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On the Suppression of Self-excited Vibration by Servodamper*

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This paper deals with a technique to suppress the self-excited chatter vibration in machine tools by servodamper method proposed by the authors in the previous papers. Firstly, it is shown that the servodamper designed by applying an output feedback control theory is capable of increasing stability in cutting process against the occurrence of the chatter. Secondly, from a viewpoint of model cutting experiment, the capability of the servodamper to eliminate the chatter is presented. Thirdly, by installing the servodamper in a large-scale vertical lathe which has been required a countermeasure for the chatter occurring frequently, this paper shows the results of a cutting experiment in which a servodamper proves to be effective for eliminating the chatter under various cutting conditions.

1. Introduction

A self-excited chatter vibration occurring in a cutting process causes not only surface finish, dimensional accuracy, tool life but also machine life itself to deteriorate so much that many papers, in recent years, have tried to study the causes of the chatter phenomena⁽¹⁾ as well as the methods^{(2),(3)} to suppress the chatter. The countermeasures for the self-excited chatter vibration proposed so far are basically classified into the following categories.

i) Selection and setting cutting conditions so as to avoid the chatter

ii) Suppressing the chatter positively
As for the former measure^{(2),(3)}, in order to avoid the chatter the methods how to select and set the cutting conditions such as feed, width of cut and spindle speed are proposed; however, from a viewpoint of productivity, such a measure is not necessarily recommendable. On the contrary, as long as the latter measure is concerned, the efforts have been made on research and development of a control technique to positively eliminate the chatter, and the approach of this kind is expected to bring about a great improvement in stability margin against the occurrence of the chatter. One of the measures to suppress the chatter in machine tools is to improve the dynamic stiffness of the structure so as to enhance its stability

in cutting process against the occurrence of the chatter. This is particularly useful for machine tool structures such as a vertical lathe or a horizontal boring machine, which have to hold a cutting tool by means of a cantilever for their own machining purpose. Furthermore the application of a damper is now regarded as the only measure to improve the dynamic stiffness of the structure.

Generally speaking, a dynamic damper⁽⁴⁾⁻⁽⁶⁾ is known as the typical damper; however, the practical use of this damper is difficult for the following reasons. Firstly, the effectiveness of the damper in absorbing the vibration is not enough to suppress the chatter. Secondly, the range of the admissible parameters in designing the damper is so restricted that the practical use of this device is limited. Thirdly, the damper can not be applied when the dynamic characteristics of a structure vary frequently and widely.

To eliminate these defects, Bollinger^{(7),(8)} reported an attempt to design a modified dynamic damper by adding a self-optimizing mechanism to the damper, but it is still impossible for this new type damper to suppress the vibration of a structure on which a general force such as a random or an impulsive force is acting. Thus, the dynamic damper has many limitations in practical application to machine tools.

In order to overcome the difficulties mentioned above, the authors proposed a servodamper, which is an absolute type active damper, in the previous papers⁽⁹⁾⁻⁽¹¹⁾. As for the design of the servodamper control system, a systematic design procedure was presented in terms of output feedback control. In addition, it was verified that the servodamper was effective for advantageous modification of the dynamic characteristics of structures.

This paper presents a solution to

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eliminate the self-excited chatter vibration by applying the servodamper proposed in the previous papers to cutting process. First, the relationship between the effectiveness of the servodamper on enhancing the dynamic stiffness of the structures and the stability margin against the occurrence of the chatter vibration in cutting process is established. Then from a viewpoint of model cutting experiment, the suppression of self-excited chatter occurring in machining process is demonstrated. Furthermore, referring to the results of a model experiment the possibility to apply the servodamper to a real machining process is discussed. Next, adopting a large-scale vertical lathe as a control object, which has been required for the immediate measure to eliminate the chatter occurring frequently in the actual machining process, the servodamper system is designed from an output feedback control point of view. Moreover, for the purpose of eliminating the chatter vibration occurring in the lathe operation, the servodamper is set in the tool holder, and a cutting experiment is made. As a result, the suppression of the chatter is realized so that the machining efficiency as well as the machining accuracy are greatly improved.

