Development of an Active Attenuator for Pressure Pulsation in Liquid Piping Systems* (Trial Construction of the System and Fundamental Experiments on Attenuation Characteristics)

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A new technique of an active attenuator for pressure pulsation in liquid piping systems, which detects the progressive wave component of fluid-borne vibration and then controls the second source feedforwardly by this detected signal so as to completely eliminate the progressive wave in its downstream pipe by producing the canceling fluid vibration, has been presented, together with experimental results. As a preliminary investigation in this study, an experiment on the attenuation characteristics has been carried out for only the simple harmonic fluid vibration, though the present active attenuator using the transfer-function-based control method is also applicable to the wide-band random fluid vibration. A general-purpose digital signal processor has been used for the high-speed operation of converting the pressure difference signal produced by two pressure transducers into the progressive wave signal of fluid vibration and for the successive operation of producing the control signal to the second source (electrohydraulic servo cylinder). It was confirmed by the test in a model experimental pipeline that, when the present control system was operated, the pressure pulsation in a downstream pipe of the second source was reduced, as expected, to about 1/10 to 1/15 (that is, a transmission loss of about 20 to 25 decibels) of that in the case where the control system was not used over the frequency range of 20 to 250 Hz.

Key Words: Pulsation, Fluctuating Pressure, Noise, Vibration Control, Fluid-Borne Noise, Active Attenuator, Active Noise Control, Digital Signal Processor

1. Introduction

An active pulsation control technique based on Huygens' principle has made rapid progress on the basis of recent advances in microelectronics; some of their techniques are now at the practical application stage in the field of noise control in an air-conditioning duct⁽¹⁾⁻⁽⁶⁾. These active pulsation control techniques are divided into the following two classes from the signal processing point of view: the wave-synchronism-based control method for the periodic harmonic pulsation and the transfer-function-based control method for the wide-band random pulsation.

In a previous paper⁽⁷⁾, two of the present authors proposed a real-time measurement method for the progressive wave of the pulsation in a pipe, which is

necessary for the development of a sophisticated active attenuator of pressure pulsation in liquid piping systems, and confirmed by an experiment that it could be measured in real time with sufficient accuracy for practical usage.

This paper presents a newly devised sophisticated active attenuator for pressure pulsation in liquid piping systems, which detects the progressive wave component of fluid-borne vibration and then controls the second source feedforwardly by this detected signal so as to completely eliminate the progressive wave in its downstream pipe by producing the canceling fluid vibration, and examines its attenuation performance by using a small-sized model experimental pipeline. Although the present active pulsation control technique has been devised for the attenuation of pressure pulsation in liquid piping systems such as stock piping systems of paper-making machines, it can also be used for noise control in air-conditioning ducts by replacing the pressure transducer and servo

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actuator (second source) with a microphone and loud-speaker, respectively.

