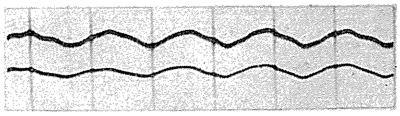


FIG. 44. Cutting speed 4.4 m/min.

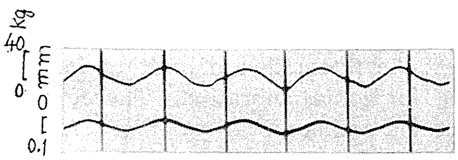


FIG. 45. Cutting speed 8.4 m/min.

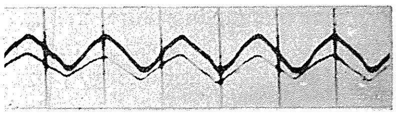


FIG. 46. Cutting speed 12.0 m/min.

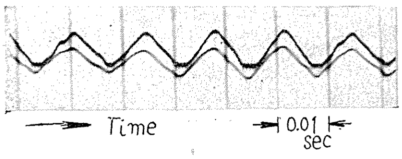


FIG. 47. Cutting speed 18.0 m/min.

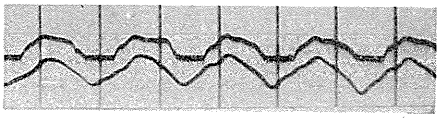


FIG. 48. Feed 0.052 mm.

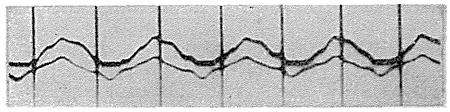


FIG. 49. Feed 0.092 mm.

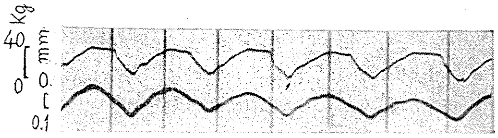


FIG. 50. Feed 0.151 mm.

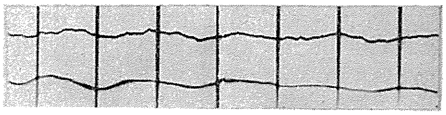


FIG. 51. Feed 0.197 mm.

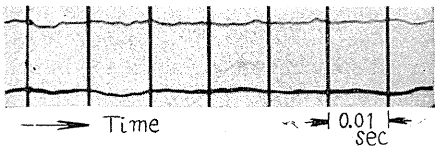


FIG. 52. Feed 0.296 mm.

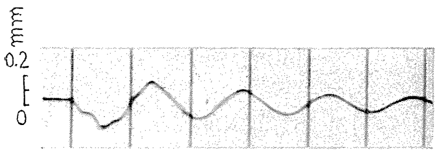


FIG. 53. Natural vibration.

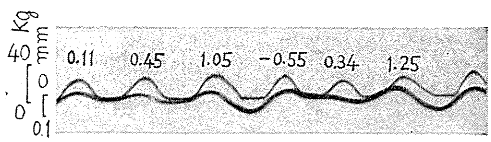


FIG. 54. Cutting speed 8.4 m/min.

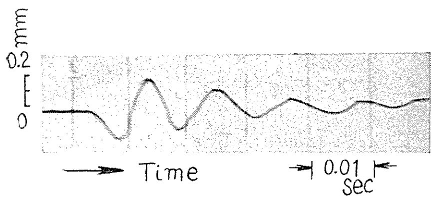


FIG. 56. Natural vibration.

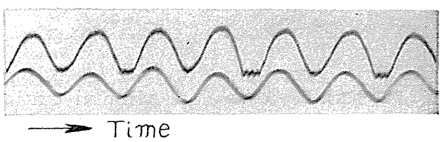


FIG. 55. Cutting speed 12 m/min.

In Figs. 43-52 and 54, 55, the upper curve shows the horizontal cutting force and the lower the horizontal vibration of work.

deflection curves of work and tool, the cutting edge should deflect about two-thirds of the displacement of work in the case of the tool length 70 mm, and the amount corresponding to remaining one-third of the displacement is cut as the thickness of chip.

Tests were done on the effect of the length of tool. In the case of a long tool, the tool vibrates in such a way that it follows the motion of work. An increase in the length of tool decreases the tendency for the workpiece to vibrate.

Figs. 54, 55 show the results of experiment in which an 8″ chuck is employed. In the case of cutting speed 8.4 m/min the period of vibration is irregular and the amplitude is unstable as shown in Fig. 54. In the case of the cutting speed 12 m/min, the period of vibration is regular and the amplitude is stable as shown in Fig. 55. The vibration is of the same mannar with the case of 16″ chuck. The frequency of vibration is about 85/sec which is nearly equal to that of the natural vibration shown in Fig. 56.

In Figs. 44–52 and Figs. 54, 55 it is seen that the fluctuation of cutting force has a little time lag in comparison with that of horizontal vibration. Therefore, it is thought that some energy is available for maintaining vibration. Figs. 57, 59 are obtained from the experimental results shown in Figs. 47, 55 respectively. In the displacement AB in these figures, the work moves toward the cutting edge against the horizontal cutting force dissipating the energy of vibration. In the displacement BC in which the work moves away from the cutting edge, the cutting force acts in the same direction with the displacement of work so that the vibratory system gains the energy for maintaining vibration. The net energy per cycle is

$$E=\int_A^B Fdx+\int_B^C Fdx \qquad \text{where} \quad \int_A^B Fdx<0,$$

Figs. 58, 60 are obtained by plotting F kg (cutting force) in ordinate and x mm (displacement measured from a base line) in abscissa at each phase of the vibration in Figs. 57, 59. The full line in the figure shows a previous cycle of vibration and the broken line shows the next cycle. The closed areas of these lines give the amount of energy E concerning to the amplitude. These energies estimated from Fig. 58 diagrammatically are 1.82, 1.72 kg mm and those from Fig.

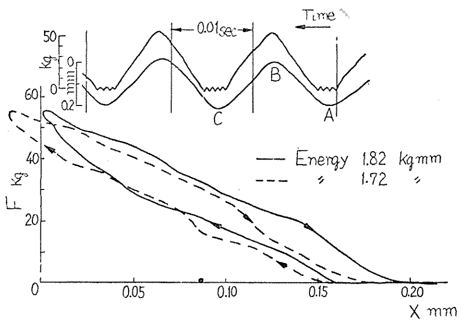


FIG. 57 (*above*). Horizontal cutting force and vibration of work.
FIG. 58 (*below*). Force-displacement curve.

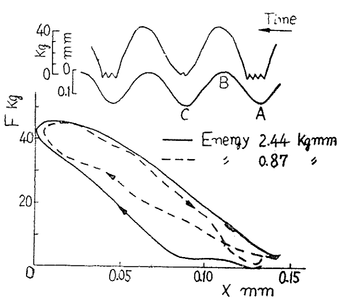


FIG. 59 (*above*). Horizontal cutting force and vibration of work.
FIG. 60 (*below*). Force-displacement curve.