2. Improvement of stability margin against the occurrence of chatter vibration

In the previous papers,⁽⁹⁾⁻⁽¹¹⁾ the effectiveness of the servodamper driven by an output feedback control law was shown analytically and experimentally. From a viewpoint of Merritt chart,⁽⁹⁾ this section presents a relationship between the effectiveness of servodamper to improve the dynamic stiffness of structures and the stability margin against the occurrence of the chatter in cutting process. The design parameters of a cantilever type structure adopted here are as follows: the overhang length of the beam, $l=65$ cm; the sectional view, 68×68 mm, $t=9$ mm; the first natural frequency of the beam, $\omega_n=68$ Hz; static stiffness $k_m=302$ kg/mm. Taking into consideration^{(10),(11)} both the simplification of the system and the effectiveness of control, the following state variables are measured as output variables, that is, the displacement of the beam X_1 , the velocity of the beam X_2 , and the relative displacement between a piston and a cylinder X_8 . Furthermore, the output feedback control law with respect to the best performance point in velocity is the following; $G_1=189.3$ V/cm, $G_2=0.235$ V/cm/sec, $G_8=1$ V/cm, where G_1 , G_2 , and G_8 mean a feedback gain from the variables X_1 , X_2 , and X_8 , respectively. Fig.1 shows the dynamic compliance of the structure with the beam mentioned above. By applying the servodamper driven by the output feedback control law described previously, the dynamic characteristic of the system is changed into an improved one as shown in Fig.2. Fig.3 shows a Merritt chart on which these two dynamic compliances are superimposed. As shown in Fig.3, in the case of the dynamic compliance without the servodamper, the gain-phase plot of the compliance with a parameter, $k_c/k_m=0.01$, already intersects with the critical locus of stability

ty where the overlap factor μ is 1.0, so that a self-excited vibration is expected to be occurring under this condition. In addition, the critical value of k_c/k_m which gives the absolute stability is 8.5×10^{-3} and the chatter frequency in this case is 69 Hz. Here, k_c , y and u used in Fig.3 denote a directional static cutting stiffness, an instantaneous uncut chip thickness and relative displacement between tool and work-piece, respectively. On the other hand, with the aid of the servodamper compensation, stability margin against the chatter is largely improved. As a result, the value of k_c/k_m giving the absolute stability threshold is increased to 0.8, so that the stability against the chatter is improved 94.1 times over that without the servodamper compensation.

Fig.1 Dynamic compliance without the servodamper compensation

Fig.2 Dynamic compliance with the servodamper compensation

Fig.3 Merritt chart

3. Elimination of self-excited vibration in a model cutting experiment

In advance of applying the servodamper to an actual machining process, the effectiveness of the servodamper to suppress the chatter under an ideal circumstance is checked in a model cutting experiment.

3.1 Make-up of the apparatus for cutting experiment

A view of a cutting experimental setup is shown in Fig.4. As illustrated in Fig.5, the device is placed close to the top of a ram where the servodamper is fixed. For the convenience of a model cutting test, a cutting tool is set at the top of the ram, and instead of moving the tool, a workpiece is designed to move to get a feed and a depth of cut. Also, as mentioned earlier three state variables X_1 , X_2 , and X_8 are measured for feedback signals. Both X_1 and X_8 are detected by an inductance type vibrometer, and X_2 is obtained by integrating the output of an accelerometer.

Fig.4 Photo of cutting experimental apparatus

Fig.5 Schematic view of cutting experiment

As for the chatter vibration, the relative displacement between a cutting tool and a workpiece should be measured; however, the vibration is difficult to detect, so the relative displacement between the housing of a bearing supporting a workpiece and the tool box, is measured instead.

