Development of an Active Attenuator for Pressure Pulsation in Liquid Piping Systems*

(A Real Time-Measuring Method of Progressive Wave in a Pipe)

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This paper deals with a real-time measuring method of the progressive wave of fluid velocity pulsation in a pipe, which is necessary for the development of an active attenuator of pressure pulsation in liquid piping systems. The principle of the present measurement is to obtain the fluid velocity (cross-sectional average velocity) signal by integrating the difference between signals produced by two pressure transducers spaced a suitable distance apart, on the basis of the momentum equation, and then to obtain the progressive wave component of fluid velocity pulsation from the pressure and velocity signals by a simple algebraic operation according to the plane wave theory. A general-purpose digital signal processor (DSP) has been used for the high-speed calculation necessary for the real-time measurement. The measured values agree with the theoretical results within the experimental errors which are mainly due to the detection accuracy of the pressure transducer and the resolving power of the A/D converter of the DSP, except for the frequency ranges of nearby resonant frequencies. The applicable limit of this measurement is the frequency range above about 15Hz, mainly because of the detection accuracy of the pressure transducer.

Key Words: Measurement, Pulsation, Unsteady Flow, Oscillatory Flow, Active Filter, Active attenuator, Progressive Wave, Digital Signal Processor

1. Introduction

An active pulsation control technique based on Huygens' principle that cancels the original pulsation by using an anti-phase wave from the second source has made rapid progress on the basis of recent advance in electronics; some of their techniques are now at the practical application stage in the field of noise control in a duct⁽¹⁾. These active noise control systems are all composed of microphones (detectors), a signal processor (controller) and loudspeakers (second sources), and the signals from the detectors are used to drive the second source by a controller whose characteristics are specified so that the sound pressure becomes zero downstream of the second source. In all the present systems, however, the second source is controlled only by the detected pressure signal itself, but the progressive wave of pulsation has never been used for the control signal. Therefore, the

target characteristics of the controller specified by the requirement for the sound to be zero at the downstream of the second source is basically inapplicable in a monopole system, for instance, or it is very difficult to match the characteristics of two second sources, for instance, in a dipole system⁽²⁾. Thus, there is substantial room for improvement on points of both hardware and software.

The purpose of this study is to develop a sophisticated active attenuator for pressure pulsation in piping systems, which detects the progressive wave component of fluid velocity pulsation in real time by the signals from two pressure transducers spaced a suitable distance apart and then controls the second source feed-forwardly by this signal so that the progressive wave in the downstream pipe of the second source is eliminated. Of these, in this paper, a newly developed real-time measuring method of the progressive wave of fluid velocity pulsation in a pipe is shown, and the validity and an applicable limit of this measurement are investigated. Moreover, the liquid piping system, which requires much faster signal processing than the gas piping system, has been chosen as the subject of study, so that this control system can also

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be used for the attenuation of pressure pulsation in piping systems such as the stock piping system of paper-making machines.

2. Nomenclature

- A_c : Cross-sectional area of the actuator
 A_p : Cross-sectional area of the pipe
 c : Speed of sound in the fluid in the pipe
 E : Amplitude of the sinusoidal voltage
 $F_1(t)$: Progressive wave of the fluid velocity pulsation at the position of x_0
 $F_2(t)$: Regressive wave of the fluid velocity pulsation at the position of x_0
 f : Frequency of the pulsation
 f_s : Sampling frequency
 $G_f(S)$: Transfer function of F_1 to $p_1/\rho c$
 $G_p(S)$: Transfer function of p to p_1
 $G_u(S)$: Transfer function of u to $p_1/\rho c$
 l : Distance between the detection position x_0 and actuator (second source)
 N : Number of the right shift in DSP
 p : Pressure pulsation at the position of x_0
 p_1 : Pressure pulsation at the position of $x_0 - \Delta x/2$
 $\bar{p}_{1-n}$: Amplitude of n th harmonic of p_1
 p_2 : Pressure pulsation at the position of $x_0 + \Delta x/2$
 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
 Δt : Sampling period ($=1/f_s$)
 u : Cross-sectional average velocity pulsation at the position of x_0
 $\bar{u}_n$: Amplitude of n th harmonic of u
 u_s : Fluid velocity pulsation of the original source
 v_c : Velocity of the actuator (second source)
 x_0 : x coordinate of the intermediate point between two pressure transducers
 Δx : Distance between two pressure transducers
 δ : Step width of quantization in the A/D converter of DSP
 ν : Kinematic viscosity of the fluid
 ρ : Fluid density
 ϕ_n : Phase angle between u and p_1 for n th harmonic
 ψ_n : Phase angle between F_1 and p_1 for n th harmonic
 ω : Angular frequency of the pulsation

3. The Principle of the Proposed Active Attenuator for Pressure Pulsation in a Pipe

The outline of the devised active attenuation system is shown in Fig. 1. The principle of this system is as follows, but, in order to simplify the explanation,

the discussion will neglect the flow resistance in this section.