2. Nomenclature

- A_c : Cross-sectional area of the servo actuator (second source)
 A_p : Cross-sectional area of the pipe
 c : Speed of sound in the fluid in the pipe
 f : Frequency of the pulsation
 $f_1(t, x)$: Progressive wave of the fluid velocity pulsation at time t and position x
 $F_1(s, x)$: Laplace transformation of $f_1(t, x)$
 $f_2(t, x)$: Regressive wave of the fluid velocity pulsation at time t and position x
 $G_a(s)$: Transfer function of the servo actuator
 $G_c(s)$: Transfer function of the controller
 $[=G_s(s) \cdot G_a(s)]$
 $G_c^*(s)$: Target (desired) characteristics of $G_c(s)$
 $G_{c,p}(s)$: Transfer function of $P(s, x)$ to $U_c(s)$
 $G_{c,w}(s)$: Transfer function of $W(s)$ to $U_c(s)$
 $G_s(s)$: Transfer function of the signal processor
 $G_s^*(s)$: Target (desired) characteristics of $G_s(s)$
 $G_{w,p}(s)$: Transfer function of $P(s, x)$ to $W(s)$
 K : Gain factor set up in the signal processor [see Eq. (28)]
 l : Length of the pipe (with regard to the suffix, see Fig. 1)
 $p(t, x)$: Pressure pulsation at time t and position x
 R_f : Resistance factor of the pipe flow ($=8\nu/r_0^2$)
 r_0 : Inner radius of the pipe
 s : Laplace operator
 t : Time
 $u(t, x)$: Cross-sectional average fluid velocity at time t and position x
 $u_c(t)$: Cross-sectional average fluid velocity at the second source
 $u_s(t)$: Cross-sectional average fluid velocity at the original source
 $v_c(t)$: Velocity of the servo actuator
 $w(t)$: Output signal of the detecting element
 x : Coordinate of the pipe from the original source
 x_0 : x coordinate of the intermediate point between two pressure transducers
 $y_c(t)$: Displacement of the servo actuator
 $z(t)$: Control signal of the servo amplifier
 Z_0 : Characteristic impedance of the pipe ($=\rho c$)
 ν : Kinematic viscosity of the fluid
 $\xi(s)$: Wave propagation coefficient of the pipe
 ρ : Fluid density
 τ : Wave propagation time ($=l_1/c$)
 τ_e : Delay time set up in the DSP
 ω : Angular frequency of the pulsation

3. The Outline of an Active Attenuator for Wide-Band Random Pressure Pulsation in a Pipe

3.1 Fundamental principle and basic theory

Various systems of active attenuators for wide-band random pressure pulsation using the transfer-function-based control method have been devised in the field of noise control in an air-conditioning duct. However, the fundamental constitution of all systems is the same and can be shown by a diagram, as in Fig. 1. That is, all the systems are designed to control the second source feedforwardly so as to completely eliminate the pressure pulsation in its downstream pipe by producing the canceling fluid vibration, using any state variable of pressure pulsation detected by the pressure sensor (microphone). Therefore, the characteristics of the signal processor are determined so that the second source generates the 180° out-of-phase wave of the same intensity as the progressive wave propagating from the original source, taking into consideration the fluid wave propagation characteristics in the pipe and the dynamic characteristics of the second source including the servo amplifier. In this paper, the desired characteristics of the signal processor which should be set up are called the target characteristics.

If we assume the original source to be a flow pulsation source generating the cross-sectional average fluid velocity of $u_s(t)$, and let fluid velocity at the second source connected to the pipe with a branch be $u_c(t)[=v_s(t)]$, the output signal from the detecting element (in other words, input signal to the signal processor) be $w(t)$ and pressure pulsation at the position of x be $p(t, x)$, the mathematical model of the system can be represented in the Laplace domain as follows:

$$U_c(s) = G_c(s) W(s) \quad (1)$$

$$W(s) = G_{s,w}(s) U_s(s) + G_{c,w}(s) U_c(s) \quad (2)$$

$$P(s, x) = G_{s,p}(s) U_s(s) + G_{c,p}(s) U_c(s). \quad (3)$$

These equations produce the relationship between

Fig. 1 Fundamental constitution of an active attenuator for the wide-band random pulsation in a pipe

$P(s, x)$ and $U_s(s)$:

$$P(s, x) = \{ [G_c(s)G_{c,p}(s)G_{s,w}(s) + G_{s,p}(s) - G_c(s)G_{c,w}(s)G_{s,p}(s)] / [1 - G_c(s)G_{c,w}(s)] \} U_s(s). \quad (4)$$