3.2 procedure of cutting experiment

The conditions of cutting experiment are as follows:

- the hangover length of the ram, 65 cm;
- material of workpiece, mild steel;
- the outer diameter of workpiece, 58mm;
- the width of workpiece, 30 mm;
- the cutting tool, cemented carbide;
- the entering angle of the cutting tool, 90°;
- the feed, 0.1 mm/rev;
- the depth of cut, 0.05~0.5 mm;
- the cutting speed, 30~200 m/min;

3.3 Results of cutting experiment

In the cases where the servodamper was not employed, a violent chatter phenomenon was observed under all the cutting conditions. Consequently, it turns out that the structures of this kind were no longer applicable for machining process unless they were compensated by a certain control method. In Fig.6 is recorded the chatter vibration occurring under the following conditions; that is, the depth of cut 0.1 mm, the feed rate 0.1 mm/rev, and the cutting speed 55 m/min. On the other hand, by setting the servodamper on, an impetuous chatter was suddenly suppressed and a stable cutting process with so-called flow-type chips was realized. As shown in Fig.6, the self-excited chatter vibration with the amplitude up to 170 μ m was suppressed to a stable state with the amplitude of 10 μ m.

Fig.6 Chatter vibration and the effectiveness of the servodamper

Next, the effectiveness of the servodamper on eliminating the chatter is shown from a power spectral point of view. Fig.7 presents a result of power spectral analysis of both signals recorded in Fig.6. As seen from Fig.7, a peak corresponding to the chatter was prominent at 70 Hz and the frequency coincided with that of the ram system 68Hz, so that the chatter occurring in the cutting process was regarded as a regenerative chatter. If the spectral value of the chatter was set at 100, then the value was subdued to 1.4 by the servodamper compensation. In other words, it can be said that the chatter occurring in the cutting process was eliminated. Then, from a standpoint of surface finish, the difference between the cases with and without the servodamper was demonstrated. For example, Fig.8 shows the surface finish obtained from machining under the same condition as the case shown in Fig.7. As seen from Fig.8, the so-called chatter mark completely disappeared from the surface through the servodamper compensation, and an improvement in surface finish was obviously attained. Fig.9 shows a surface roughness curve of the test piece taken under the following conditions; the cutting speed 180 m/min, the depth of cut 0.1 mm, and the feed rate 0.1 mm/rev. In this case, the maximum roughness R_{max} was 120 μ m, but with the aid of the servodamper, the chatter mark vanished completely and R_{max} was suppressed to 7 μ m. Thus, in the case where the servodamper was not employed, the maximum roughness R_{max} had values between 100 μ m and 300 μ m; however, through the servodamper compensation, the maximum roughness was suppressed to 7~10 μ m.

Fig.7 Power spectral analysis

Fig.8 Surface finish

Fig.9 Surface roughness curve

Thus it was verified that the chatter vibration occurring due to the lack of the dynamic stiffness of structures was suppressed by the servodamper compensation and a practical perspective to eliminate the chatter in actual machining process has been opened.

4. Elimination of self-excited vibration in a large scale vertical lathe.

4.1 The vertical lathe used in the experiment

Fig.10 shows a vertical lathe (DBM-40A) used for the cutting experiment, and the specification of the lathe is as follows:

Fig.10 Large scale vertical lathe

the maximum diameter of work is 6500 mm,
the maximum weight of work is 50000 kg,
the maximum hangover length of the ram is 1600 mm,

In advance of the cutting experiment, a preparatory experiment was conducted to get the necessary information to design the servodamper system. Some of the experimental results are as follows; the static stiffness of the ram k_m at the length of 1600 mm was 720 kg/mm, the first natural frequency ω_n was 38 Hz, and the damping ratio ζ was 0.0373.

In addition, taking into consideration the protection of the servodamper, the tool holder of the ram was remodeled so that the servodamper could be loaded in it. The dead mass of the servodamper used in this experiment was 2 kg and the allowable stroke of the piston was ± 7 mm.