60 are 2.44, 0.87 kg mm. According to the results of applying the same process to the other experimental records, the net energies are always positive, because the fluctuation of cutting force lags a little behind that of vibration, and the time in which the cutting force increases from zero to maximum opposing to the movement of work is shorter than that in which the cutting force decreases from maximum to zero.

Next, the energy which is dissipated in one cycle of vibration can be estimated from the natural vibrations shown in Figs. 53, 56. In this estimation is used an equivalent mass in regard to chuck and work which is supposed to be concentrated at the cutting position.

Fig. 61 shows the balance of these energies. Though the points plotted in this figure may be said to be quite scattered, both energies are on the whole equal to each other. It is found that in such vibrations in which the cutting force remains zero over a part of one cycle, both energies fairly coincide with each other, but in such cases of the large feed beyond which the chatter comes to stop, the available energy is generally larger than that lost for damping.

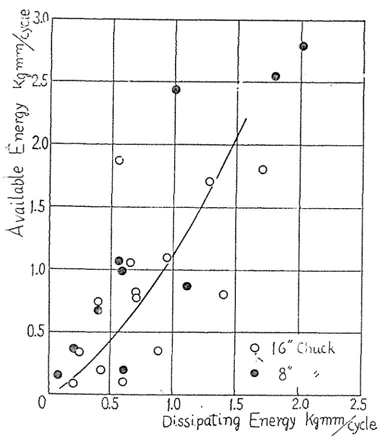


FIG. 61. Balance of available and dissipating energies.

Variations in the amplitude correspond to the amount of available energies, which is estimated in each cycles in Fig. 54 from the left side, as follows: 0.11, 0.45, 1.05, −0.55, 0.34, 1.25 kg mm. It is evidently seen that the amplitude of work varies directly with the amount of these available energies.

CONCLUSION

In this chatter vibration, the horizontal cutting force does not reach a maximum value when the work moves horizontally nearest to the cutting edge. When the work rotates a little after that instant and chip is produced in maximum thickness, the horizontal cutting force becomes maximum and subsequently it sustains comparatively high values in the period of movement of work away from the cutting edge. According to this lag in phase, some amount of energy per cycle is available for maintaining vibration. It is ascertained that these net energies estimated from the experimental results coincide nearly with the energies lost for damping in vibration. Therefore, this chatter is a kind of self-excited vibration caused by the lag in fluctuation of horizontal cutting force behind that of horizontal vibration of work.

Experiment V. On the Causes of Chatter Vibration[14]

METHOD OF EXPERIMENT

In the present experiment to ascertain further the causes of chatter, the vibrations of work and the cutting force were measured simultaneously. The lathe and the cutting conditions in this experiment were the same as those in Experiment IV. The scheme of experimental apparatus is illustrated in Fig. 62. The light which passes through the lens 1, the small circular hole 2 and the time-marker 3 is projected toward the lathe as shown in the figure. A part of that light passing through the lens 4 is reflected by the mirror 5 pasted on the lower end of tool and the reflected light is recorded on the rotating film. The lens 4 is adjusted so as to bring the focus of a small hole on the rotating film. Thus the cutting force is measured by means of the deflection angle of tool end.

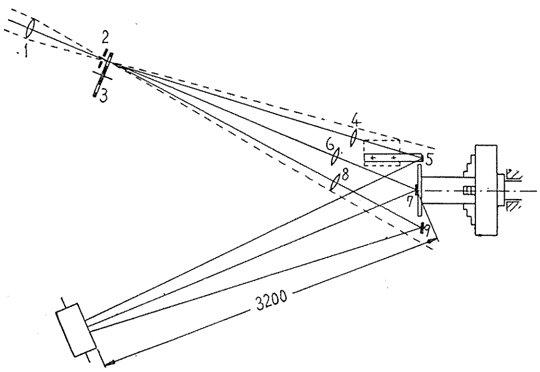


FIG. 62. Method of experiment.

Next, to record the lateral vibrations of work, another part of the above light passing through the lens 6 is reflected by the mirror 7 and recorded on the same film. The mirror 7 is so pasted on the center of work end, the surface of the mirror being precisely perpendicular to the rotating axis of work that it deflects only due to the lateral vibration of work, without being affected anyway by the rotation of work. To enlarge the displacement of the reflected light, the distance between the mirror and the film is enlarged. Further another part of the above light passing through the lens 8 is reflected by the mirror 9 which is stationary and recorded on the same film, as the measuring basis of the reflected lights above mentioned.

In order to find the relation between the cutting force and the vibration of work in each phase, the light is interrupted by the time-marker 3 at intervals of 0.001 sec, and to record further the same instant of these three lights, the thick mark is made at intervals of 0.02 sec. Then the cutting force and the vibration of work in each phase are ascertained at each period of 0.001 sec.

When the statical loads were applied on the cutting edge of tool and on the part operated of workpiece, the relation between the deflection angles of the mirrors 5, 7 and the deflections of cutting edge and work were measured preliminarily. According to these tests, it was found that there existed nearly linear relations between the load-the deflection and the deflection angle.

RESULTS OF EXPERIMENT

Fig. 63 is the records obtained in the cutting operation with the cutting speed 37 m/min, the feed 0.05 mm, the cutting angle 85° and the thickness of flange 6 mm. The records (*a*), (*b*), (*c*) in the figure represent the vibration of work, the fluctuation of cutting force and the stationary position respectively. The large points at every twenty points in each record are at the same instant. These points are connected by lines to make clear the correspondency among themselves. The position of each point in the records (*a*), (*b*) was compared with that of the corresponding point at the same instant in record (*c*) by a sensitive comparator

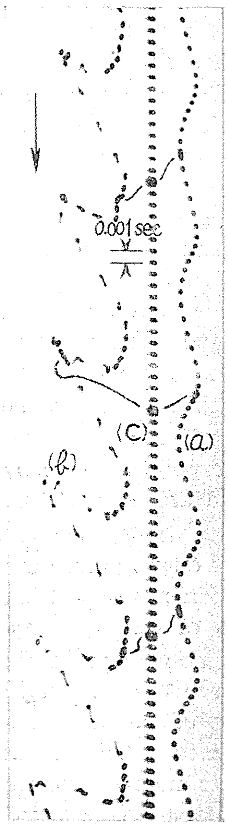


FIG. 63

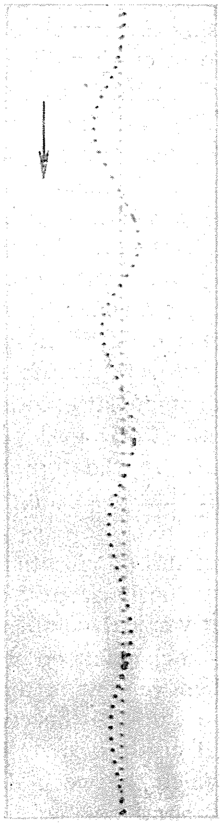


FIG. 65

FIG. 67

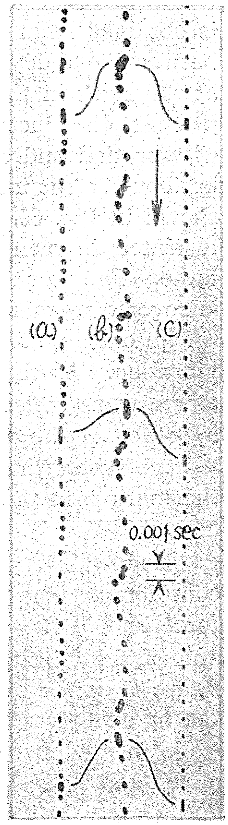


FIG. 70

Records (*a*), (*b*), (*c*) represent the vibration of work, fluctuation of cutting force and stationary position respectively. Fig. 65 shows the record of natural vibration of work.

