Self-excited Pressure Vibration in the Low-Pressure Pipeline
Using an Automatic Pressure-reducing Valve (II)
-Prediction of Occurrence of Self-excited Pressure Vibration Based on a Period of Water Pressure Oscillation in a Closed Conduit-

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Abstract: In this study, a waveform of a self-excited pressure vibration that occurs in low-pressure pipeline systems was analyzed using a pressure-reducing valve. This analysis was conducted on the basis of field measurement data that was obtained for the condition in which the pressure-reducing valve is placed in the middle of the pipeline and a direct-acting constant-flow valve is installed at the end. On obtaining the intrinsic oscillation period from the transfer matrix and the oscillation period of the field measurement waveform from the spectral analysis, it was clarified that the theoretical period of the intrinsic oscillation of the pipeline approximates the shortest oscillation period based on the measurement data and provides an indication of the periodicity of the pipeline. Moreover, on verifying the cross-correlation function and the phase-shift time between the primary and secondary pressure of the pressure-reducing valve, it was clarified that they depend on each other and the secondary pressure propagates as the primary pressure via the pressure-reducing valve. In addition, the efficacy of the installation of the surge tank and air stick for controlling the pressure oscillation was theoretically and experimentally demonstrated. Based on these results, it was proposed that the occurrence of the self-excited pressure vibration be determined based on the intrinsic oscillation period by using the dimensions of the pipeline.

Keywords: Pressure-reducing valve; Self-excited pressure; Pressure variation; Period of pressure oscillation; Low-pressure pipeline; Pressure oscillation model

1 Introduction
In gravity-flow pipeline systems—such as those used in farm irrigation districts—comprising a low-pressure pipeline using an automatic pressure-reducing valve, high-pressure self-excited pressure vibrations that exceed the design pressure can occur as shown in Figure 1. Hence, there is a requirement for clarifying the mechanism of pipeline accidents and establishing the corresponding effective countermeasures.

Akiyoshi et al. (2017) indicated the following using field measurement data and a numerical model. Firstly, the pressure-reducing valve enlarges the minimum pressure vibration, which occurs on the downstream side, and propagates it towards the upstream side. Secondly, the pressure variation at the upstream and downstream sides of the pressure-reducing valve can develop into a self-excited pressure vibration while shutting in the pipe when the pressure-reducing valve is placed in the middle of the pipeline. Finally, a self-excited pressure vibration can occur when valves having a flow area that decreases corresponding to the increase in the water pressure, such as a direct-acting constant-flow valve, are installed at the downstream end.

It is assumed that a self-excited pressure vibration occurs when initial external disturbances such as the start or the stop of the water diversion occur at the downstream side of the pressure-reducing valve and the system converts the disturbance into an exciting force.

Figure 1: Assumption of accidents in the low-pressure system

The authors analyzed the pressure waveform of the self-excited pressure vibration that occurs when the pressure-reducing valve is placed in the middle of the pipeline and the direct-acting constant-flow valve is placed at the end by using field measurement data. The result strongly suggested that the self-excited pressure vibration occurs owing to the intrinsic oscillation period of the pipeline on the upstream and downstream sides of the pressure-reducing valve. Based on this result, it was proposed in this study that the occurrence of the self-excited pressure vibration be assessed by using the intrinsic oscillation period of the pipeline.
2 Intrinsic oscillation period obtained from transfer matrix of pipeline

2.1 Oscillation period of general pipeline

A self-excited pressure vibration can occur on the upstream side owing to the pressure-reducing valve when the pressure-reducing valve is placed in the middle of the single pipeline and the pipeline has a mechanism or property by which a minimal external disturbance is converted into an exciting force at the downstream end (Akiyoshi et al., 2017).

In this case, the pressure oscillation periods of the pipeline on the upstream and downstream side of the pressure-reducing valve are approximately equivalent. Hence, the pressure oscillation period \( t_{o} \) can be calculated using \( t_{o} = 4L/c \) (where \( L \) is the pipeline length and \( c \) is the wave velocity) under the boundary conditions of a constant head at one end point and zero flow rate at the other end point.

However, actual pipeline systems comprise pipe networks that branch out dendritically, complicated boundary conditions due to the intermingling of farms and paddy fields, various transitional facilities such as pressure-reducing facilities and gate valves, divergences and junctions. In addition, the pipe diameter and material vary widely.