The fluid velocity variation u and pressure variation p at the position x_0 and time t can be represented in the following form, using a progressive wave F_1 and regressive wave F_2 .

$$u = F_1(t - x_0/c) + F_2(t + x_0/c) \quad (1)$$

$$p = \rho c [F_1(t - x_0/c) - F_2(t + x_0/c)] \quad (2)$$

Hence, the progressive wave component of the fluid velocity pulsation at the position of x_0 (fixed value) and time t , $F_1(t - x_0/c)$ (hereafter referred to as $F_1(t)$), can be expressed in terms of u and p as follows:

$$F_1(t) = \frac{1}{2} \left[u + \frac{p}{\rho c} \right]. \quad (3)$$

This progressive wave $F_1(t)$ is transferred to the position of $x_0 + l$ at the time of $t + \tau$ after τ seconds ($\tau = l/c$), with no change of shape. The proposed active attenuator is to be designed to produce a 180° -out-of-phase velocity pulsation signal of the same intensity as $F_1(t)$ into the downstream pipe by the actuator just when this progressive wave $F_1(t)$ arrives at the position of $x_0 + l$, and then to cancel the original $F_1(t)$ in the downstream of the actuator. It is unnecessary to say that, if the progressive wave is completely cancelled, the pressure pulsation becomes zero in all regions downstream of the actuator, since the regressive wave reflected at the pipe end also is zero. In practice, this can be realized by moving the actuator, which is connected to the pipe with a branch as shown in Fig. 1, in the following form.

$$v_c = -2 \frac{A_p}{A_c} F_1(t - \tau). \quad (4)$$

Figure 2 shows the sample calculation of the distributions of fluid velocity and pressure pulsations along the pipe. It can be seen that both pulsations expectedly become zero when the present control system is operated. In other words, the proposed active attenuator can be physically explained to be the control system that drives the actuator so that the wave from the original source is reflected, such as at the open end at the actuator end, and then the fluid wave is not trans-

Fig. 1 Layout of the devised active attenuation system for pressure pulsation in a pipe

Fig. 2 Sample calculation for the performance of the proposed active attenuator

mitted to downstream of the actuator.

4. Theory on the Real-Time Measuring Method of Progressive Wave of Fluid Velocity Pulsation

As stated before, if the pressure pulsation p and velocity pulsation u can be measured, the progressive wave $F_1(t)$ can be obtained in real time by a simple mathematical operation as shown in Eq. (3). It is not at all difficult to measure the pressure pulsation; however, the problem with measuring the progressive wave arises with the measurement of the velocity pulsation.

Regarding the real-time measurement of cross-sectional average velocity that does not use a resistance device, such as an orifice or Venturi tube, methods of obtaining it by a high-speed conversion operation from the signal of the fluid velocity at the centerline axis of the pipe measured by LDV⁽³⁾, from the signal of the pressure gradient between two points a suitable distance apart measured by the differential pressure transducer⁽⁴⁾, and other such methods have been proposed. However, these methods are restricted in application to practical piping systems since a transparent acrylic tube is needed in the former using LDV and a U-shaped bend is needed in the latter using the differential pressure transducer to measure the pressure difference.

The principles of the proposed measuring method are to obtain the fluid velocity signal by integrating the difference between signals produced by two pressure transducers spaced a suitable distance apart, on the basis of the momentum equation, in the same manner as that in an acoustic intensity probe, and then to obtain the progressive wave component of fluid velocity pulsation from the pressure and velocity signals by an simple algebraic equation according to the plane wave theory. Now, unlike the above-

mentioned studies, the direct purpose of this study is not merely to measure the velocity pulsation, but to obtain the progressive wave component from measured velocity and pressure, and then to use this data as a signal for the feed-forward control of the second source.

