Active Chatter Suppression of Slender Boring Bar Using Piezoelectric Actuators*

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The chatter suppression described in this paper is based on the application of active dampers to a slender boring bar. Chatter vibration signals detected by a pickup are fed to a computer. After calculating the chatter frequency and the corresponding phase shift parameter, the computer supplies the amplified signals to piezoelectric actuators with the same phase as that of the vibration velocity of the boring bar. As a result of this, the actuators generate damping forces; that is, they act as active dampers. It has been confirmed in cutting tests that the active damping system adapts to change and fluctuation of the chatter frequency and suppresses chatter well. Furthermore, it has become clear that there is an optimum position of the active damper for chatter suppression.

**Key Words**: Chatter Vibration, Cutting Tool, Damper, Boring Bar, Chatter Suppression, Piezoelectric Actuator, Surface Roughness

1. Introduction

Piezoelectric actuators are now widely applied to ultraprecision turning machines and high-precision X-Y stages[^1][^2][^3]. In these fields, piezoelectric actuators are used as micropositioning elements since they have excellent positioning accuracy. On the other hand, these actuators are used as active dampers, that is, elements for vibration suppression in this study, making use of the characteristics of high-frequency response and ease of control.

Self-excited chatter vibrations frequently occur in boring operations due to the low stiffness and low damping property of a slender boring bar itself. When chatter vibrations occur in boring operations, they degrade accuracy, productivity and surface integrity. Representative suppression methods of chatter vibrations are the application of high-stiffness or high-damping property material to the boring bar and the use of a dynamic damper[^4][^5][^6]. In these cases, the vibration energy is dissipated passively. Therefore, these passive methods are effective only under limited conditions.

As for other suppression methods, there are active control methods. Comstock[^6] first proposed active control in turning. In this case, the cutting edge position was controlled by the feedback of the relative displacement of the cutting edge to the workpiece. Thus, this method can be referred as “cutting edge position control.” On the contrary, the active damping system proposed by us[^7] is a “vibration velocity control system.” This system creates damping forces in response to the vibration velocity of the cutting edge. In this study, the proposed system is improved for practical use; that is, the system is afforded flexibility adaptive to change of chatter vibration characteristics, by using a computer.

2. Chatter Stability Analysis for Boring Bar with Directionality

A boring bar has directionality in dynamic characteristics if dampers are attached to it. Therefore, it
is assumed in this study that the boring bar has two degrees of freedom (Fig. 1). The chatter stability of the boring bar is analyzed by the regenerative feedback loop, including the cutting process and the structural dynamics, since the stability limit calculated by the regenerative chatter theory is lower than that obtained by the coupled oscillation theory. In orthogonal cutting, the instantaneous uncut chip thickness \( u(s) \) is expressed using the nominal depth of cut \( u_0(s) \) and the displacement of the tool \( y(s) \):

\[
u(s) = u_0(s) - y(s) + \mu e^{-\eta y(s)},
\]

where \( s \) is the operator in Laplace transformation and \( \mu \) is the overlap factor. When the undulation on the workpiece's surface is cut by the cutting tool which vibrates in the direction normal to the surface, the resultant cutting force \( F(s) \) can be expressed using both the instantaneous uncut chip thickness and the penetrating velocity of the tool in the \( y \)-direction as

\[
F(s) = k_c u(s) - k_{sp} y(s),
\]

where \( k_c \) is the static cutting stiffness and \( k_{sp} \) is the coefficient of dynamic cutting force. Using the structural dynamics in the \( \xi_1 \) - and \( \xi_2 \) -directions, the displacement of the cutting tool is given by

\[
y(s) = F(s)G_1(s)\cos(\theta - \eta)\cos \theta 
+ G_2(s)\sin(\theta - \eta)\sin \theta,
\]

where

\[
G_{1,2}(s) = \frac{1}{k_{s1,2} + \frac{s^2}{\omega_{1,2}^2} + 2\xi_{s1,2}\frac{s}{\omega_{1,2}} + 1}.
\]

The chatter stability limit is determined using Eqs. (1)-(3), as

\[
\text{Re}\left[ \frac{k_c G_m(s)}{1 + k_{sp} G_m(s)} \right]_{\text{min}} = -\frac{1}{2},
\]

where

\[
G_m(s) = G_1(s)\cos(\theta - \eta)\cos \theta 
+ G_2(s)\sin(\theta - \eta)\sin \theta.
\]

In order to obtain higher stability, it is necessary to decrease the dynamic compliance \( G_m(s) \), namely, increase the stiffness and/or the damping ratio of the boring bar. We intend to obtain a high damping ratio by actuating the active dampers.

Calculated results of the chatter stability in orthogonal cutting are shown in Fig. 2. These results have been obtained by changing only the damping ratio \( \xi_1 \) in the \( \xi_1 \) -direction. The damping ratio, 0.012, is obtained in the experiment without the active dampers. The other three damping ratios are those obtained when the dampers are operated. The ordinate expresses the dimensionless critical width of cut which is divided by the critical width of cut of the solid boring bar. From this figure, it can be seen that high stability is obtained by operating the active dampers if the boring bar is set in an appropriate principal mode direction.

3. Active Damping System for Slender Boring Bar

3.1 Chatter suppression method

In general, the vibration mode of a slender boring bar is primary bending vibration since chatter frequency is close to the lowest natural frequency of the boring bar. Let us consider that at the moment, the boring bar illustrated in Fig. 3 is deflected downward. The piezoelectric actuators attached to the lower side are then elongated by applying voltage. As a result of this, the downward vibration is suppressed. When the boring bar deflects upward, the vibration is prevented by applying voltage to the upper-side actuators. One should note that the voltage is applied with the same phase as the vibration velocity, not the vibration displacement, of the cutting edge.