Therefore, a water-hammer pressure model is required to be applied as the oscillation period varies significantly according to the structure of the system and the simple pressure oscillation period, which can be determined from the length of the pipeline and the pressure propagation velocity, cannot be applied.

2.2 Wave model and oscillation model

The wave model and the oscillation model are used in the assessment of the water-hammer pressure. They differ in the distribution of the elastic energy; the wave model takes into consideration that the constant pressure oscillates (propagates) in the direction of the tube axis, while the oscillation model takes into consideration that the pressure oscillates vertically throughout the pipeline.

In addition, the wave model is suitable when the time scale of the flow rate control (operation time of the valve) is significantly smaller than the response time scale of the system (intrinsic oscillation period) in a simple pipeline such as that in a power generation facility. In contrast, the oscillation model is suitable when both the aforementioned time scales roughly match in the complex pipeline, which forms an arborescent pipeline or pipe networks (Mitsuno et al., 1978, Mitsuno et al., 1982).

The phenomenon that actually occurs has a character that is intermediate between both the aforementioned models and can be assumed to approach either in response to the given conditions. Hence, in this study, an oscillation model is developed by using the transfer matrix that is used for finding the resonant period in the case of the forced oscillation phenomenon, and it is used to collectively evaluate the oscillation period of the complicated pipeline as the intrinsic oscillation period (Mitsuno, 1979; 1982).

2.3 Transfer matrix of pipeline

2.3.1 Wave equation

Considering unsteady phenomenon in the pipeline flow, Eq. (1) gives the continuity equation, and Eq. (2) gives the equation of motion when the friction loss term and pipe slope term are omitted.

\[
\frac{A}{K} \frac{\partial p}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad \text{(1)}
\]

\[
\frac{1}{A} \frac{\partial q}{\partial t} + \frac{1}{\rho} \frac{\partial p}{\partial x} = 0 \quad \text{(2)}
\]

where \( A \) is the cross-section area of the pipe, \( x \) is the distance from a reservoir, \( t \) is the time, \( p \) is the piezometric head in the pipe, \( q \) is the volumetric flow rate (= \( Av \)), \( \rho \) is the density and \( K \) is the combined modulus of elasticity of the pipe and fluid.

The one-dimensional wave equation, given by Eqs. (3) and (4), is obtained by eliminating \( p \) from Eqs. (1) and (2).

\[
\frac{\partial^2 q}{\partial t^2} - \frac{K}{\rho} \frac{\partial^2 q}{\partial x^2} = a^2 \frac{\partial^2 q}{\partial x^2} \quad \text{(3)}
\]

\[
a = \sqrt{\frac{K}{\rho}}
\]

\[
q = X(x) \sin(\omega t + \phi) \quad \text{(4)}
\]

where, \( a \) is the propagation speed of the wave.

Eqs. (5) and (6) are obtained when \( q \) is obtained from Eq. (4) and substituted in Eq. (3).

\[
\frac{\omega^2}{a^2} X + \frac{d^2 X}{dx^2} = 0 \quad \text{(5)}
\]

\[
X(x) = B \sin \frac{\omega t}{a} + C \cos \frac{\omega t}{a} \quad \text{(6)}
\]

where \( B \) and \( C \) are arbitrary constants.

\( q \) is obtained by substituting Eq. (6) in Eq. (4).

\[
q(x, t) = \left( B \sin \frac{\omega t}{a} + C \cos \frac{\omega t}{a} \right) \sin(\omega t + \phi) \quad \text{(7)}
\]

\( p \) is obtained by substituting Eq. (7) in Eq. (1) and integrating it with respect to time.

\[
p(x, t) = \frac{p_A}{A} \left( B \cos \frac{\omega t}{a} - C \sin \frac{\omega t}{a} \right) \cos(\omega t + \phi) \quad \text{(8)}
\]

The flow rate and the pressure of the pipeline are obtained from Eqs. (7) and (8).