4.2 Determination of output feedback control law

Referring to the design procedure proposed in the previous papers, the decision of the output feedback control law is achieved based on the design parameters taken from a preparatory experiment. As for the performance function, since the working accuracy of a machine tool involving a ram structure is mainly dominated by the vibration of ram, the control law should be obtained such that the fluctuation of the ram X_1 is minimized. Therefore, the performance function is defined as follows:

$$J = \int_0^{\infty} (\rho x_1^2 + u^2) dt \quad (1)$$

where ρ means a weighting factor to show the control effect. Furthermore, the control input u is described as an output feedback form in the following:

$$u = -Gy \quad (2)$$

where G and y mean an output feedback gain matrix and an output vector, respectively. As for output variables, the following state variables are fed back as done in the model cutting experiment, i.e.; X_1 , the displacement of the ram; X_2 , the velocity of the ram; X_8 , the relative displacement between a piston and a cylinder of the servodamper. Therefore, eq. (2) is described as

$$u = -G_1 x_1 - G_2 x_2 - x_8 \quad (3)$$

where G_1 and G_2 mean feedback gains from the state variables X_1 and X_2 , respectively.

In addition, the feedback gain from the variable X_8 is set at 1 V/cm with a view to getting equilibrium between the piston and the cylinder of the servodamper.

As was presented in the previous paper⁽¹⁰⁾, the output feedback gain matrix G is obtained as a function of ρ , the weighting factor, which is given by solving numerical-

ly both the Riccati equation and the Lyapunov equation. Then, based on the proposition of the best performance point, the amount of the weighting factor ρ is determined such that ρ gives the optimum control law.

X_{11}^C and X_{22}^C defined in the following equations meaning a squared mean value of displacement and velocity respectively, are also used for performance criteria of a damper as discussed in the previous paper.

$$X_{11}^C = E\{x_1^2(t)\} \quad (4)$$

$$X_{22}^C = E\{x_2^2(t)\} \quad (5)$$

where E means an expectation.

With the determination of the output feedback gain matrix G , X_{11}^C and X_{22}^C are obtained numerically by solving a covariance matrix equation as shown in Fig.11. In order for X_{11}^C and X_{22}^C to be dimensionless, the values at $\rho = 0$ are set at 100 as in Fig.11. Moreover, the gain matrix G is a function of the factor ρ so that X_{11}^C and X_{22}^C are also functions of ρ . Then, by determining the best performance point ρ^* which makes the control effect optimum, in other words, which minimizes X_{11}^C or X_{22}^C , the output feedback gain matrix G is obtained.

Fig.11 ρ - X_{11}^C , X_{22}^C diagram

Next, let us investigate the characteristics of the output feedback control system by means of ρ - X_{11}^C , X_{22}^C chart in Fig. 11. With an increase of ρ up to $\rho_{11}^* = 2.5 \times 10^4$, which means the best performance point in displacement, both X_{11}^C and X_{22}^C decrease sharply so that the vibration level in both the lower and the higher frequency range is suppressed. However, when ρ becomes larger than ρ_{11}^* , X_{11}^C representing the vibration level in the lower frequency range increases even though X_{22}^C is still reducing. This phenomenon is seen from the root locus of the system with a parameter ρ as shown in Fig.12. Namely, the decrease of X_{11}^C would be achieved by letting a pair of the poles of the ram system A move away from the imaginary axis; however, there exists a pair of poles B interfering with the expected movement of the poles A, so that X_{11}^C is not much reduced in comparison with X_{22}^C . As a result, since the characteristic poles of the ram system A move toward the origin without gaining enough damping, X_{11}^C begins to grow in proportion as ρ becomes larger than ρ_{11}^* . On the other hand, a pair of poles B moves toward the higher frequency range while being damped, so X_{22}^C still keeps on reducing with an increase of ρ even after exceeding ρ_{11}^* .

Fig.12 Root loci diagram of the servodamper system

Therefore, for the reasons mentioned above is adopted a control law with respect to ρ_1^* which gives the maximum damping to the system, i.e., $G_1 = 70.5 \text{ V/cm}$, $G_2 = 0.035 \text{ V/cm/s}$.