Hence, the target characteristics of the controller which result in a $P(s, x)$ of zero can be obtained as follows:

$$G_c^*(s) = \frac{G_{w,p}(s)}{G_{c,w}(s)G_{w,p}(s) - G_{c,p}(s)}. \quad (5)$$

On the other hand, if we let the fluid velocity pulsations and the pressure pulsations at the upstream end and downstream end of the pipe element of length L be $U_u(s)$, $P_u(s)$ and $U_d(s)$, $P_d(s)$ respectively, the following relationships between these variables are found:

$$U_d(s) = \cosh \left\{ \frac{s\xi(s)L}{c} \right\} U_u(s) - \frac{1}{\xi(s)Z_0} \times \sinh \left\{ \frac{s\xi(s)L}{c} \right\} P_u(s) \quad (6)$$

$$P_d(s) = -\xi(s)Z_0 \sinh \left\{ \frac{s\xi(s)L}{c} \right\} U_u(s) + \cosh \left\{ \frac{s\xi(s)L}{c} \right\} P_u(s) \quad (7)$$

where the wave propagation factor, $\xi(s)$, is given by the following equations depending on the flow condition:

$$\left. \begin{aligned} (1) \quad & \text{Two-dimensional, unsteady and laminar flow}^{(8)}: \\ & \xi(s) = [1 - 2J_1\{j\gamma_0(s/\nu)^{1/2}\} / j\gamma_0(s/\nu)^{1/2} \\ & \quad \times J_0\{j\gamma_0(s/\nu)^{1/2}\}]^{-1/2} \\ & \quad \approx 1 + \sqrt{\frac{\nu}{r_0^2 s}} + \frac{\nu}{r_0^2 s} \\ (2) \quad & \text{One-dimensional, steady and laminar flow:} \\ & \xi(s) = \sqrt{1 + 8\nu/r_0^2 s} \\ & \quad \approx 1 + 4\nu/r_0^2 s = 1 + R_f/2s. \\ (3) \quad & \text{Nonviscous flow:} \\ & \xi(s) = 1. \end{aligned} \right\} \quad (8)$$

By substitution of the transfer functions, $G_{c,p}(s)$, $G_{s,w}(s)$, $G_{s,p}(s)$ and $G_{c,w}(s)$ in Eq. (4) and Eq. (5), which are obtained by using Eq. (6), Eq. (7) and the continuity equation at the branch section of the second source (these equations are omitted on account of space considerations), into Eq. (4), the equation for $P(s, x)$ can be reduced to:

$$\left. \begin{aligned} x \leq x_0 + l_1: \\ P(s, x) &= \frac{\xi(s)Z_0 \sinh \{s\xi(s)(x_0 + l_1 - x)/c\}}{\cosh \{s\xi(s)(x_0 + l_1)/c\}} U_s(s) \\ x \geq x_0 + l_1: \\ P(s, x) &= 0. \end{aligned} \right\} \quad (9)$$

That is, the pressure pulsation becomes zero in all of the regions downstream of the second source ($x \geq x_0 + l_1$), as expected, if the controller perfectly satisfies

the target characteristics given by Eq. (5). However, it should be noted that the pressure pulsation of the vibration mode, in which the velocity variation is constant at $x=0$ and the pressure variation is zero at $x=x_0 + l_1$ is generated in the region upstream of the second source, and that the pressure pulsation may often be amplified on the contrary by the second source.

3.2 Stability of the system

The characteristic equation of the system can be derived from Eq. (9) as follows:

$$\cosh \{s\xi(s)(x_0 + l_1)/c\} = 0.$$

If we assume the resistance of the pipe flow to be one-dimensional, steady and laminar in order to simplify the explanation, and then substitute $\xi(s)$ of the second equation in Eq. (8) into the above equation, the following transcendental equation can be derived as a characteristic equation of the system