2.3.2 Transfer matrix of direct pipe element

In a pipeline of length \( l \) and cross-sectional area \( A \), the pressure and flow rate at a selected point \( x \) within pipe elements are given by Eqs. (7) and (8). The amplitude of the
pressure and the flow rate at \( x = 0 \) (the left end of the pipeline) are set as \( P_1 \) and \( Q_1 \), and the boundary conditions are given by Eqs. (9) and (10).

\[
p(x,t) = P_1 \cos(\omega t + \phi) \tag{9}
\]
\[
q(x,t) = Q_1 \sin(\omega t + \phi) \tag{10}
\]

The arbitrary constants \( B \) and \( C \) in Eqs. (7) and (8) are given as follows.

\[
B = \frac{AP}{\rho a} \tag{11}
\]
\[
C = Q_1 \tag{12}
\]

Therefore, if the amplitude of the pressure and the flow rate at \( x = 0 \) is given, the temporal variation of the pressure and the flow rate at a selected point \( x \) can be described using Eqs. (13) and (14).

\[
p(x,t) = \left( P_1 \cos \frac{\omega t - \rho a x}{a} - \frac{\rho a}{A} Q_1 \sin \frac{\omega t}{a} \right) \cos(\omega t + \phi) \tag{13}
\]
\[
q(x,t) = \left( \frac{A}{\rho a} P_1 \sin \frac{\omega t - \rho a x}{a} + Q_1 \cos \frac{\omega t}{a} \right) \sin(\omega t + \phi) \tag{14}
\]

Eq. (15), which transmits the status of the inlet port 1 to the outlet port 2, is obtained by substituting \( x = l \) (the right end of the pipeline) in Eqs. (13) and (14). Setting the amplitude of the pressure and the flow rate as \( P_2 \) and \( Q_2 \), picking out the section relating to the amplitude and expressing it as a matrix.

\[
\begin{bmatrix} P_2 \\ Q_2 \end{bmatrix} = \begin{bmatrix} \cos \left( \frac{\omega t}{a} \right) & -\frac{\rho a}{A} \sin \left( \frac{\omega t}{a} \right) \\ \frac{A}{\rho a} \sin \left( \frac{\omega t}{a} \right) & \cos \left( \frac{\omega t}{a} \right) \end{bmatrix} \begin{bmatrix} P_1 \\ Q_1 \end{bmatrix} \tag{15}
\]

### 2.3.3 Transfer matrix of complex pipeline

The pressure and flow rate in the junction of each pipeline elements of the pipeline system that comprises \( n \) pipes are continued and combined with transfer matrices of each element, as shown in Eq. (16).

\[
\begin{bmatrix} P_n \\ Q_n \end{bmatrix} = \begin{bmatrix} T_{11}(\omega) & T_{12}(\omega) \\ T_{21}(\omega) & T_{22}(\omega) \end{bmatrix} \begin{bmatrix} P_1 \\ Q_1 \end{bmatrix} \tag{16}
\]

where \( T \) is the transfer matrix of the overall pipeline.

When the dead end of this pipeline system is completely shut and the boundary has a zero flow rate (\( Q_a = 0 \)), Eq. (17) is derived.

\[
Q_a = T_{21}(\omega) P_1 + T_{22}(\omega) Q_1 = 0 \tag{17}
\]

In addition, when a constant head boundary condition (\( P_1 = 0 \)) is considered at the start of the pipe, the frequency of Eq. (18) is obtained by applying the boundary condition to Eq.

\[
T_{22}(\omega) = 0 \tag{18}
\]

The frequency equation is given by Eq. (19) when two different pipes are connected. This study takes into consideration a pipeline of lengths \( l_1 \) and \( l_2 \), cross-sectional areas \( A_1 \) and \( A_2 \), and wave propagation speeds \( a_1 \) and \( a_2 \).

\[
T_{22}(\omega) = \cos \frac{\omega l_1}{a_1} \cos \frac{\omega l_2}{a_2} - \frac{A_2}{A_1} \sin \frac{\omega l_1}{a_1} \sin \frac{\omega l_2}{a_2} \tag{19}
\]

The intrinsic oscillation period \( T_0 \) is given by Eq. (20) on applying the Newton–Raphson method to Eq. (19), finding the solution and assuming the maximum intrinsic frequency.

\[
T_0 = \frac{2\pi}{\omega} \tag{20}
\]

This method can be applied to general pipelines including parallel sections, tandem sections, junctions and surge tanks, and for determining the intrinsic oscillation periods (Mitsuno, 1978; 1982).

### 3 Field measurement of intrinsic oscillation period of pipeline

3.1 Layout of the pipeline

Inagaki et al. (2007) conducted field measurement in a gravity-flow pipeline the total length of which was approximately 1.7 km and that obtained water from a water reservoir with a management water level of 167.4 m (NWL), as shown in Figure 2. The low-pressure pipeline adopted the single-stage decompression method, which reduces the static water level by approximately 28 m from the NWL of 167.4 m via an automatic pressure-reducing valve and decreases the control water level on the downstream side of the pressure-reducing valve to a WL of 139.0 m.