Therefore, it is necessary to reduce the operation time as much as possible even if the accuracy of the conversion operation (that is, the accuracy of the measurement) is decreased somewhat within an allowable limit for practical usage, and to further control the drift completely. As will be described later, this problem can be settled by detecting the alternating component of pressure signals only, and by taking account of the flow resistance in the momentum equation. Hence, in this study, the resistance of pipe flow at the detection section of the pressure gradient is approximated with a steady and laminar resistance so that the impulse response of the fluid velocity to the unsteady pressure gradient can be represented by that in the first-order lag element. Thus, the equation of motion for the liquid flow through a detection section may be given by the following equation:

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} - R_f u. \quad (5)$$

Approximating the pressure gradient $\partial p/\partial x$ at the position of x_0 with the average pressure gradient between the positions of $x_0 - \Delta x/2$ and $x_0 + \Delta x/2$ as in following equation,

$$\frac{\partial p}{\partial x} = \frac{p_2(t) - p_1(t)}{\Delta x}, \quad (6)$$

and performing the Laplace transformation, Eq. (5) becomes

$$U(s) = \frac{1}{\rho(s + R_f)} \frac{P_1(s) - P_2(s)}{\Delta x}. \quad (7)$$

Furthermore, representing a convolution integral, then

$$u(t) = \frac{1}{\rho} \int_{-\infty}^t e^{-R_f(t-\sigma)} \frac{p_1(\sigma) - p_2(\sigma)}{\Delta x} d\sigma. \quad (8)$$

Thus, the fluid velocity pulsation $u(t + \Delta t)$ at the time of $t + \Delta t$ can be given in the form of the following recurrence equation.

$$\begin{aligned} u(t + \Delta t) &= \frac{1}{\rho} \int_{-\infty}^{t + \Delta t} e^{-R_f(t + \Delta t - \sigma)} \frac{p_1(\sigma) - p_2(\sigma)}{\Delta x} d\sigma \\ &= \frac{e^{-R_f \Delta t}}{\rho} \int_{-\infty}^t e^{-R_f(t - \sigma)} \frac{p_1(\sigma) - p_2(\sigma)}{\Delta x} d\sigma \\ &\quad + \frac{e^{-R_f \Delta t/2}}{\rho} \frac{p_1(t) - p_2(t) + p_1(t + \Delta t) - p_2(t + \Delta t)}{2\Delta x} \Delta t \\ &= e^{-R_f \Delta t} u(t) + \frac{\Delta t}{2\rho \Delta x} e^{-R_f \Delta t/2} \{p_1(t) - p_2(t) \\ &\quad + p_1(t + \Delta t) - p_2(t + \Delta t)\} \end{aligned} \quad (9)$$

Equation (9) is the equation for a high-speed conversion operation obtaining the fluid velocity pulsation from the signals produced by two pressure

transducers. Moreover, approximating the pressure $p(t)$ at the position of x_0 with the average value of $p_1(t)$ and $p_2(t)$ in the same manner as in an acoustic intensity measurement, the equation for a high-speed conversion operation which yields the progressive wave component, $F_1(t)$, of velocity pulsation can be given by Eq. (3) as follows:

$$F_1(t) = \frac{1}{2} \left\{ u(t) + \frac{1}{\rho c} \frac{p_1(t) + p_2(t)}{2} \right\}. \quad (10)$$

5. Experimental Results and Considerations

5.1 Experimental apparatus and method

The layout of the small-sized model experimental apparatus is shown in Fig. 3. The pipe used in this test was a straight steel pipe of an inner diameter of 19.6 mm and a length of 4.49 m. The pulsation was produced in the pipe by vibrating the hydraulic cylinder with a magnetic vibrator. The end of the pipe was closed, with an obvious boundary condition, so that the theoretical value could be predicted as correctly as possible for comparison with the measured value. The distance between the two pressure transducers was determined to be $\Delta x = 540$ mm, taking into consideration the amplitude and frequency range of pulsation of the subject and the resolving power of the detector. Pulsations of various amplitudes and frequencies were produced in the pipe by feeding the sinusoidal voltage signal to the magnetic vibrator through an amplifier from a function generator. Pressure pulsations, p_1 and p_2 , were measured by two semiconductor pressure transducers (maximum pressure: 1 MPa). These signals were fed into the signal processing circuitry through the amplifiers and high-pass filters, and then the fluid velocity pulsation and its progressive wave component were calculated in it. A general-purpose digital signal processor (hereafter referred to as DSP) was used for signal processing, which converted ± 2.5 V of analog voltage into 12 bits of digital signal at the input unit, and performed the

Fig. 3 Experimental apparatus

mathematical operation after shifting them to the left automatically by 4 bits, and converted 16 bits of digital signal into ± 10 V of analog voltage at the output unit. In this experiment, the magnification factors of the amplifiers for the two pressure transducers were chosen so that 0.1 MPa of pressure was converted into 1 V of DSP input voltage. Hence, the step width of quantization in the A/D converter of the DSP (hereafter referred to as the resolving power of DSP) became $0.5 \text{ MPa}/2^{12} = 1.22 \times 10^{-4} \text{ MPa}$ ($1.22 \times 10^{-3} \text{ V}$).