$$1 + G(s)e^{-2(x_0 + l_1)s/c} = 0 \quad (10)$$

where

$$G(s) = e^{-R_f(x_0 + l_1)/c}. \quad (11)$$

Hence, it can be seen from the Nyquist stability criterion that the system is always stable in the Lyapunov sense independent of the length of the pipe $x_0 + l_1$, frequency of the pulsation ω and speed of sound c , because the vector of $G(j\omega)$ is always located within the unit circle if the flow has any resistance. However, the degree of stability is very low because R_f is commonly very small and thus $|G(j\omega)|$ is very close to unity (i.e., the gain margin is very small). Hence, for the random pulsation, the attenuation of the transient pressure fluctuation is bad, and howling, at frequencies of $(2n-1)c/4(x_0 + l_1)$; $n=1, 2, 3, \dots$, is likely to be generated in the upstream pipe of the second source. In order to prevent this phenomenon, it is necessary to reduce $G_{c,w}(s) [= W(s)/U_c(s)]$, which is the transfer function of $W(s)$ to $U_c(s)$ (i.e., acoustic feedback gain of the wave propagation path in the pipe) to as small an amount as possible. However, the stability problem is beyond the scope of this paper and will be considered in detail in the next paper.

4. The Control Method of the Proposed Active Attenuator

4.1 The control method of the proposed system

The key objectives of the design of an active attenuator for the wide-band random pressure pulsation may be said to be the following: (1) to obtain a good attenuation performance by matching a transfer function of the signal processor with the desired (target) characteristics as precisely as possible and, (2) to prevent howling by increasing the degree of stability. Various techniques for satisfying these required conditions have been devised. The outline

and features of the proposed active attenuator will be explained from the standpoint of the above-described objective (1) in this section, and then the comparison with conventional systems (in the field of active noise control in air-conditioning ducts) will be made in section 4. 2.

The fluid velocity variation $U(s, x)$ and pressure variation $P(s, x)$ at the position of x can be represented in the following forms using a progressive wave component $F_1(s, x)$ and a regressive wave component $F_2(s, x)$ of the fluid velocity variation:

$$U(s, x) = A(s)e^{-s\xi(s)x/c} + B(s)e^{s\xi(s)x/c} \quad (12)$$

$$\equiv F_1(s, x) + F_2(s, x)$$

$$P(s, x) = \xi(s)Z_0\{A(s)e^{-s\xi(s)x/c} - B(s)e^{s\xi(s)x/c}\} \quad (13)$$

$$\equiv \xi(s)Z_0\{F_1(s, x) - F_2(s, x)\}.$$

Hence, the progressive wave component of the fluid velocity variation at the position of x_0 can be expressed in terms of $U(s, x_0)$ and $P(s, x_0)$ as follows:

$$F_1(s, x_0) = A(s)e^{-s\xi(s)x_0/c} \quad (14)$$

$$= \frac{1}{2} \left\{ U(s, x_0) + \frac{P(s, x_0)}{\xi(s)Z_0} \right\}.$$

Furthermore, the relationship between two progressive wave components, $F_1(s, x_0)$ and $F_1(s, x_0 + l_1)$, at the positions of x_0 and $x_0 + l_1$, can be expressed from Eq.(14) as follows:

$$F_1(s, x_0 + l_1) = A(s)e^{-s\xi(s)(x_0 + l_1)/c} \quad (15)$$

$$= F_1(s, x_0)e^{-s\xi(s)l_1/c}.$$

The proposed active attenuator is to be designed to produce a 180° out-of-phase velocity pulsation signal of the same intensity as $F_1(s, x)$ into the downstream pipe by the second source connected to the pipe with a branch, and then to cancel the original $F_1(s, x_0 + l_1)$ (to attenuate the pressure pulsation in the ultimate) in the downstream of the second source. Specifically, the actuator is to be designed to produce the following form of fluid velocity pulsation from the second source corresponding to the signal of $F_1(s, x_0)$ detected at the position of x_0

$$U_c(s) [= V_c(s)] = -2 \frac{A_p}{A_c} F_1(s, x_0) e^{-s\xi(s)l_1/c}. \quad (16)$$