The pressure acting on a safety valve on the upstream and downstream sides of the pressure-reducing valve is 0.598 MPa (182.6 EL.m) on SF1 and 0.255 MPa (149.0 EL.m) on SF2. In addition, the set flow rate of the direct-acting constant-flow valve Q1 and Q2 is 0.0185 m³/s. The pressure-reducing valve.

3.2 Intrinsic oscillation period of the pipeline

The self-excited pressure vibration can occur when an automatic pressure-reducing valve is placed in the middle of the low-pressure pipeline. In this study, the installation position of the pressure-reducing valve is defined by the intrinsic oscillation period of the pipe.

Figures 3 and 4 show a plane development diagram of the pipeline on the upstream and downstream sides of the pressure-reducing valve.
Based on the plane development diagram, the authors determined the intrinsic oscillation period $T_0$ on the upstream and downstream side by constructing the transfer matrix of the complex pipeline. The intrinsic oscillation period is $T_{01} = 16.9$ s on the upstream side and $T_{02} = 15.3$ s on the downstream side as shown in Figure 2. The intrinsic oscillation period of the upstream and downstream side of the pressure-reducing valve on the pipeline are roughly equal. Therefore, the installation of the pressure-reducing valve in the middle of the pipeline allows the pressure oscillation periods of the pipeline system on the upstream and downstream sides of the pressure-reducing valve to be approximately equal ($T_{01} \approx T_{02}$).

### 4 Spectral analysis of waveform based on field measurements

The authors conducted an analysis of the pressure waveform based on the field measurement data in order to clarify a relationship between the intrinsic oscillation period of the pipeline and the occurrence of the self-excited pressure vibration.

#### 4.1 Field measurements

The field measurements were obtained using a combination of the sludge discharge valve, float-type hydrant, constant-flow valve, and safety valve, which are used to record the pressure waveform under various conditions. The history of the pressure variation for 9 h is collected as the field measurement data.

The authors show an analysis result of the field measurement data that was collected on opening the end valves S4 and S5 when the gate valves S2 and S3 are opened fully and on activating the constant flow valves Q1 and Q2 one-at-a-time or at the same time in order to verify the self-excited pressure vibration that occurs when the direct-acting constant-flow valve is installed at the end.

#### 4.2 Spectral analysis

Spectral analysis was applied as a method for analyzing the periodicity of the time-series behavior (Wada, 1997). Spectral analysis is an analytical method that can be used to evaluate the value, period and strength (amplitude) of the time-series data. In the spectral analysis, the periodic com-
ponents (spectrum) of the measured pressure waveform were researched using the fast Fourier transform (FFT), which is a method for obtaining a power spectrum by Fourier-transforming the time-series data directly.

4.3 Case A: constant flow valve Q1 is activated
The temporal variation in pressure on the upstream and downstream sides of the pressure-reducing valve and the upstream side of the constant flow valve is shown in Figure 5, which was obtained for a case wherein the constant flow valve Q1 on the branch line diverging from the downstream side of the pressure-reducing valve was operated.

Figure 6 shows the power spectrum of the period and the amplitude that was obtained by conducting a Fourier analysis of the pressure history shown in Figure 5. The result shows that the oscillation period based on the pressure waveform shown in Figure 5 is 19.5 s, which is slightly greater than the theoretical value obtained using the transfer matrix.

4.4 Case B: constant flow valve Q2 is activated
The temporal variation in pressure on the upstream and downstream sides of the pressure-reducing valve and the upstream side of the constant flow valve is shown in Figure 7, which was obtained for a case wherein the constant flow valve Q2 on the branch line diverging from the downstream side of the pressure-reducing valve was operated. Figure 8 shows the power spectrum obtained by conducting a Fourier analysis of the pressure waveform shown in Figure 7. The result shows that the amplitude is 0.042 MPa and the
The oscillation period is 15.8 s, and the oscillation period is roughly equivalent to the theoretical value obtained using the transfer matrix.

4.5 Oscillation period obtained field measurement data

Figure 9 shows the combination of the oscillation period and the amplitude for cases A and B whenever the experimental condition is different, and the primary pressure and secondary pressure of the pressure-reducing valve under the same experimental condition are connected by straight lines.