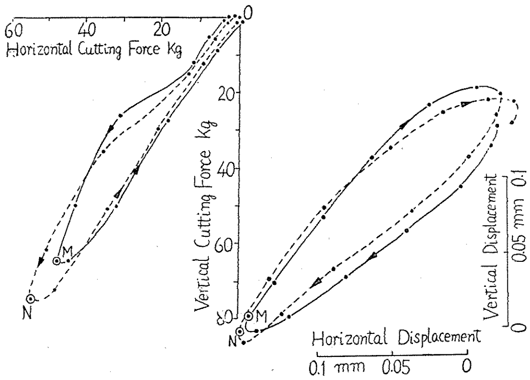


FIG. 64. Cutting force and vibration of work.

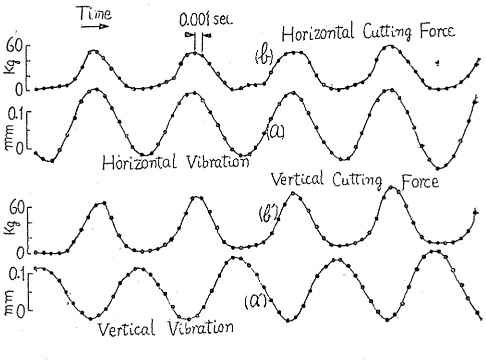


FIG. 66. Horizontal and vertical components of cutting force and vibration of work.

and thus the velocity of measuring film could be put out of consideration. Fig. 64 is obtained from Fig. 63 by this process using the curves expressing the relations between load-deflection and deflection angle of cutting edge and work. The curve at the right in the figure represents the vibration of work and the left one represents the fluctuation of cutting force. The full line shows the previous cycle of vibration and the broken line the next cycle. The frequency of this vibration is about 77/sec and this is nearly equal to that obtained from the natural vibration shown in Fig. 65. The vibration of work and cutting force in the figure are illustrated in such a way as observed at the situation of recording film toward the lathe. The work vibrates in somewhat elliptical orbit and its rotational direction is reverse to that of the work. This vibrating manner of work varied according to the cutting conditions, and it had no close connection with the occurrence of vibration. As shown in the figure the tool deflects almost in the same direction as the work deflects, and it also deflects in somewhat elliptical orbit. Then, in the approach of the work to the cutting edge, the horizontal cutting force fluctuates a little faster than the vertical cutting force. In the figure, the points shown by the mark ◉ in the curve of vibration and in that of cutting force are at the same instant.

Now, the horizontal and vertical components of vibration and cutting force are considered. Fig. 66 (b), (a), (b'), (a') show the horizontal components of cutting force and of the vibration of work, and the vertical components of cutting force and of the vibration of work respectively. Each point on the same vertical in the figure is at the same instant. The upward movement in the curve (a) shown in the figure corresponds to approaching of the work to the cutting edge. In each cycle in the curves (b), (a), the horizontal cutting force becomes maximum at about 0.0005 sec later than the instant at which the work deflects nearest to the cutting edge. Then, the fluctuation of horizontal cutting force lags about 0.0005 sec behind the horizontal vibration of work. Further, the time in which the horizontal cutting force increases from zero to maximum in each cycle is usually shorter than that in which the force decreases from maximum to zero. Therefore, some energy is available for maintaining the horizontal vibration. It is seen in the curves (a), (b') that the fluctuation of vertical cutting force depends on the horizontal vibration of work and it lags about 0.001 sec behind the horizontal vibration of work. Therefore, it is considered that the chatter is caused by the horizontal vibration of work. In the curves (b'), (a') the phase of vertical vibration lags about 140° behind the fluctuation of vertical force. It was ascertained that the amout of this lag in phase differed widely according to the cutting conditions.

Next, tests were done in the feeds 0.026–0.2 mm. In the case of large feed, the horizontal cutting force in approaching of the work to the cutting edge increased comparatively faster than the vertical cutting force in each cycle, and the time in which the cutting force sustained a high value was long and then the cutting force suddenly decreased. It is considered that this sudden decrease in cutting force is caused by the occurrence of crack in chip.

Tests were done on the cutting speeds 20–78 m/min in feed 0.05 mm. At the high cutting speed, the horizontal cutting force increased comparatively faster than the vertical cutting force as in the case of large feed. But in this case the cutting force fluctuated speedily at the time at which the cutting force was large.

Next, instead of a 16″ chuck, an 8″ chuck was used. The diameter of workpiece was 73 mm and the length was 290 mm. The rigidity of workpiece was about 70% of that in the above experiment. Fig. 67 shows the record obtained in the cutting operation: cutting speed 34 m/min, feed 0.05 mm, thickness of flange 3 mm. The amplitude of vibration in the figure is increasing rapidly with the time. From this record the vibration of work and the fluctuation of cutting force are obtained as shown in Fig. 68. The work vibrates linearly with a large amplitude in oblique direction. The horizontal cutting force in the period of approaching of work to cutting edge increases faster than the vertical cutting force.

Fig. 69 (*b*), (*b′*), (*a*), (*a′*) shows the horizontal and vertical components of cutting force and vibration of work. At the cycle (1) in the figure, the fluctuation of horizontal cutting force does not lag behind the horizontal vibration, and in this cycle there is no increase in amplitude of vibration. In the cycles (2)-(4), the horizontal cutting force sustains comparatively high values in the period of movement of the work away from the cutting edge and then the amplitude of vibration increases rapidly. In the figure, the increase of horizontal amplitude is a little faster than that of vertical amplitude, because the vibration is caused by the horizontal vibration of work.

In the cycle (2), the vertical vibration of work lags about 110° behind the fluctuation of vertical cutting force, and these lags in the cycles (5), (6) are about 160°. Then the amount of this lag is in close connection with the amplitude of vibration.