In the case where the pipe with diameter greater than around 100 mm is used as in ordinal piping for plants, the effect of fluid viscosity on the wave propagation in a pipe is relatively small and can be ignored in the practical application, unless fluid with an especially high viscosity is used. In such a case, Eq.(14) and Eq.(16) can be reduced to, respectively,

$$F_1(s, x_0) = A(s)e^{-sx_0/c} \quad (14)'$$

$$= \frac{1}{2} \left\{ U(s, x_0) + \frac{P(s, x_0)}{Z_0} \right\}$$

$$U_c(s) [= V_c(s)] = -2 \frac{A_p}{A_c} F_1(s, x_0) e^{-st}. \quad (16)'$$

In the proposed active attenuator, the progressive wave component of fluid velocity pulsation is mea-

sured in real time by integrating the difference between signals produced by two pressure transducers spaced a suitable distance apart, on the basis of the momentum equation, using a general-purpose digital signal processor. For further details, the reader is referred to the author's previous paper⁽⁷⁾.

4. 2 Control signals and target characteristics of the signal processor in conventional systems and the proposed system

Figures 2 (a) and (b) show the control signals (i.e., detected signals) in conventional systems for noise control in an air-conditioning duct. Of these, system (a) uses one pressure signal for controlling the second source, and system (b) uses two pressure signals where one is delayed by the time of $\Delta x/c$. Figure 2 (c) shows the control signal in the proposed system in which the signal of the progressive wave component of the fluid velocity pulsation is used for controlling the second source. Hence, the output signal of the detecting element (the control signal) and the target characteristics of the controller in the fundamental constitution of the system shown in Fig. 1 can be expressed for each system as follows:

system (a) :

$$\left. \begin{aligned} W(s) &= P_1(s) \\ G_c^*(s) &= -\frac{1}{\xi(s)Z_0} \frac{A_p}{A_c} \frac{1}{\sinh\{s\xi(s)l_1/c\}} \end{aligned} \right\} \quad (17)$$

system (b) :

$$\left. \begin{aligned} W(s) &= P_1(s) - P_2(s)e^{-s\xi(s)\Delta x/c} \\ G_c^*(s) &= -\frac{1}{\xi(s)Z_0} \frac{A_p}{A_c} \frac{e^{-s\xi(s)(l_1 - \Delta x)/c}}{\sinh\{s\xi(s)\Delta x/c\}} \end{aligned} \right\} \quad (18)$$

system (c) :

$$\left. \begin{aligned} W(s) &= F_1(s, x_0) \\ G_c^*(s) &= -2 \frac{A_p}{A_c} e^{-s\xi(s)l_1/c} \end{aligned} \right\} \quad (19)$$

Furthermore, the output signal of the detecting element, $W(s)$, in system (b) can be expressed also in the following form from Eq.(13) and Eq.(18), using the progressive wave component $F_1(s, x_0)$,

Fig. 2 Control signals (detected signals) in conventional systems [(a) and (b)] and the proposed system [(c)]

$$\begin{aligned}
W(s) &= P_1(s) - P_2(s)e^{-s\xi(s)\Delta x/c} \\
&= \xi(s)Z_0A(s)e^{-s\xi(s)x_0/c}\{1 - e^{-2s\xi(s)\Delta x/c}\} \\
&= \xi(s)Z_0\{1 - e^{-2s\xi(s)\Delta x/c}\}F_1(s, x_0). \quad (20)
\end{aligned}$$

Therefore, it should be noted that system (b) does not accurately detect the progressive wave component and thus differs essentially in signal processing from system (c).

If we assume the fluid to be nonviscous (i.e., $\xi(s) = 1$) for simplification, the target characteristics of the controller in each system for wide-band random fluid vibration are considered in the following manner.

In system (a), it is difficult to set up the desired characteristics using the signal processor (the FIR digital filter is usually used for this), since the target characteristics of the controller, $G_c^*(j\omega)$, are the phase lead characteristics over the entire frequency range, as shown in Eq.(17).

In system (b), $G_c^*(j\omega)$ shows also phase lead characteristics in the low-frequency range of $f < c/4(l_1 - \Delta x)$. In the case of $c = 1500$ m/s and $l_1 - \Delta x = 5$ m for instance, the lower limit of the frequency range where the target characteristics of the controller can be realized by the FIR filter is around 75 Hz and thus attenuation of the wave in the low-frequency range, which is one of the advantages of the active attenuator, is impossible. Furthermore, since the second source is usually the phase lag element, the lower limit of the frequency range where the target characteristics of the signal processor, $G_s^*(j\omega) = [G_c^*(j\omega)/G_a(j\omega)]$ show the phase lag characteristics becomes lower than the value described above.

