A Study of the Vibrationless Forge Hammer*

(Verification of the Pole-Zero Vibration Control Method)

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In order to enhance a control effect for suppressing an impact vibration, a new active vibration control method, that is, a pole-zero active vibration control method, was proposed by the authors. It is the purpose of this paper to realize the vibrationless forge system with the pole-zero active control and to verify the capabilities of the proposed method. First, this paper investigates the control effect of a pole control method constructed by using a feedback control. Then, adding a zero control method in terms of a feedforward control to the system, the pole-zero active control method is realized, and its effectiveness for the suppression of impact vibration is demonstrated. Next, with a view to clarifying the robustness of the control system, the effects of experimental conditions such as test-piece material and dropping stroke of a hammer-head are discussed.

Key Words: Shock, Impact Vibration, Active Control, Feedforward-Feedback Control, Pole-Zero Active Force Control

1. Introduction

In the past, quite a few efforts^{(1)~(4)} have been made to isolate the vibration transmission from machines to the ground and vice versa. Among them, the most typical measure is to use a spring support. This method can be realized by simple mechanism; however, it contains undesirable aspects. For instance, as a result of applying the spring support method to a vibrating machine, the machine itself also vibrates, so that dimensional accuracy, machine life and productivity are not only diminished, but even the machine itself becomes an oscillating source causing vibration.

In order to overcome these defects, the authors have proposed a pole-zero active vibration isolation method⁽⁵⁾, superior to the conventional active vibration isolation method in the references^{(6)~(8)}. The optimal design procedure of the vibrationless forge sys-

tem with the pole-zero control was also shown.

It is the purpose of this paper to realize the pole-zero active vibration control system and to verify the capability of the newly proposed system experimentally. First, this paper conducts an experiment to demonstrate the control effect of a pole control method based upon a feedback technique, the characteristics of the system being investigated. Next, adding a zero control method based upon a feedforward technique to the vibrationless forge system, the control effect for suppressing the impact vibration is clarified.

In an actual forging process, the magnitude of an impact force depends upon a work hardening, manipulation of a petal, materials of works, etc.. Taking into consideration the variable conditions in a forging operation, this paper deals with various types of impact forces produced by changing a dropping stroke of a hammer head as well as a material of a test piece, the influence on the control effect being discussed. In addition, it is also anticipated that in the actual case the weight of an anvil varies because works with various weights will be set on the anvil, with the result that the characteristics of an anvil and support system

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will be changed. Therefore in the impact experiment, the influence of varying vibratory characteristics on the hybrid control effect is also considered.

2. Experiment of a Pole-Zero Vibration Control System

2.1 Experimental setup

A pole-zero vibration control method consists of a feedback control and a feedforward control. Figure 1 shows a block diagram of the vibrationless forge system with the pole-zero control method. With respect to the feedback control method, a signal of an anvil displacement is used for constructing the feedback loop.

In the impact test, a hammerhead weighing 28 kg is dropped from an arbitrary height, hitting a test piece on an anvil supported by four coil springs. Under each coil spring, a force transducer is set to measure the transmitted force f_t , with a maximum measured force of 200 kN and resonant frequency of 45 kHz. Two kinds of anvils weighing 488 kg and 309 kg are provided, the corresponding resonant frequencies being 20.9 Hz and 26.3 Hz, respectively. An active controller is mounted on the back of the anvil.

An impact force f_{im} is measured by a force transducer set between a test piece and an anvil, with a maximum measured force of 400 kN and resonant frequency of 30 kHz. An anvil displacement, the signal of which is used for constructing a feedback loop, is detected by an optical sensor, and its signal is entered into an analog computer where a feedback element $G_b(s)$ is programmed to obtain a feedback signal u_b . Likewise, the signal in terms of an impact force f_{im} is entered into the analog computer to make a feedforward signal u_f . Furthermore, the sum of these signals ($u_b + u_f$) is fed into a servo amplifier, and is transformed into an electric current to control a servo valve driving the active controller.

2.2 Experimental conditions

With regard to the feedback element $G_b(s)$

Fig. 1 A block diagram of the pole-zero vibration control system

presented in the previous paper [1], its fundamental form is nearly the same as that of a pure integrator, so its gain will be too large for an actual system. Therefore, $G_b(s)$ is modified as an approximate integrator so as to make the gain low, that is,

$$G_b(s) = \gamma_b + \frac{\beta_{b-1}s^{b-1} + \dots + \beta_1s + \beta_0}{(s + \omega_0)^b} \dots\dots\dots (1)$$

In the experiment, the order b of the feedback element up to 3 is used, while the value of the breakpoint frequency ω_0 is fixed to 10π rad/s.