4.3 Improvement of stability against the chatter by means of servodamper

In constituting the control system by applying the output feedback control law obtained in the previous chapter, the measurement of the output feedback signals, especially the measurement of the ram displacement, is of great importance. From among several attempts to measure those variables, this paper presents the result of an experiment using the strain of the ram as the displacement X_1 . As for the velocity of the ram X_2 , it is obtained by integrating the output of a charge amplifier. As for the relative displacement between a piston and a cylinder of the servodamper X_8 , this is measured by a differential transformer loaded in the servodamper and is fed back with a gain of 1 V/cm .

Preceding the cutting experiment, an exciting experiment was conducted on the ram structure to see the effectiveness of the servodamper with respect to the output feedback control law. As a result, in setting the feedback gain G_1 , a proper gain was found out, which was somewhat smaller than the theoretical value. This was partly because a band-pass filter whose cut-off frequencies were 2 and 120 Hz had been used to eliminate the influence of the higher modes detected by a strain gauge. Therefore, taking into consideration the influence, the appropriate feedback gains obtained experimentally were used for the cutting experiment, that is, $G_1 = 50 \text{ V/cm}$, $G_2 = 0.035 \text{ V/cm/s}$, $G_8 = 1 \text{ V/cm}$.

The gain-phase locus resulting from the exciting experiment was plotted on the Merritt chart as shown in Fig.13. As obvious from Fig.13, the stability margin against the occurrence of the chatter was improved by 4.2 times over that in the case where the servodamper was not employed.

Compared with the improvement achieved in the model experiment, the improvement in stability in this case did not seem to be conspicuous. However, this was because the damping of the vertical lathe used in the experiment was ten times as much as that of the beam used in the model experiment.

Fig.13 Merritt chart

4.4 Procedure of cutting experiment

The hangover length of the ram was set at 1600 mm and 1400 mm. In the cutting experiment, with

the outer diameter of workpiece : 1253mm,
the inner diameter of workpiece : 1010mm,
the height of workpiece : 1190mm,
the material of workpiece : FC25, iron cast,
the cutting tool : cemented carbide (36-5 type, K-10, TH-10)
the feed S : 0.2 mm/rev, 0.125 mm/rev,
the cut of depth t : 2 mm, 0.8mm, 0.32mm,
the speed : 25 rpm,

the traverse cutting operation was repeated. Under each cutting condition, first, without operating the servodamper, traverse cutting was done to 5 mm width, then with the servodamper on, the cutting operation was carried on to 10 mm width.

During the traverse cutting operation, however, the ram length varied and the characteristics of the ram system also changed. In order to keep the same cutting condition, the following operation was made in this experiment; when the ram length became 30 cm longer than the reference length, the cross rail was shifted downward by the same amount.

4.5 Results of cutting experiment

In the case where the servodamper was not driven, a violent chatter vibration occurred under every cutting condition. In Fig.14. the vibration of the ram structure owing to the chatter is shown under the cutting condition $\{l = 1600 \text{ mm}, t = 0.8 \text{ mm}, s = 0.2 \text{ mm/rev}\}$. As seen from Fig.14, the chatter occurring in this cutting process is impetuous, for the maximum amplitude of the vibration $X_{\max}$ amounts to $70 \sim 80 \mu\text{m}$. On the other hand, with the servodamper on, such a violent chatter vibration is suddenly suppressed to a few μm in $X_{\max}$ as shown in Fig. 14. The power spectrum of the vibration is shown in Fig.15. Without the servodamper, the spectrum referring to the chatter is dominant at 38 Hz, and this frequency corresponds with the natural frequency of the ram, so that the chatter occurring in the cutting experiment is recognized as a regenerative chatter caused by the lack of enough damping of the ram structure. As shown in Fig.15, the spectrum referring to the chatter is completely eliminated.