Fig. 70 shows the record of vibration of small amplitude which occurs slightly in the cutting operation in which the length of work is 90 mm, cutting speed 20 m/min, and feed 0.05 mm. In this operation the turner of the lathe was scarcely

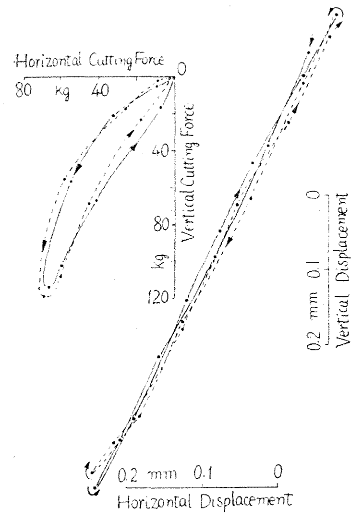


FIG. 68. Cutting force and vibration of work.

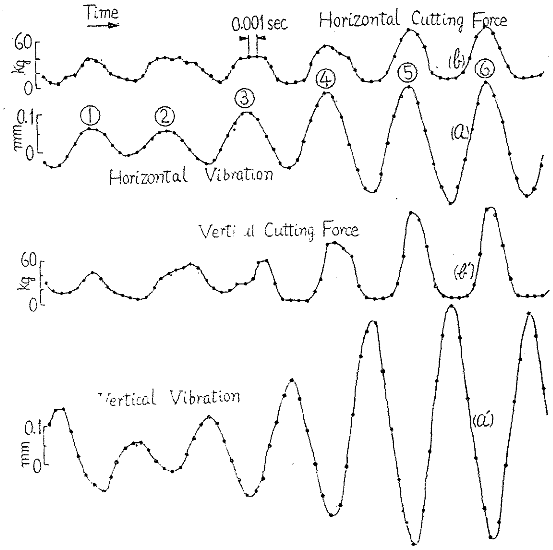


FIG. 69. Horizontal and vertical components of cutting force and vibration of work.

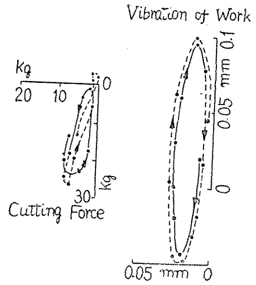


FIG. 71. Cutting force and vibration of work.

aware of the occurrence of vibrations. Fig. 71 shows the vibration of work and the fluctuation of cutting force obtained from Fig. 70.

In the figure, the work vibrates in an elliptical orbit and the horizontal amplitude is comparatively small as compared with the vertical amplitude. Fig. 72 shows the horizontal and vertical components of cutting force and of vibration. In the figure, the fluctuation of horizontal cutting force has not nearly any time lag compared with the horizontal vibration, and the horizontal amplitude is so small that the work does not move apart from the cutting edge over one cycle of vibration. The vertical vibration lags about 100° behind the fluctuation of vertical cutting force. This vibration has usually an unstable amplitude and it has some tendency to come to stop or to increase its amplitude. This vibration is considered to be the same kind of vibration as occurred with a small amplitude in the neighborhood of the thickness of flange beyond which the amplitude of vibration suddenly increased in a case of the cutting angle 80° in Fig. 36, or in cases of the feeds 0.4, 0.5 mm in Fig. 40.

From the results of the above experiment, the amount of energy which was available for maintaining vibration was estimated by the method described in Experiment IV. Fig. 73 shows the example of this process obtained from the experimental results shown in Fig. 66. The closed areas of curves correspond to the amounts of available energies.

A certain available energy was ascertained, without exception, in seventeen experiments. Fig. 74 and 75 show the amounts of these energies in comparison with the energies lost for damping in the horizontal and vertical directions respectively. In the figures, the available energies are a little larger than that estimated for dissipation. But on the whole, both energies coincide nearly with each other. The plotted points in these figures are well disposed compared with those of Fig. 61 in Experiment IV, because the measuring accuracy in this experiment is better than that in Experiment IV.

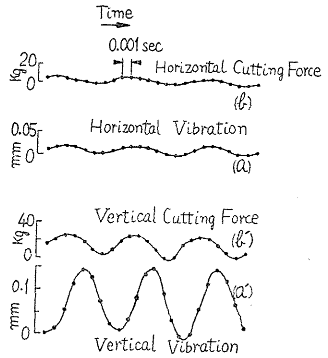


FIG. 72. Horizontal and vertical components of cutting force and vibration of work.

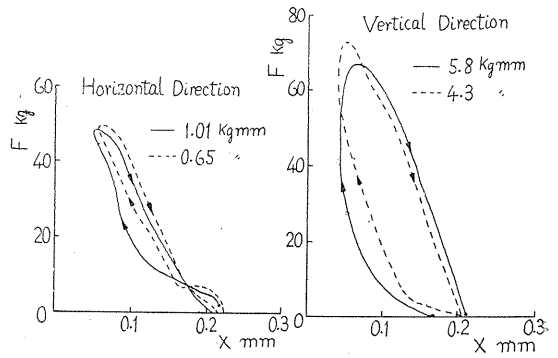


FIG. 73. Force-displacement curve.

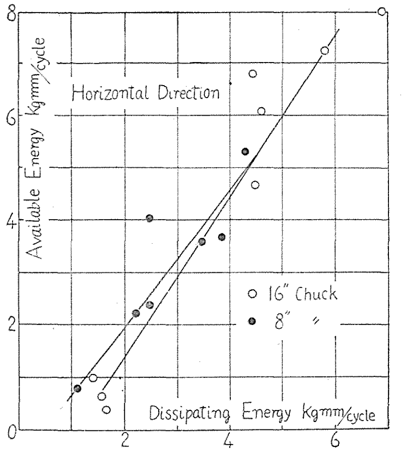


FIG. 74. Balance of available and dissipating energies.

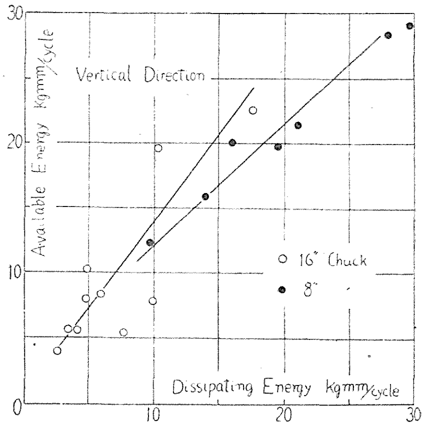


FIG. 75. Balance of available and dissipating energies.

CONCLUSION

It was ascertained that during chatter vibrations the fluctuations of horizontal and vertical cutting force depended on the horizontal vibration of work. The fluctuation of horizontal cutting force lags about 0.0005–0.001 sec and the vertical cutting force lags about 0.001–0.0015 sec behind the horizontal vibration of work. The vertical vibration of work lags about 100°-170° behind the fluctuation of vertical cutting force and this amount of lag depended on the cutting conditions and it had no close connection with the occurrence of chatter.

It is the same conclusion as obtained in Experiment IV that the chatter vibration is a kind of self-excited vibration caused by the lag in fluctuation of horizontal cutting force behind the horizontal vibration of work. Due to this lag some amount of energy per cycle is available for maintaining or increasing the vibration. The amount of this energy estimated from the experimental results coincides nearly with the energy estimated for dissipation.