Before performing the main experiments, the effects of the sampling frequency and the amplitude of pressure pulsation on the accuracy of the high-speed operation were examined by feeding the equivalent voltage signal $\Delta E (= E \sin 2\pi ft)$ instead of the pressure difference signal of $p_1(t) - p_2(t)$ in Eq. (9) to the DSP through the amplifier from the function generator and then analyzing the waveform of the fluid velocity signal obtained by the operation of Eq. (9). Figure 4 shows the relationship between the non-dimensional sampling frequency, f_s/f , relative to the pulsation frequency f and the non-dimensional amplitude of the fundamental component of fluid velocity pulsation, $\bar{U}_1/\bar{U}_1^*$, relative to the corresponding amplitude $\bar{U}_1^*$ at $f_s = 19.2 \text{ kHz}$. Figure 5 shows the relationship between the non-dimensional step width of quantization in the A/D converter of the DSP, δ/E , relative to the sinusoidal differential voltage amplitude E and the non-dimensional amplitude of the fundamental component of fluid velocity pulsation, $\bar{U}_1/\bar{U}_1^{**}$, relative to the corresponding amplitude at $\delta/E = 0.0122$. It can be seen from these results that the sampling frequency of $f_s > 20f$ and the input voltage of $E > 10\delta$ (in regard to the resolving power, $\delta < 0.1E$) is needed to keep the operation error within 5%.

5.2 Experimental results and considerations

The solid lines in Figs. 6(a) and (b) show the

Fig. 4 Effect of the sampling frequency on the accuracy of the measurement of fluid velocity

time histories of u and F_1 obtained from the high-speed conversion operation by the DSP according to Eq. (9) and Eq. (10) (in this paper, referred to as measured values of u and F_1). While the input signal from the function generator is exactly sinusoidal, pressure pulsation generated in the pipe deviates somewhat from the sinusoidal wave and contains its harmonic components caused by nonlinearity in the magnetic vibrator-hydraulic cylinder system. Hence, wave analysis was done by means of the FFT in investigating the experimental results. In this paper,

Fig. 5 Effect of the resolving power of the A/D converter of DSP on the accuracy of the measurement of fluid velocity

(a) $f=61\text{ Hz}$,

the validity, accuracy, applicable limit, and so on of this measuring method were examined by comparing the measured values u and F_1 with those obtained from the plane wave theory for the fluid in the pipe using the measured value of p_1 (hereafter referred to as the theoretical values), as indicated as follows.

If the flow in a pipe is two-dimensional, unsteady and laminar, and if the downstream end of the pipe is closed, the velocity u and pressure p at the position of x_0 are related to the pressure p_1 at the position of $x_0 - \Delta x/2$ by the following equation in the frequency domain :

$$P(j\omega) = G_p(j\omega)P_1(j\omega) \quad (11)$$

$$U(j\omega) = G_u(j\omega)P_1(j\omega)/\rho c, \quad (12)$$

where

$$\left. \begin{aligned} G_u(j\omega) &= \frac{j}{\xi(j\omega)} \frac{\sin\left\{\frac{\xi(j\omega)\omega}{c}l\right\}}{\cos\left\{\frac{\xi(j\omega)\omega}{c}(l+\Delta x/2)\right\}} \\ G_p(j\omega) &= \frac{\cos\left\{\frac{\xi(j\omega)\omega}{c}l\right\}}{\cos\left\{\frac{\xi(j\omega)\omega}{c}(l+\Delta x/2)\right\}} \end{aligned} \right\} \quad (13)$$

and

$$\xi(j\omega) \doteq 1 + \sqrt{\frac{\nu}{2r_0^2\omega}} - j\left\{\sqrt{\frac{\nu}{2r_0^2\omega}} + \frac{\nu}{r_0^2\omega}\right\}.$$