In system (c) of the present discussion, it can be seen from Eq.(20) that $G_c^*(j\omega)$ is always the phase lag element with constant gain over the entire frequency range, and thus the establishment of $G_s^*(j\omega)$ by the FIR filter is very easy. The accuracy of the active control at low-frequency range becomes worse also in system (c), because the progressive wave component of fluid velocity pulsation, whose measuring accuracy decreases in the low-frequency range under about 15 Hz, is used as a control signal. However, this problem is not due to the control method, but merely due to the detection accuracy of the pressure transducer.

4.3 Signal processing circuit and driving method of the second source in the proposed system

As the displacement control-servo actuator (cylinder) is used as the second source in the proposed system, its displacement, $y_c(t)$, can be given from Eq.(16) as follows:

$$Y_c(s) = -2 \frac{A_p}{A_c} \frac{e^{-s\xi(s)\tau}}{s} F_1(s, x_0). \quad (21)$$

Hence, if we set the dynamic characteristics of the servo actuator as $G_a(s)$, the output signal of the signal processing circuit, $Z(s)$, can be given as follows:

$$\begin{aligned}
Z(s) &= -2 \frac{A_p}{A_c} \frac{1}{G_a(s)} \frac{e^{-s\xi(s)\tau}}{s} F_1(s, x_0) \\
&\equiv G_s^*(s) F_1(s, x_0) \quad (22)
\end{aligned}$$

where $G_s^*(j\omega)$ is the target characteristics of the signal processor in the fundamental constitution shown in Fig. 1, and can be given by

$$G_s^*(s) = -2 \frac{A_p}{A_c} \frac{1}{G_a(s)} \frac{e^{-s\xi(s)\tau}}{s}. \quad (23)$$

When the target characteristics of the signal processor have been determined by the above equation, $z(t)$ can be given in the form of a convolution integral of Eq.(22) as follows:

$$z(t) = \int_0^t g_s^*(t - \sigma) f_1(\sigma, x_0) d\sigma \quad (24)$$

where $g_s^*(t)$ is the impulse response of $G_s^*(s)$. The arithmetic operation of Eq.(24) can easily be fulfilled by using the FIR digital filter.

5. Experimental Results and Considerations

5.1 Experimental apparatus and method

As preliminary investigation for the study, an experiment on the attenuation characteristics was carried out for the simple harmonic pulsation only, though the proposed active attenuator using the transfer-function-based control method is also applicable to the wide-band random pulsation.

In addition, it could be found from preliminary considerations that the resistance of pipe flow must be treated with some precision, because the effect of viscous resistance cannot be disregarded in such a case which uses a pipe of relatively small bore and fluid of relatively high viscosity as in this small-sized model experimental pipeline. Thus, in this study, the flow in a pipe was treated as two-dimensional, unsteady and laminar, and the viscous resistance of Brown's approximation⁽⁸⁾ was used. Hence, the wave propagation coefficient $\xi(s)$ in Eq.(23) can be given from the first equation in Eq.(8) in the frequency domain as follows:

$$\begin{aligned}
\xi(j\omega) &\approx 1 + \sqrt{\frac{\nu}{2r_0^2\omega}} - j\left(\sqrt{\frac{\nu}{2r_0^2\omega}} + \frac{\nu}{r_0^2\omega}\right) \\
&\equiv \xi_r(\omega) - j\xi_i(\omega). \quad (25)
\end{aligned}$$

Substituting Eq.(25) into Eq.(22) gives

$$Z(s) = -2 \frac{A_p}{A_c} \frac{e^{-\xi_i(\omega)\tau\omega}}{|G_a(j\omega)|} \frac{1}{s} F_1(s, x_0) e^{-\tau e^s}. \quad (26)$$