Fig.14 Chatter vibration and its suppression

Fig.15 Power spectral analysis

Furthermore, the effectiveness of the servodamper is discussed in terms of the worked surface. Fig.16. shows the surface machined with the ram length $l = 1600 \text{ mm}$. The improvement in surface finish is best seen in the figure. The surface roughness measured in the direction of feed under the cutting condition $\{l = 1400 \text{ mm}, t = 0.8 \text{ mm}, S = 0.2 \text{ mm/rev}\}$ is illustrated in Fig.17. With the benefit of the servodamper, the maximum roughness is improved from $40 \mu\text{m}$ to

$10 \mu\text{m}$. Under all of the cutting conditions adopted in this experiment, the effectiveness of the servodamper on the reduction of the chatter is expressed in terms of the maximum amplitude of the vibration of the ram $X_{\max}$, and the maximum height in roughness $R_{\max}$ as shown in Figs.18 and 19. The cases with and without the servodamper are identified by white and black marks. Without the servodamper compensation, in the case of $l = 1600 \text{ mm}$, a chatter results in the maximum amplitude of chatter $X_{\max}$ in the range from $50 \mu\text{m}$ to $80 \mu\text{m}$ and the maximum height in surface roughness $R_{\max}$, in the range from $25 \mu\text{m}$ to $50 \mu\text{m}$. On the other hand, when the servodamper is driven, $X_{\max}$ is improved to $5 \sim 10 \mu\text{m}$ and $R_{\max}$ to about $10 \mu\text{m}$. The same effect is obtained in the case of $l = 1400 \text{ mm}$ as well. In this case, static stiffness is 50 % higher than that at $l = 1600 \text{ mm}$ so that $X_{\max}$ is lowered to $30 \mu\text{m}$ in the case where the servodamper is not employed.

In addition, a heavy cutting test was also conducted with the depth of cut, $t = 5 \text{ mm}$, but on this particular occasion the feed, S , was set at 0.16 mm/rev , so that Figs.18 and 19 did not include this specific case for the expedience of arrangement. However, even in such a heavy cutting, the effectiveness to eliminate the chatter was verified. In the case of $l = 1600 \text{ mm}$, for instance, $X_{\max}$ and $R_{\max}$ were improved to $6 \mu\text{m}$, and $5 \mu\text{m}$, respectively.

Fig.16 Finish surface

Fig.17 Surface roughness curve

Fig.18 Maximum amplitude of the ram X_{max} under various cutting conditions

Fig.19 Maximum roughness R_{max} under various cutting conditions

5. Conclusions

This paper demonstrates a method to eliminate the self-excited chatter vibration in machine tools caused by the lack of dynamic stiffness of the structures. First of all, a model cutting system consisting of a cantilever type structure is taken into consideration. By applying the servodamper driven in accordance with output feedback control law, the stability margin against the occurrence of chatter in cutting process has been improved by a factor of 94.1. Then, in a model cutting experiment, when the servodamper was not employed, a violent chatter occurred with the maximum amplitude of vibration X_{max} ranging from 100 μm to 200 μm under every cutting condition; however, with the benefit of the servodamper compensation, the chatter was suddenly suppressed and good surface finish with R_{max} 7~10 μm was obtained successfully.

Next, using as a control object a large scale vertical lathe, which had needed an immediate countermeasure against the occurrence of chatter, the servodamper control system was designed in terms of output feedback control theory, and the optimum control law was presented to achieve the improvement of dynamic stiffness of the structure. Finally, with the overhang length of the ram, $l = 1600$ mm, a cutting experiment was conducted, resulting in the occurrence of an impetuous chatter with the maximum amplitude of the vibration X_{max} ranging from 50 μm to 80 μm in the case where the servodamper was not driven; however, just as in the case of the model cutting experiment which preceded this experiment, the chatter was subdued precipitously to 5~10 μm in X_{max} , and the chatter marks disappeared as well. Furthermore, the maximum roughness in surface finish R_{max} was also improved to one-third to one-fifth of that of the uncompensated case so that the working efficiency and the working precision were successfully enhanced.

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