Furthermore, F_1 can be expressed as a function of p_1 as follows :

$$F_1(j\omega) = G_f(j\omega)P_1(j\omega)/\rho c, \quad (14)$$

where

(b) $f=152\text{ Hz}$

Fig. 6 Measured and theoretical time histories of u and F_1 ($f_s=10.24\text{ kHz}$, $N=4$)

$$G_f(j\omega) = \frac{1}{2} \{G_u(j\omega) + G_p(j\omega)\}. \quad (15)$$

Hence, setting the amplitude of the n th harmonic of measured p_1 as $\bar{P}_{1,n}$ and the phase angle of the n th harmonic of the fundamental component as $\angle P_{1,n}$, the theoretical waveforms of u and F_1 can be given by

$$u = \sum_{n=1}^{\infty} \frac{\bar{P}_{1,n}}{\rho c} |G_u(j\omega_n)| \sin(\omega_n t + \phi_n) \quad (16)$$

$$F_1 = \sum_{n=1}^{\infty} \frac{\bar{P}_{1,n}}{\rho c} |G_f(j\omega_n)| \sin(\omega_n t + \phi_n), \quad (17)$$

where

$$\phi_n = \angle G_u(j\omega) + \angle P_{1,n} \quad (18)$$

$$\phi_n = \angle G_f(j\omega) + \angle P_{1,n}.$$

The dotted lines in Figs. 6(a) and (b) show the theoretical time histories of u and F_1 obtained from Eq. (16) and Eq. (17) using measured values of $\bar{P}_{1,n}$ and $\angle P_{1,n}$ (provided that the sum of the components up to the 5th harmonic is considered).

Figure 7 shows a comparison of measured values ($\circ$ and $\triangle$) with theoretical values regarding the fundamental component of u . For the amplitude, in this study, both values are compared in the form of transfer functions in order to show the wave mode in the fluid column in a pipe altogether, though it is straightforward to compare the measured value of $\bar{U}_1$ and its theoretical value calculated from Eq. (16) using the measured value of $\bar{P}_{1,1}$. That is, the transfer function of the measured value of $\bar{U}_1$ to the measured value of $\bar{P}_{1,1}$, $\bar{U}_1/(\bar{P}_{1,1}/\rho c)$, and the transfer function determined only by the parameters of the pipeline, $|G_u(j\omega)|$, are used as the experimental and theoretical values of $\bar{U}_1$, respectively. Figure 8 shows the results in the relatively low-frequency range obtained from an experiment conducted separately from that of

Fig. 7 Measured and theoretical values of the fundamental component of velocity pulsation ($f_s = 10.24$ kHz, $N = 4$)

Fig. 7. Figure 9 shows a comparison of the measured values ($\circ$ and $\triangle$) with the theoretical values (solid lines) of the fundamental component of F_1 . In regard to the amplitude, both are compared in the forms of $\bar{F}_1/(\bar{P}_{1,1}/\rho c)$ (measured value) and $|G_f(j\omega)|$ (theoretical value) in the same manner as in u . The experiments were all carried out at a sampling frequency of $f_s = 10.24$ kHz.

It can be seen from the results of Fig. 6 to Fig. 9

Fig. 8 Measured and theoretical values of the fundamental component of velocity pulsation ($f_s = 10.24$ kHz, $N = 4$)

Fig. 9 Measured and theoretical values of the fundamental component of progressive wave ($f_s = 10.24$ kHz, $N = 4$)

that, regarding the amplitude, the measured values agree with the theoretical results within the maximum error of 5 %, except for the frequency ranges of nearby resonant frequencies (to be exact, frequencies where the detection position x_0 coincides with antinodes of velocity pulsation, i. e., nodes of pressure pulsation) and less than about 15 Hz. Meanwhile, for the phase angle, the measured values always lag behind the theoretical results by approximately the amount of the sampling period ($360 f/f_s$ degree in phase). However, both agree well except for this difference. These facts show that the mathematical operations of Eq. (9) and Eq. (10) can be completed in the sampling period of 10.24 kHz used in these tests. (It has been confirmed by separate experiments that the above-mentioned operations are practical up to the sampling frequency of 19.2 kHz.) Moreover, it may be considered that the above-mentioned error in the phase angle can be compensated by including it in the delay time τ in Eq. (4); thus, it is no problem in practical application, because it depends almost exclusively on the sampling frequency.