As for the cause of lag in fluctuation of horizontal cutting force an explanation is given as follows: The horizontal cutting force in chatter does not reach a maximum value when the work moves horizontally nearest to the cutting edge. When the work rotates a little after that instant and chip is produced in maximum thickness, the horizontal cutting force becomes maximum and subsequently it sustains comparatively high values in the period of movement of the work away from the cutting edge.

Experiment VI. On the Chatter Patterns Produced on the Work Surface by Chatter Vibration[15]

PURPOSE OF EXPERIMENT

When the chatter vibrations occur in machining operations, orderly patterns are produced on the work surface as shown in Fig. 76. The phase of undulation of this pattern lags usually about 60° behind that of previous passage and then orderly spiraled patterns are produced on the work surface. If the direction of feed is reversed, the counter-spiraled patterns are produced. The purpose of this experiment is to ascertain why the vibration lags about 60° behind that of previous passage and what effects are to be done on the next cut by the previous undulations.

Method of Experiment

The same lathe was used as that in Experiments IV, V. In order to experiment during the several revolutions of work in either case in which the previous patterns are present or not, a square thread was preliminarily made on the workpiece as shown in Fig. 77. The tool was made from a 19 mm square rod of high speed steel, with cutting angle 80°, clearance angle 10°. It was fitted into the tool post in such a way as shown in Fig. 77 and fed in longitudinal direction corresponding to the pitch of the square thread of work.

The undulations of cut surface were measured by a sensitive dial indicator.

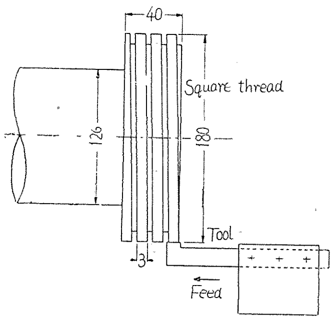


FIG. 77. Method of experiment.

Results of Experiment

At first, tests were made on the work on which previous undulations were not present. Fig. 78 shows the undulations formed by the vibration set up for the cutting speed 24 m/min and the thickness of chip 0.05 mm. In the figure, cutting operation is done along the curve *ab*, the part *bc* not being cut, because the amplitude of vibration is so large that the work is apart from the cutting edge over a part of one cycle. The distance *ac* of work corresponding to one pitch of vibration is about 6.3 mm and the frequency of vibration is about 66/sec. According to this experiment, chatter vibration occurs in a case of no previous undulations. Then, it is evident that the previous undulations are not the fundamental cause of chatter.

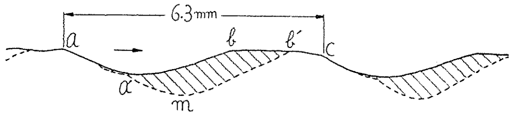


FIG. 78. Undulations on work surface.

Now, the second cut with the same cutting condition was made on the work which had the previous undulations as shown by a full line in Fig. 78. This cut was done along the curve *a′b′* shown by a broken line in the figure. This undulation lagged regularly about 60° behind the previous undulation. The frequency of vibration in the second cut was the same as that of the first cut, but the amplitude of this vibration was very much larger than that of the first cut. The situation of the point *a′* in Fig. 78 is lower than that of the point *b′* and then it is evident that the passage *mb′* is larger than that of *a′m*. Then, it is considered that the horizontal cutting force acts subsequently longer in the period of movement of the

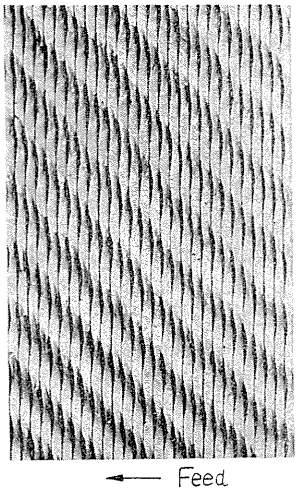


FIG. 76. Chatter patterns.

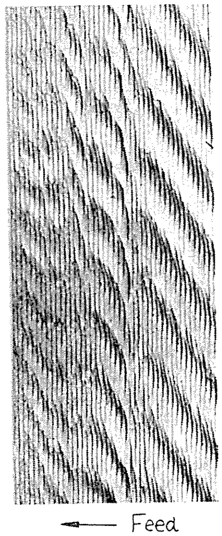


FIG. 88. Chatter patterns.

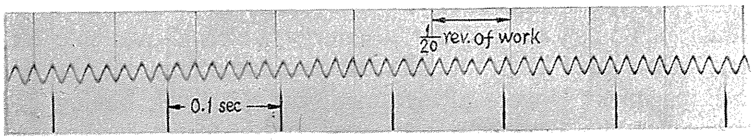


FIG. 83. Vibration of work.

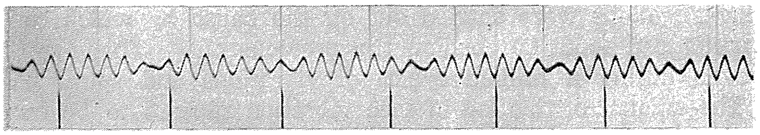


FIG. 84. Vibration of work.

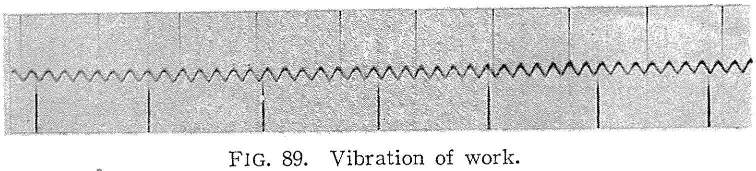


FIG. 89. Vibration of work.

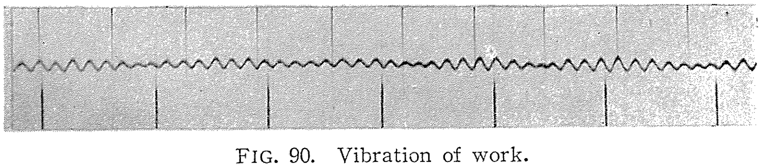


FIG. 90. Vibration of work.

work away from the cutting edge than in the period of approaching of it, and the available energy for maintaining the vibration becomes larger than in the case of first cut. To ascertain this matter, the following experiments were carried out:

When a cut was made on the work having no previous undulations, the cutting force and the vibration of work were measured simultaneously as shown in Fig. 79. It is the same with the previous experiment that the fluctuation of horizontal cutting force lags a little behind the horizontal vibration of work and some energy is available for maintaining the vibration. But in this case the time in which the horizontal cutting force increases from zero to maximum is almost equal to that in which the force decreases from maximum to zero.

Next, Fig. 80 shows the cutting force and vibration of work when cutting was done on the work having previous undulations. In each cycle in the figure the time in which the horizontal cutting force increases from zero to maximum is shorter than that in which the horizontal cutting force decreases and horizontal cutting force subsequently sustains high values in movement of the work away from the cutting edge.