As long as the feedforward element $G_f(s)$ is concerned, it is reported [1] that a sufficient control effect is obtained by using the 2nd order of the dynamic compensator, so that we take the same type of the feedforward element presented in the reference, that is,

$$G_f(s) = \gamma_f + \frac{\beta_1s + \beta_0}{(s + \omega_0)^2} \dots\dots\dots (2)$$

where ω_0 is set at 10π rad/s.

Table 1 shows the values of the optimal parameters of $G_b(s)$ and $G_f(s)$, and the control effect f_{ip} corresponding to the mean square of the transmitted force f_t .

3. Verification of a Pole-Zero Vibration Control Effect

With a view to verifying the capabilities as well as the feasibility of the pole-zero vibration control method, an experiment was carried out. In the impact experiment, a hammer-head was dropped from a height of 20 cm, hitting a test piece (70 mm in diameter and 5 mm thick) made of hard rubber which was placed on an anvil. First, the control effect for suppressing the transmitted force f_t was verified by the pole control method. Then, adding a zero control method to the system, the pole-zero vibration control method was applied. It proved to be effective in eliminating the impact vibration.

As noted in the previous section, the transmitted force f_t is measured by four force transducers, although the waveforms depicted in the figures represent only one of these measurements. With regard to the control effect f_{ip} , the value obtained by experiment should be multiplied by 16 in order to be comparable with the analytical value. Because the transmitted force illustrated in the figures is a quarter of the total force, the control effect f_{ip} referring to the transmitted power becomes 1/16 of the resultant power.

3.1 Verification of the pole vibration control method

Based on the design parameters shown in Table 1, the feedback element $G_b(s)$ was constructed. Figure 2 illustrates the experimental results of transmitted forces suppressed by the pole vibration control

Table 1 Values of optimal design parameters and the control effect

Type	f_{tp} ($\text{kN}^2\cdot\text{s}$)	$G_b(s)$				$G_c(s)$		
		γ_b	β_0	β_1	β_2	γ_c	β_0	β_1
$b=1, f=0$	0.2322	4.085×10^2	2.944×10^4					
$b=2, f=0$	0.1676	5.160×10^2	5.325×10^4	8.769×10^3				
$b=3, f=0$	0.1613	5.429×10^2	2.227×10^4	7.462×10^4	5.409×10^3			
$b=1, f=2$	0.1153	4.085×10^2	2.944×10^4			8.264×10^{-6}	3.260×10^{-1}	6.995×10^{-4}
$b=2, f=2$	0.0744	5.160×10^2	5.325×10^4	8.769×10^3		7.977×10^{-6}	3.339×10^{-1}	1.023×10^{-3}
$b=3, f=2$	0.0694	5.429×10^2	2.227×10^4	7.462×10^4	5.409×10^3	7.900×10^{-6}	3.296×10^{-1}	1.112×10^{-3}

Fig. 2 Suppression of transmitted forces in terms of the pole control method

Fig. 3 Force transmissibility using the pole control method

method. In the case without control, an impact vibration was observed, with a maximum amplitude $f_{t \max}$ of 1.675 kN and f_{tp} of 1.775 $\text{kN}^2\cdot\text{s}$. By applying the pole control method ($b=1\sim 3$), such a violent vibration was suppressed and the residual vibration vanished. It can be seen that as the order b of the feedback element increases, f_{tp} decreases. For instance, in the case of $\{b=3, f=0\}$, f_{tp} is suppressed to 0.153 $\text{kN}^2\cdot\text{s}$, while the analytical value is 0.16 $\text{kN}^2\cdot\text{s}$, showing a good agreement. Figure 3 gives the force transmissibility for this case. As is clear from the figure, the resonant peak at 20.9 Hz is completely suppressed by the pole control method; however, the increment of a spectrum at around 65 Hz becomes prominent due

Fig. 4 Suppression of transmitted forces in terms of the pole-zero control method

Fig. 5 Force transmissibility using the pole-zero control method

to an excessive feedback gain, leading to an instability of the system. This phenomenon is reflected in the transmitted force as shown in Fig. 2.

3.2 Verification of the pole-zero vibration control method

Adding a feedforward element to the feedback control system, a pole-zero control method was established. Using the pole-zero vibration control method, the suppression of an impact vibration was achieved as shown in Fig. 4. In this figure, the amount of f_{tp} experimentally obtained over each waveform is shown. The results show a high degree of agreement between the experimental and analytical values. In the cases of both $\{b=2, f=2\}$ and $\{b=3, f=2\}$, for

instance, experimental values turn out to be somewhat larger than the analytical ones. This is because the noise-to-signal ratio tends to be higher when the transmitted force is completely suppressed as shown in Fig. 4. As a result, the accuracy in calculating f_{tp} deteriorates, so that in such a case the experimental value is likely to be larger than the analytical one.