Next, the applicable limit of this measuring method will be considered by examining the cause of error in the frequency range mentioned above. First, with regard to the error in the frequency ranges of very large velocity amplitude (that is, the frequency ranges where the detection position reaches the antinodes of velocity pulsation, i. e., the nodes of pressure pulsation), it may be considered that a greater part of it is caused by the approximation of the flow resistance in Eq. (5) with a steady and laminar resistance. In order to reduce this error, introduction of a method that treats the flow resistance accurately as two-dimensional, unsteady and laminar, and then represents the transfer function of the fluid velocity to the pressure gradient with a plural number of first-order lag elements may be considered. This error, however, may not be a serious problem so long as the detection of the progressive wave for a control signal of the active attenuator is the main purpose, since the effects of viscous resistance are virtually restricted to the frequency range of very large velocity amplitude. Furthermore, the measurement at antinodes of velocity pulsation may also be avoided by changing the detection position in practical application.

Next, regarding the error in the low-frequency range, this may be considered to be caused mainly by insufficiencies in the resolving power of the A/D convertor of the DSP and the detection accuracy of pressure transducer for the magnitude of pressure difference, $p_1 - p_2$. That is, the amplitude of pressure difference, $p_1 - p_2$, at the frequency of 10 Hz is only 8

$\times 10^{-4}$ MPa (8×10^{-3} V) when the amplitude of pressure pulsation p_1 is around 0.1 MPa (1V). Meanwhile, the resolving power of the DSP is 1.22×10^{-4} MPa in the case without a right shift during signal processing, as described before. In this study, the scale factors of two amplifiers were adjusted with a four-figure digital millivolt meter so that the pressure of 0.1 MPa indicated the voltage of 1 Volt, while a pressure of 0.8 MPa was applied to the fluid in the pipe (that is, while entirely the same pressure was equally applied to the two pressure transducers). The read accuracy of this millivolt meter was about 0.1 % of the indicated value. Thus, if the pressure is correctly set up, the detection accuracy of the pressure transducer is also about 0.1 % of its measured value. In this case, the detection error of the pressure transducer is, at most, $\pm 1 \times 10^{-4}$ MPa (1×10^{-3} V) for the pressure variation of 0.1 MPa, and then the detection error of the pressure difference is, at most, $\pm 2 \times 10^{-4}$ MPa (2×10^{-3} V).

Therefore, the errors of measurements of u and F_1 become considerably larger in the lower frequency range than around 10 Hz, and the measurement should become practically impossible since the amplitude of the pressure difference for the pulsation of the frequency of 10 Hz is only about four times the detection accuracy of the pressure difference (about 6.5 times the resolving power of the DSP) in the test piping system. Regarding the setting error, even if the set value of pressure has an error of 1 % (which is common in the two pressure transducers) in adjusting the scale factor of the amplifier, the measured values of u and F_1 merely have an error of 1 % because the error of the pressure difference due to this setting error is cancelled. In the case when the amplitude of the pressure pulsation is the same value of 0.1 MPa, the errors of measured values of u and F_1 at the frequency of 20 Hz are within the permissible limit for practical usage, since the amplitude of the pressure difference between p_1 and p_2 increases to about 2.5×10^{-3} MPa (2.5×10^{-2} V).

From the considerations of the errors mentioned above, it is concluded that, as long as the distance between the two pressure transducers is fixed at the constant value of $\Delta x = 540$ mm in the test piping system, the lowest limit of frequency of measurable pulsation is around 15 Hz for the pulsation of amplitude of around 0.1 MPa.

In order to extend the measurable lowest limit to a lower frequency, such countermeasures as to increase the distance Δx (in this case, however, the approximation of pressure gradient by Eq. (6) is insufficient in a high-frequency range) or as to increase the pressure difference by bringing the detection position close to the node of pressure pulsation, if

possible, may be considered. These matters will be explained in detail in the next paper.

6. Conclusions

A real-time measuring method of the progressive wave component of fluid velocity pulsation in a pipe, which is necessary for the development of a sophisticated active attenuator of pressure pulsation in liquid piping systems, was proposed, and the validity, accuracy and applicable limit of the present high-speed conversion equation and signal processing were examined.

Consequently, it was confirmed that the velocity pulsation and its progressive wave component can be measured in real time with a maximum accuracy of about 5 % throughout the frequency range from 15 Hz to 350 Hz, for the pressure pulsation with an amplitude of around 0.1 MPa, except for the frequency ranges of nearby resonant frequencies.

The characteristics of the newly developed active attenuator that uses the progressive wave as a signal for a feed-forward control of a secondary source, as

well as countermeasures for an improvement of the measurement accuracy in a low-frequency range, will be reported in the next paper.

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