The curve at the left in Fig. 81 is to show the relation between the horizontal cutting force and horizontal displacement of the work in one cycle obtained from Fig. 79 and the one at the right in the figure is obtained similarly from Fig. 80. The areas of these closed curves correspond to the energies 0.63 kgmm per cycle and 1.83 kgmm per cycle respectively. Therefore, it is evident that when the previous undulations exist, the amount of energy which is available for maintaining the vibration becomes large and chatter vibration occurs with large amplitude. The tests in Experiment *V* were always made on the work having the previous undulations, because the flange of work was cut by cross feeding. Then, the fluctuating manners of horizontal cutting forces were always the same as those in Fig. 80.

Next, investigations were carried out on the cause by which the phase of vibration was lagged about 60° behind the previous cut. This lag is produced regularly even during a million cycles of vibrations and spiral patterns are produced. The amount of this lag in each vibration appears to be more regular than the regularity of rotation of work and it is expected that there exist some

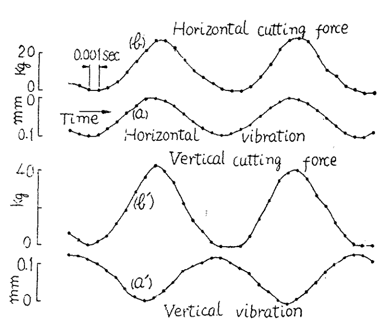


FIG. 79. Cutting force and vibration of work.

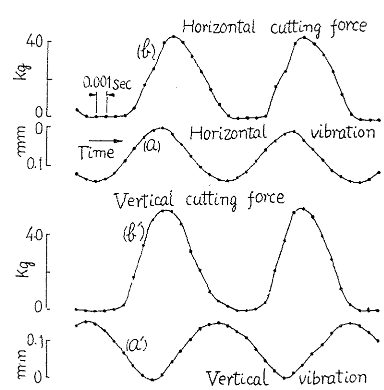


FIG. 80. Cutting force and vibration of work.

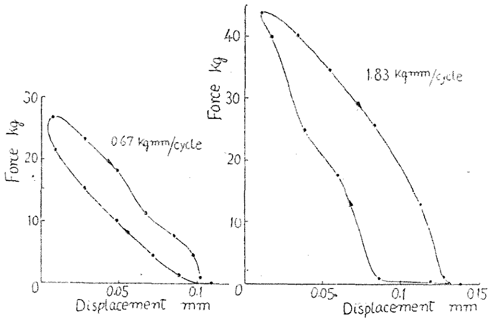


FIG. 81. Force-displacement curves.

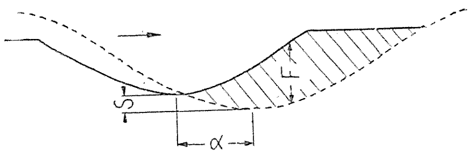


FIG. 82. Undulation on work surface.

connections between the vibration and the previous undulation.

When the cutting edge digs in the work in each cycle, the cutting edge may rub somewhat the work surface. The wear of tool heightens this tendency. This rubbing phenomenon of cutting edge will promote more or less the lag in phase. But the fundamental cause of the lag in phase is considered as follows: Assuming that the previous undulations exist as shown by full line in Fig. 82, the second cut of the feed (s) is made as shown by broken line. In this cutting, available energy for maintaining the vibration is estimated diagrammatically from the horizontal cutting force corresponding to the depth of cut (F) and the displacement of work in each phase of vibration. It is ascertained that this energy is maximum when the lag (α) in phase is about 60°.

Further, tests on lag in phase were made as follows: At first, cutting operation with the revolution of work 42.2/min was made on the work having no previous undulation. The amplitude of this vibration is very stable as shown in Fig. 83. Next, the second cut in which the revolution of work was lowered to 36.8/min, was made on the undulation formed in the first cut. This vibration is illustrated in Fig. 84. The amplitude fluctuates orderly at every interval of several cycles of vibration. Fig. 85 shows the frequency of this vibration. The frequency of certain one cycle decreases orderly at every interval of several cycles of vibration.

The undulations of cut surface were measured comparing with the previous undulations as shown in Fig. 86. The full line in the figure shows the previous undulation and the broken line shows that of the second cut. At the cycle (1) in the figure the lag in phase is about 60° and the amplitude of vibration is large. It is seen in the cycles (2)-(6) that the lag in phase decreases gradually from 60°

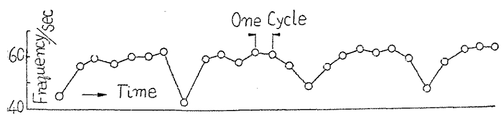


FIG. 85. Frequency of vibration.

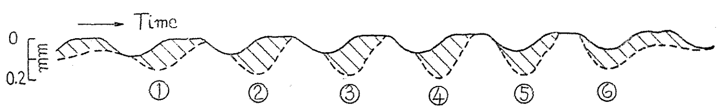


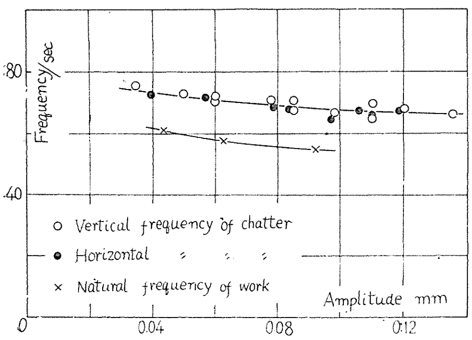
FIG. 86. Undulations on work surface.

and the amplitude of vibration decreases. Then, after one cycle which has a long period and a very small amplitude, the lag in phase becomes again about 60° naturally, and the amplitude of vibration increases. Instead of that one cycle of a long period, there was the case of two cycles of a short period. Then, it is seen that the vibration has a tendency to maintain naturally the lag in phase of about 60°.

Fig. 87 shows the frequency of chatter vibration which is set up on the work having no previous undulation. As shown in the figure, the frequency of chatter vibration has a certain value which is a little larger than the natural frequency of work. The frequency shown in Fig. 85 is slower 6-8 cycles/sec than that of Fig. 87. Therefore, the frequency of vibration has naturally the tendency to agree with the pitch of the previous undulation.

Fig. 88 shows the chatter patterns produced in outer turning by a roughing tool, when the revolution of work was gradually decreased. As the revolution decreases, the spiral of pattern becomes slight due to the decrement of lag in phase and the amplitude of vibration decreases gradually. Finally, the number of patterns increases naturally corresponding to the decrease of the revolution of work.