The force transmissibility using a pole-zero vibration control method is illustrated in Fig. 5. As can be seen, the main role of the pole control method is to suppress the resonant peak at 20.9 Hz, while that of the zero control method is to eliminate the force spectra in the wide frequency range of 7 to 80 Hz. Note that the spectrum increased at around 65 Hz due to the pole control being suppressed by 10 dB, so that the influence of the phenomenon on the waveform of the transmitted force cannot be seen. As a result, the amount of f_{tp} is decreased to $0.081 \text{ kN}^2\cdot\text{s}$, a 47.1 percent reduction from that of the case of $\{b=3, f=0\}$, and $f_{t \max}$ from 1.057 kN to 0.768 kN, corresponding to a reduction of 27.3 percent. Figure 6 shows state variables of the pole-zero vibration control system in

Fig. 6 State variables in terms of the pole-zero control method

Fig. 7 Waveforms of impact force with a number n of impact times ($h=30 \text{ cm}$)

the case of $\{b=3, f=2\}$, such as displacement x of the anvil, displacement x_d of the mass of the active controller, and control signal u .

4. Pole-Zero Control Effect under Impact Conditions

4.1 Effect of the number of impacts

In this section, the effect of a varying impact force f_{im} due to the number, n , of impacts is investigated. For this purpose, the test piece made of hard rubber was replaced by one made of lead (50 mm in diameter and 20 mm thick) and the dropping stroke of the hammerhead was set at 30 cm.

Experimental results with $n=1, 5$ and 10 are shown in Fig. 7. It is clear from these results that in the initial impact, the shape of the impact force appears like a sawtooth waveform; however, in the cases of $n \geq 2$, those shapes are completely different from the initial one. In the case of $n=10$, for instance,

Fig. 8 f_0 and $f_{im \max}$ versus n

Fig. 9 Suppression of transmitted forces in terms of the pole-zero control method with n

the rising of the waveform becomes extremely sharp, and the duration of the impact force is reduced by half of that at $n=1$. The maximum value of $f_{im\max}$ increases by nearly 2.5 times, from 50.2 kN to 125.4 kN. Figure 8 gives an $f_{im\max}$ and f_0 versus n plot. It is clear from the figure that as n increases, so does $f_{im\max}$; however, f_0 increases little, with only a 20 percent difference between $n=1$ and 10.

Next, let us investigate the effect of the fluctuation of f_{im} . Waveforms of transmitted forces with and without control are illustrated with $n=1, 5$ and 10 in Fig. 9. As can be seen, the residual vibration is completely suppressed in each case; however, the evaluating degree of improvement in the control effect decreases as n increases. If the ratio of f_{ip} with control to that without control is evaluated, it is 5.3 percent for $n=1$, however, 5.84 percent for $n=5$, and 7.73 percent for $n=10$. With regard to $f_{i\max}$, it does not change as much as f_{ip} with increased n , however, the ratio of f_{ip} values with and without control slightly increases as 50.3 percent, 51.5 percent, 54.6 percent for $n=1, 5$ and 10.

4.2 Effect of height of a hammerhead

In this section, the pole-zero control effect under the condition that height h of a hammerhead is varied from 10 cm to 100 cm is investigated. A test piece made of lead was used and the number of impacts in

Fig. 10 Waveforms of impact force with a dropping stroke h ($n=1$)

Fig. 11 f_0 and $f_{im\max}$ versus h

this case is one. Figure 10 shows waveforms of impact force f_{im} with a parameter h . Unlike the previous case where n increased the maximum value $f_{im\max}$ of the impact force increases, while the duration of the impact force remains near 2.4 ms. As a result, impulse f_0 increases. The values of f_0 and $f_{im\max}$ versus h are plotted in Fig. 11. Evidently, as h increases, so do these values increase. For example, the value of $f_{im\max}$ is 79.98 kN at $h=100$ cm, which is 63.8 percent of the corresponding value shown in Fig. 8; however, the value of f_0 becomes 121.6 N·s, that is, 1.47 times larger than that in Fig. 8.

Figure 12 shows the pole-zero control effect in the case of $\{b=3, f=2\}$ obtained by changing dropping stroke h as 10 cm, 50 cm and 100 cm. In all cases, the residual vibrations disappear, however, the control effect in the case of $h=100$ cm considerably deteriorates, and f_{ip} becomes 14.7 percent of that without control. To see this more clearly we proceed as

Fig. 12 Suppression of transmitted forces in terms of the pole-zero control method with a dropping stroke h

Fig. 13 Force transmissibility in terms of the pole-zero control method ($h=100$ cm)

follows. Figure 13 shows the force transmissibility in the case of $\{b=3, f=2\}$. As is obvious from the figure, the resonant peak at 20.9 Hz is completely suppressed, and the increment in gain at around 65 Hz is not observed. Thus, the pole control works significantly. Therefore, despite the fact that the control signal with a large amplitude due to a big stroke such as $h=100$ cm, induces a fluctuation in the system parameters, the pole control still maintains the control effect.