Hence, $z(t)$ for the pulsation of frequency ω can be found by Eq.(24) as follows:

$$\begin{aligned}
z(t) &= -2 \frac{A_p}{A_c} \frac{e^{-\xi_i(\omega)\tau\omega}}{|G_a(j\omega)|} \int_0^t f_1(\sigma - \tau_e, x_0) d\sigma \\
&\equiv K \int_0^t f_1(\sigma - \tau_e, x_0) d\sigma \quad (27)
\end{aligned}$$

where

$$\begin{aligned}
\tau_e &= \xi_r(\omega)\tau - \angle G_a(j\omega)/\omega \\
K &= -2 \frac{A_p}{A_c} \frac{e^{-\xi_i(\omega)\tau\omega}}{|G_a(j\omega)|} \quad (28)
\end{aligned}$$

Thus, the input signal to the servo amplifier, $z(t + \Delta t)$, at the time of $t + \Delta t$ can be given approximately in the form of the following recurrence equation.

$$z(t + \Delta t) \approx z(t) + \frac{K}{2} \{ f_1(t - \tau_e, x_0) + f_1(t + \Delta t - \tau_e, x_0) \} \Delta t \quad (29)$$

The layout of the proposed attenuator system and its small-sized model experimental pipeline is shown in Fig. 3. The pipe used in this test was a straight steel pipe with inner diameter of 19.6 mm and total length of 7.91 m ($x_0 = 0.81$ m, $l_1 = 5.87$ m, $l_2 = 1.23$ m). A hydraulic cylinder with a magnetic vibrator was used as the original source, and simple harmonic pulsations of various frequencies were produced in the pipe by feeding the sinusoidal voltage signal to it through an amplifier from a function generator. The electrohydraulic servo cylinder with the frequency response characteristics shown in Fig. 4 was used as the second source, which was connected to the pipe with a branch at the position of $x = 6.68$ m. The downstream end of the pipe was closed with an obvious boundary condition, so that the theoretical value could be predicted as accurately as possible for comparison with the measured value. The distance between the two pres-

Fig. 3 Proposed attenuation system and its small-sized model experimental pipeline

Fig. 4 Frequency response characteristics of the second source (electrohydraulic servo cylinder) used in this test

sure transducers for detecting the progressive wave component of the pulsation was determined to be $\Delta x = 540$ mm, taking into consideration the amplitude and frequency range of the pulsation of the subject and the resolving power of the detector. The general-purpose digital signal processor (DSP) was used for the high-speed-conversion operation of the two pressure signals, $p_1(t)$ and $p_2(t)$, into the progressive wave component of the pulsation, $f_1(t, x_0)$, and for the calculation of Eq. (29). For details of the equation for the high-speed-conversion operation, the resolving power of the DSP and the detection accuracy of the pressure transducer, the reader is referred to the previous paper⁽⁷⁾.

5.2 Experimental results and considerations

The solid lines in Fig. 5 show the measured time histories (waveforms) of p_1 , p_2 , f_1 , z and y_c in the case where the present control system was operated. The measured waveform of f_1 stands for that obtained from high-speed-conversion operation by the DSP according to Eq. (14) (strictly speaking, Eq. (10) in the previous paper) using the measured values of p_1 and p_2 . The dotted lines show the desired time histories of z and y_c obtained from the plane wave theory for the fluid in a pipe and the target characteristics of the signal processor on the basis of the measured value of p_1 . It can be seen from these results that the actual movement (measured value of y_c) of the second source realized by the present control almost agrees with the desired one. Upon closer inspection, however, the measured value is larger than the desired one by around 5% in amplitude (in peak-to-peak value). This difference occurs mainly because the desired values of z and y_c were obtained by using only a fundamental component of p_1 , although the pressure pulsation generated in a pipe deviates somewhat from

Fig. 5 Time histories of p_1 , p_2 , f_1 , y_c and z in the case of the present control system being "on"

the sinusoidal wave and contains harmonics components caused by nonlinearity in the magnetic-hydraulic cylinder system, while the input signal from the function generator is exactly sinusoidal.