On the other hand, tests were made when the revolution of work was increased. Fig. 89 shows the stable amplitude of vibration set up in the first cut with the revolution of work 42.9/min. Then, the second cut with the revolution of work 46.8/min was made on the undulation formed in the above cut. As shown in Fig. 90 the amplitude of vibration fluctuates orderly at every interval of several cycles. Fig. 91 shows the frequency of this vibration. This frequency is larger by 4-6 cycles/sec than the original frequency of chatter. In this cutting the undulation of cut surface was measured together with the previous undulation. The full line in Fig. 92 shows the undulation of the first cut and the broken line shows that of the second cut. It is seen that when the lag in phase is about 60°, the amplitude is largest and the lag in phase increases gradually in each cycle and the amplitude decreases. Finally, after one or two cycles of a short period, the lag in phase becomes again about 60° naturally and the amplitude increases.



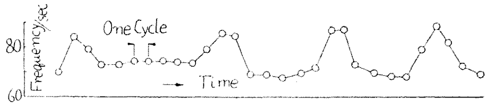


FIG. 87 (*left*). Frequency of chatter vibration.
FIG. 91 (*right*). Ferquency of vibration.

FIG. 92. Undulations on work surface.

Conclusion

Chatter vibrations have naturally the tendencies to maintain the lag in phase about 60° behind that of the previous revolution and to agree with the pitch of previous undulations, because in this tendency energy is fed into the vibrating system at the maximum rate. This matter is due to the principle of minimum energy. But the previous chatter patterns are not the fundamental cause of chatter vibration.

As ascertained in Experiment *V*, the fundamental cause of this chatter is due to the fluctuation of horizontal cutting force which has a little lag of time behind the horizontal vibration of work, and this chatter is a kind of self-excited vibration. But the previous patterns have effects to enlarge the amplitude of chatter or to promote the occurrence of chatter, and exert an influence as like a character of the forced vibration upon the chatter.

Part III. On Chatter Vibration Caused by Headstock Gears of Lathe[16)]

Experiment VII. On the Characters and Causes of Chatter

Purposes of Experiment

It is well known that when faulty gears are used as the gears of headstock, chatter vibration frequently occurs producing the chatter marks on the workpiece. This chatter is a forced vibration.

The purposes of this experiment are to ascertain characters and causes of this chatter and to compare its characters with those of self-excited chatter.

Method of Experiment

The lathe used in the experiment had the swing 400 mm. The main spindle of the lathe and the method of experiment are illustrated diagrammatically in Fig. 93. The vibration of work was recorded on films by the same method as described in Experiments III, IV. The diameter of workpiece was 75 mm and the length was 300 mm. The gear fitted on the main spindle had 80 teeth and its modul was 2.5 mm, and the gear on the driving shaft had 40 teeth. In order to record the number of tooth engagement, the light passing through the slit (1) was projected on the side surface of tooth of a gear fitted on the main spindle. Then, the light was interrupted by a tooth which ran across the passage of the light and when the space of teeth was in the passage, the light was recorded on the rotating

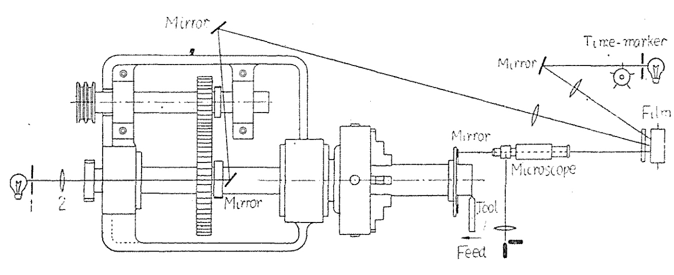


FIG. 93. Method of experiment.

film. During the cutting operation, the number of tooth engagement and the horizontal vibration of work were recorded simultaneously on the same film. The examples of records are shown in Figs. 94-96. One vibration in Fig. 94 corresponds to each black mark in the figure. It is not the case in Fig. 95. In Fig. 96 the vibration of work hardly occurs.

Results of Experiment

At first, faulty gears which were generated by an inadequate hobbing machine were used as the gears of headstock. Accuracies of these gears fitted with spindles together were checked preliminarily by a dial indicator. The reading of a dial indicator which was operated over the ball inserted in each space of teeth was about 0.1 mm in eccentricity. According to the composite test of gears, the rotational irregularity of gear per tooth was about $(2\text{-}6)\times10^{-4}$ rad.

At first, to understand easily the character of this chatter, cutting tests were made under the condition, in which the center distance of gears was so decreased by adjusting the bearings of driving shaft that the gears were maintained in mesh without backlash and thus interference of teeth might be caused.

Tests of outer turning with a roughing tool of the cutting angle 70° were made in various cutting speeds. The feed was 0.065 mm, and the depth of cut was 0.09-0.36 mm. The horizontal vibrations of work obtained in these tests are shown in Fig. 97. The marks ○ and ◉ in the figure represent the amplitudes of vibrations, of which one's frequency is the same and the other's not the same with the number of tooth engagement. The number of suffix added on the mark ◉ shows the frequency per second.

The frequencies of vibrations in the curve C in the figure are entirely the same with the number of tooth engagement, and as shown in Fig. 98 chatter patterns which are parallel to the axis of workpiece are produced corresponding to the number of teeth of gear fitted on the main spindle. Therefore it is evident that this vibration is caused by gears. The natural frequency of the work together with the chuck and the main spindle is about 111/sec. Then, the amplitude of vibration in the curve C is maximum when the number of tooth engagement coincides nearly with the natural frequency of the work, as the typical resonance curve.

In the figure, when the number of tooth engagement is in the range of 92-120/sec in the curve B or in the range of 72-140/sec in the curve A, vibrations of large amplitude are set up with the frequencies 102-111/sec. These frequencies are independent of the number of tooth engagement, the cutting speed and the feed, and they are nearly equal to the natural frequency of work. During these vibrations, patterns spiraled orderly are produced on the workpiece as shown in Fig. 99. Therefore, this vibration is considered as the chatter set up due to self-excitation, which was investigated in Experiments III-VI. Once this vibration occurs, its frequency is not affected by the number of tooth engagement. But this vibration is most liable to occur in the revolution of work, in which the number of tooth engagement corresponds to the natural frequency of work. It is seen that the amplitude of self-excited vibration is very large as compared with that of vibration set up due to gears of the headstock.

The curve D in Fig. 97 shows the tests when proper amount of backlash in

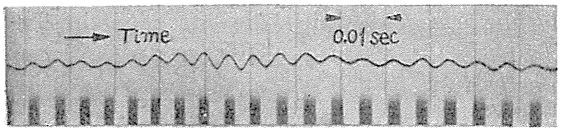


FIG. 94. Vibration of work.

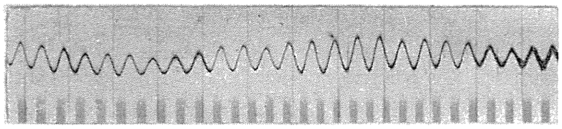


FIG. 95. Vibration of work.

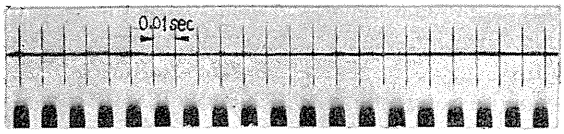


FIG. 96. Vibration of work.