On the contrary, as zero control does not possess the capability of compensating for the fluctuation in the system parameters, a notch effect characterizing the zero control method becomes prominent at 13 Hz, with the result that the control effect for suppressing force spectra in a wide frequency range diminishes.

4.3 Effect of the natural frequency of the anvil and support system

In an actual forging process, it is conceivable that a natural frequency f_n of an anvil and support system varies because of the variety of workpieces placed on the anvil. Therefore, in this section, the influence of natural frequency on the pole-zero control effect is investigated. For this purpose, the 488 kg anvil is replaced with the 309 kg so as to change the natural frequency from 20.9 Hz to 26.3 Hz. As for the test piece, hard rubber is used, and h is set at 20 cm.

Figure 14 shows the impact vibrations with and without the pole-zero vibration control method $\{b=3, f=2\}$, where the design parameters for the former case, where the natural frequency is 26.3 Hz, are used. As for f_{tp} , in the case of no control, it becomes $3.537 \text{ kN}^2\cdot\text{s}$ larger than in the former case, due to the increase in f_n . However, compared with the control effect attained in sections (4.1) and (4.2), the suppression of the impact vibration is not sufficient. Since the weight of the anvil is decreased, the mass ratio of the active controller to the anvil becomes less, so that the amount of control law in the former case turns out to be excessive in the present system, deteriorating the stability of the control system.

Fig. 14 Pole-zero control effect with a change of a natural frequency of an anvil and support system

The waveform on the right in Fig. 15 shows the impact vibration obtained by reducing the loop gain to 70 percent. Seen from this figure, the spectrum around 65 Hz completely vanishes, and f_{tp} becomes $0.122 \text{ kN}^2\cdot\text{s}$, equivalent to a 31 percent improvement over the control effect in Fig. 14. Applying the control law with less gain than in the former case, the control effect is obtained as shown on the left side of Fig. 15. As far as the waveforms in Figs. 14 and 15 are concerned, there seems to be little difference between them, although f_{tp} becomes $0.109 \text{ kN}^2\cdot\text{s}$, corresponding to a 34.6 percent increase over the former one.

In all previous papers (4, 6, 8) and in the previous one, f_{tp} has consistently been used as the performance index referring to the transmitted power from a machine to soil. As pointed out in section (3.1), however, the control law determined by minimizing the index f_{tp} might not be suitable for the stability of the control system. Therefore, in the near future a performance index taking into consideration both the stability and the control effect should be introduced for the design of a vibrationless forge hammer.

5. Conclusions

In order to enhance a control effect for suppressing impact vibration, a new control method, namely, the pole-zero vibration control method was presented, and its capabilities verified through experiments. Specific conclusions are as follows:

(1) Using the pole control method, an impact experiment was carried out to demonstrate the effectiveness for suppressing the impact vibration in the case of $b=1\sim3$. For instance, f_{tp} was reduced to $0.153 \text{ kN}^2\cdot\text{s}$ from $1.755 \text{ kN}^2\cdot\text{s}$ using the pole control method $\{b=3, f=0\}$, and thus agreed well with the analytical value of $0.161 \text{ kN}^2\cdot\text{s}$.

(2) By adding a zero control method to the system, the control effect was further improved. In the case of $\{b=3, f=2\}$, for instance, f_{tp} was decreased by 47.1 percent. It was also clarified that the role of the pole control is to suppress the resonant peak at 20.9 Hz, while the zero control reduces the force transmissibility in a wide frequency range of 7 to 80 Hz.

(3) With a view to investigating the influence of

Fig. 15 Pole-zero control effect with a loop gain of 70 percent

a work hardening on the control effect, a test piece made of hard rubber was replaced with that made of lead, and the number n of impacts was varied from 1 to 10. As a result, if the number of impact times increases, f_0 varies little, however, $f_{im\max}$ increases 2.5 times that in the case of $n=1$. By using the pole-zero control method, the impact vibration is suppressed despite the change of n , although the control effect deteriorates somewhat as n grows.

(4) Given that a hammerhead is dropped from such a high position as 100 cm, the pole control method was proven to maintain the capability of suppressing a resonant peak. On the contrary, the control effect in terms of the zero control method deteriorates due to the fluctuation of system parameters.

(5) It was shown that from a viewpoint of stability, the control law obtained by minimizing f_{ip} tends to act on the system with excessive loop gains.

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