Figure 6 shows the measured time-history waveforms of pressure pulsations in the two cases where the present control system is, and is not, operated. It can be seen from these results that when the present control system is operated, the pressure pulsations in a downstream pipe of the second source, p_3 and p_4 , are reduced to about 1/10 to 1/15 (about $-20 \sim -25$ dB) of those in the case where the present control system is not operated for the pressure pulsations of all the frequencies shown in Figs. 6 (a) ~ (d).

Next, the effect of the error in setting up the target characteristics of the signal processor

[specifically, the delay time τ_e and gain K in Eq. (28)] on the attenuation performance will be considered. Figure 7 is the measured example which shows the effect of setting error $\Delta\tau$ of the delay time τ_e (converting into the phase error, $\Delta\phi = 360f\Delta\tau^\circ$) on the attenuation of pressure pulsation p_3 and p_4 . The experimental results also proved that the phase error $\Delta\phi$ should be held within about $\pm 5^\circ$ in order to reduce the pressure pulsations p_3 and p_4 to around 1/10 of those with the control system off, as expected from the simple theory [the progressive wave of the rate $2\sin(\Delta\phi/2)$ in the case with the present control system off is not attenuated and remains intact].

Lastly, the applicable limit of the proposed active attenuator to the pulsation frequency range will be investigated. Experiments have shown that the lower and the upper limits of the frequency range of the

Fig. 6 Measured time histories of pressure pulsations in a pipe in the cases of the present control system being "off" and "on"

Fig. 7 Effect of setting error of the delay time on the attenuation performance ($f=60$ Hz)

pulsation where the proposed active attenuator works effectively are about 20 Hz and about 250 Hz, respectively (the experimental results are omitted on account of space considerations). Of these critical frequencies, the lower limit of the frequency of controllable pulsation almost agrees with the lower limit of frequency of the measurable progressive wave shown in the previous paper⁽⁷⁾. Hence, it is concluded from this fact that the lower frequency limit of application of the proposed system is not dependent on the present control method in itself, but on the accuracy of the measurement of the progressive wave, i.e., on the detection accuracy of the pressure transducer.

On the other hand, it is evident from the following considerations that the upper limit is not dependent on the dynamic characteristics of the second source, but on the setting accuracy of the delay time τ_e , so far as the present experiment is concerned. In this control system, the setting accuracy (resolving power) of the delay time is equal to the sampling period ($=1/f_s$, $f_s=10.24$ kHz in the present system), since the setting of τ_e is performed by the delay line storage in the DSP. Consequently, the setting error of the phase angle becomes $\Delta\phi=360f/f_s \approx 10.6^\circ$ at the maximum value for the pulsation of 300 Hz for instance, and the attenuation performance considerably deteriorates, as shown in Fig. 7.

6. Conclusions

A new technique of an active attenuator for pressure pulsation in liquid piping systems, which controls the second source feedforwardly by the signal of the progressive wave component of the velocity variation detected in real time at the upstream of the pipe, was devised and its attenuation characteristics were investigated by theory and experiment. As preliminary investigation for the study, an experiment on the attenuation characteristics was carried out for only the simple harmonic pulsation, though the proposed active attenuator using the transfer-function-based control method is also applicable to the wide-band random pulsation. It was confirmed by the test in a small-sized model experimental pipeline that, when the present control system was operated, the pressure pulsation in a downstream pipe of the second source was reduced to about 1/10 to 1/15 of that in the case where the control system was not used (i.e., attenuation of about -20 to -25 dB was achieved) over the frequency range of 20 to 250 Hz.

A subsequent paper will consider the design of the signal processing circuit using the FIR digital filter, and attenuation characteristics and stability of the proposed active attenuator on the wide-band random pulsation.

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