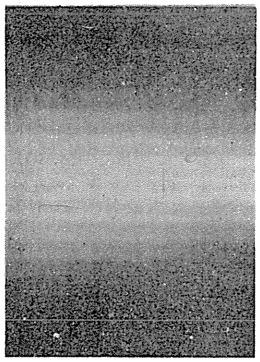


FIG. 98. Chatter patterns due to gears.

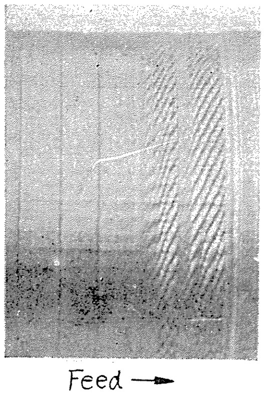


FIG. 99. Chatter patterns due to self-excited vibration of work.

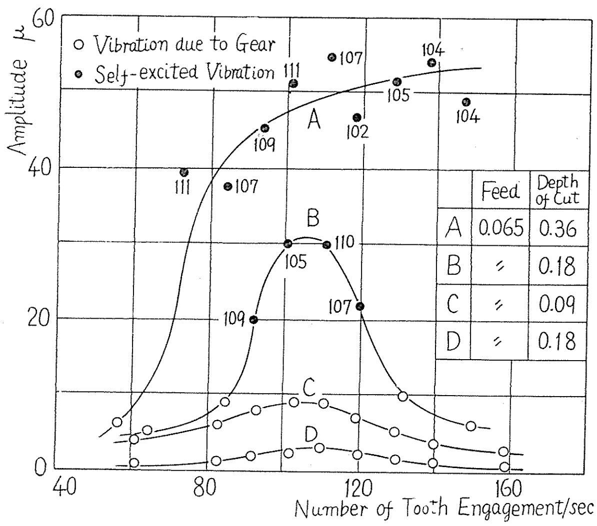


FIG. 97. Relation between horizontal vibration of work and number of tooth engagement.

gears is maintained. The amplitude of this vibration is very small as compared with that of the curve B which is set up in gears with no backlash. Therefore, the interference in gears has remarkable effects on the occurrence of this chatter.

In practice, there are frequently the cases in which the cause of chatter is obscure. The self-excited vibration and the vibration due to gears are both set up under similar cutting conditions, as shown in Fig. 97. These chatters can be easily distinguished on account of the manners of chatter patterns and the frequency of vibration which can be estimated from chatter patterns. There is the case in which chatter is set up due to the eccentricity of a driving gear. In this case, if the gear ratio of the driving and driven gears is not in round number, patterns spiraled orderly are produced on the workpiece. But these patterns can be easily distinguished from those of self-excited vibration.

Next, the length of work was shortened to 100 mm. According to the natural vibration of work in this case, the natural frequency was about 165/sec. Under these conditions, cutting tests were made in various cutting speeds as shown in Fig. 100. In this case the self-excited vibration did not occur entirely. The curve A in the figure shows the tests made without backlash is gears, and the curve B shows the case in which a proper amount of backlash in gears is maintained. As shown in the figure, the vibration due to gears is largely affected by the interference of teeth. In the curves A and B, the amplitude of vibration becomes maximum when the number of tooth engagement corresponds to the natural frequency of work. In the curve A the vibration occurs again at high cutting speeds. It is considered that as the revolution of gear increases, the impact due to interference of teeth increases to heighten the tendency to vibrate.

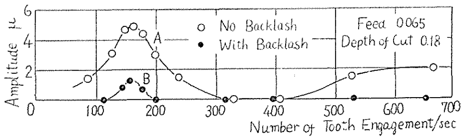


FIG. 100. Relation between horizontal vibration of work and number of tooth engagement.

Rotating the work by hand in the case at which gears are set without backlash, it is ascertained that the main spindle of the lathe deflects horizontally about 0.5 μ in every tooth engagement at the eccentric part of gears. Therefore, it is considered that the chatter is caused by the fluctuation of horizontal force which acts at the contact point of teeth, and the chatter is not nearly affected by the rotational irregularity of work.

The results of tests of a finishing tool under the conditions in which the length of work is 100 mm and gears are set to maintain the proper amount of backlash are shown in Fig. 101. The mark o in the figure shows the vibration of which the freqnency is equal to the number of tooth engagement and the mark ● shows the self-excited vibration. An increase in cutting speed increases the tendency to cause the self-excited vibration. But in the curve B' in the figure, the vibration due to gears occurs in various cutting speeds. Therefore, it is evident that the gears used in the above tests are not sufficient in accuracy as the gear of headstock. It is also seen in the figure that the finishing tool (B) which has a slightly

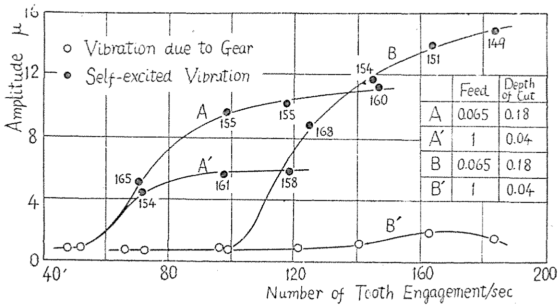


FIG. 101. Test of finishing tool.

curved cutting edge does not much cause the self-excited vibration as compared with the tool (A) of a straight cutting edge.

Next, gears were finished precisely by the Maag gear grinder and then the same experiments were carried out, using them as the gears of headstock. The accuracy of this gear fitted with the spindle, in the rough, was checked by a dial indicator. The reading of the dial indicator operated over the ball inserted in each space of teeth was about 16 μ in eccentricity per revolution. The rotational irregularity per tooth was about 1.3×10^{-4} rad.

It was ascertained that the vibration due to these gears did not occur entirely in any cutting which was tested under various conditions, and only the self-excited vibration occurred. The occurrence of self-excited vibration was not almost affected by the accuracy of gear. Only in regard to the occurrence of chatter in this lathe, this accuracy of gear is considered to be sufficient as the gear of headstock. Of course, this accuracy of gear depends on the type of lathe.

CONCLUSION

The chatter vibration on account of a faulty gear of headstock is caused by the deflection of main spindle due to the fluctuation of horizontal force which acts at the contact point of teeth. This chatter is liable to occur when the finishing tool is employed. An increase in length of work heightens the tendency for the chatter to occur. This chatter is most liable to occur in the revolution of work in which the number of tooth engagement corresponds to the natural frequency of work. The severity of vibration depends upon the degree of resonance.

It is found that the amplitude of self-excited chatter is very large compared with that of the chatter due to the gear of headstock. If the self-excited chatter once occurs, its vibration is maintained without any relation to the number of tooth engagement. Both the self-excited chatter and the chatter due to gear are liable to occur under similar cutting conditions, but these chatters can be easily distinguished from each other by their chatter patterns.

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