Figure 3 shows the block diagram of the driving system with the piezoelectric actuators acting as active dampers. Vibration signals detected by a sensor (accelerometer) are amplified and fed to a computer through an A/D converter. In the computer, the signals are delayed so that their phase will coincide.
with the phase of the vibration velocity. These signals are fed to driving amplifiers through a D/A converter and amplified eighty times. Afterwards, they are supplied to the piezoelectric actuators.

The chatter frequency depends on the dynamic characteristics of the boring bar and fluctuates even during boring. Therefore, it is essential to control the dampers in response to the changing chatter vibration. In this study, the problem is overcome by using an adaptive system with a computer, as follows. If the chatter frequency changes or fluctuates, the computer which always monitors the chatter vibration instantly detects the change. After the computer calculates a phase shift parameter for a time delay so as to generate damping forces whose phase coincides with the phase of the vibration velocity, it supplies the modified signals to the D/A converter. This adaptive control method is essential to this study. The computer program for this control is written in the widely used C language.

3.2 Boring bar used in experiment

Eight piezoelectric actuators are attached to the boring bar (material: JIS S45C) as the active dampers, as shown in Fig. 4. One piezoelectric actuator consists of about one hundred thin piezoelectric ceramic plates. The four piezoelectric actuators on each side of the boring bar compose one active damper. Thus, there are two active dampers in the boring bar. This boring bar has the following dynamic characteristics in the direction of the thrust cutting force: the stiffness of 0.61 MN/m, the damping ratio of 0.012 and the natural frequency of 195 Hz.

4. Experimental Results in Cutting Tests

Several turning tests were carried out since the aim of this study is to investigate the effectiveness of the proposed system on chatter suppression. In these tests, a throw away tip (sintered carbide, P 20) was used as a cutting edge. The tool geometry is (0, 0, 11, 15, 15, 0.4). The workpiece material is carbon steel (JIS S55C).

4.1 Effect of active dampers on vibration amplitude and power spectrum

Figure 5 is an example of the chatter vibrations occurring in boring operations. The amplitude of the vibration acceleration is very large, as shown in Fig. 5(a). The power spectra shown in Fig. 5(b) have a sharp peak at the frequency of 255 Hz. Figure 6(a) shows the process of damping chatter vibrations when the active dampers are driven. Figure 6(b) shows the rapid change of the actual charge, that is, the voltage applied to a piezoelectric actuator. Vibration control is begun by the computer at T = 255 ms. It is seen in these figures that the chatter vibrations are suppressed considerably about 30 ms after vibration control is initiated.

Vibration with a small amplitude, however, begins at T = 310 ms. This vibration has a frequency different from that of the chatter vibration just suppressed. The computer instantly responds to this vibration and drives the active dampers according to the algorithm mentioned in section 3.1. After such a damping process was repeated several times, the vibrations were almost completely suppressed, as shown in Fig. 7. Then the power of the vibrations decreased more than 20 dB.

4.2 Influence of applied voltage gain on chatter suppression process

The ratio of the applied voltage to the piezoelectric actuators to the detected vibration signal affects the chatter suppression process. Therefore, the influence of the applied voltage gain was
investigated for several amplification factors in the driving amplifiers.

Figure 8 shows the process of the decrease of the power spectra of the vibrations. In this figure, "T = 0 s" corresponds to the beginning of the chatter suppression operation and the dot-dash-line (P = −15 dB) to the extinguishment of chatter vibration. It is seen in this figure that the chatter vibration cannot be suppressed fully in the cases of gain = 40 and 48. When
Fig. 9 Effect of active dampers on chatter stability

Fig. 10 Profile curves of machined surface (V=100 m/min, u_n=0.04 mm, f=0.25 mm/rev, R=0.4 mm)

(a) Without dampers (b) With dampers

Fig. 11 Boring bar used to examine the influence of position of active dampers

Fig. 12 Influence of position of active dampers on chatter stability

The effect of the dampers on the surface roughness of the machined surface is shown in Fig. 10. The left figure, (a) shows the profile curve obtained without the active dampers. The surface roughness, R_max is about 70 \( \mu \)m. It is seen from this figure that some of the original surface of the workpiece remains. On the contrary, the surface roughness is small when the dampers are driven, as shown in the right figure, (b). The surface roughness in this case, 35 \( \mu \)m, includes the expected surface roughness, 20 \( \mu \)m. Therefore, it can be said that the integrity of the machined surface is improved considerably by the active dampers.

4.4 Influence of position of active dampers on chatter stability

Finally, the influence of the position of the active dampers on the chatter stability was examined experimentally. Four piezoelectric actuators are attached to the boring bar at position “X”, as shown in Fig. 11. In the experiments, four positions (X/L=0.13, 0.33, 0.53 and 0.73; L is the overall length) were chosen as the positions of the active dampers.

The results obtained are shown in Fig. 12. It is obvious in this figure that the chatter stability is increased considerably by using the active dampers, except for the case of X/L=0.73. Furthermore, it is seen that there is an optimum position of the active dampers, which is about X/L=0.3 for this boring bar.
5. Conclusions

A new type of boring bar with active dampers driven by a computer was proposed. The effectiveness of the active dampers was investigated through several experiments. The results obtained are as follows. (1) The proposed boring bar system is adaptive to fluctuation of the chatter frequency under various cutting conditions. (2) The system has a strong effect on chatter suppression. That is, two or five times higher stability is obtained by using the active dampers. (3) The system improves the integrity of the machined surface. (4) The optimum position of the active dampers is at about $X/L = 0.3$.

References