![Figure 9: Relationship between oscillation period and amplitude](image)

In this study, it was considered that the self-excited pressure vibration in the low-pressure pipeline was a system as follows; first, a minute agitation occurs at the end of the pipeline and propagates toward the pressure-reducing valve. Second, the secondary pressure of the pressure-reducing valve fluctuates, and the pressure wave is propagated toward the primary side via the secondary pressure control of the pressure-reducing valve. Finally, the pressure wave develops as a self-excited pressure vibration.

Spectral analysis indicates that the periods of the primary and secondary pressures are the same, but the amplitudes are different. Moreover, the phases of each waveform are not in alignment. If the correlation between time-series waveform of the primary and secondary pressures is then proved, the system in which the pressure-reducing valve propagates the secondary pressure as the primary pressure can be reinforced based on the experimental data.

5 Correlation between upstream and downstream pressure of the pressure-reducing valve

5.1 Interdependence of time-series waveform of primary and secondary pressure

The cross-correlation function indicates the extent to which two time-series waveforms are interdependent or similar, and is represented as a function of the phase-shift time $\Delta t$ of each waveform. The cross-correlation function can be determined by calculating the increase in the correlation coefficient between these waveforms, when the time-series waveforms $x(t)$ and $y(t+\Delta t)$ exist (Sato, 1999).

The cross-correlation function $R(\Delta t)$ for a certain $\Delta t$ is standardized as follows: the function takes the value of 1 when $x(t)$ and $y(t+\Delta t)$ coincide wholly and 0 when they are inconsistent at all. For instance, when $R(\Delta t)$ is 0 for any $\Delta t$, there are no interdependences or resemblances between $x(t)$ and $y(t+\Delta t)$.

5.2 Cross-correlation function

The cross-correlation function between primary and secondary pressure

Figure 10 shows the combination of the cross-correlation function between the primary and secondary pressures for cases A and B, the phase-shift time and the oscillation period.

Although each condition is different, the general characteristics can be listed as follows.

1. The primary and secondary pressures coincide under the same experimental condition and period at the constant flow valve.
2. The amplitude becomes large as the period becomes small.
3. The amplitude of the primary pressure increases up to 0.21 MPa when the period is approximately 15 s.
4. The minimum period is approximately 15 s, and periods less than 15 s are not generated.

The shortest oscillation period of 15 s that is derived from a field measurement approximates the theoretical value of the oscillation period on the upstream side ($T_{01} = 16.9$ s) and the downstream side ($T_{02} = 15.3$ s) of the pressure-reducing valve, which were obtained from the transfer matrix of the pipeline system based on the information of the pipeline. Therefore, the result implies that the theoretical value of the intrinsic oscillation period of the pipeline can be an index that shows the periodicity of the pipeline system.

In addition, the amplitude decreases as the oscillation period downstream of the pressure-reducing valve increases, and the period and the amplitude on the upstream side of the pressure-reducing valve show the same tendency. Moreover, the periods of the primary and secondary pressures are equal under the same experimental condition. This result thus implies that the pressure oscillations on the upstream and downstream sides of the pressure-reducing valve correlate strongly.

5.3 Cross-correlation function between primary and secondary pressure

Although there is a phase shift between the primary and secondary pressures, the cross-correlation function is 0.9 or more.

2. The phase-shift time is approximately $\Delta t = 2$ s near the intrinsic oscillation period. The time-series waveforms of the primary and secondary pressure
are interdependent.

3. It is shown that the secondary pressure propagates as the primary pressure via the pressure-reducing valve as the secondary pressure is phase-shifted toward the minus direction from the primary pressure.

As the verification result, it was clarified that the pressure oscillations on the upstream and downstream sides (primary and secondary sides) of the pressure-reducing valve are interdependent.

The self-excited pressure vibration in the low-pressure system can be assumed to occur because of the system, wherein the pressure variation occurs on the secondary side. This is because only the initial agitations propagate from the end to the pressure-reducing valve and toward the primary side via the secondary pressure control of the pressure-reducing valve.

6 Inhibitory effect of pressure oscillation owing to water-hammer absorption and relaxation equipment

6.1 Countermeasure for pressure oscillation control

The pressure oscillation is amplified on the upstream side when the natural oscillation periods upstream and downstream of the pressure-reducing valve are equal in the following process. The pressure wave shuttles in the pipeline as the minute pressure variation that occurs at the end is amplified and propagated by the pressure-reducing valve.

As a countermeasure for controlling the self-excited pressure vibration, a method can be considered that shifts the intrinsic oscillation period on the upstream or downstream sides of the pressure-reducing valve with the help of installed water-hammer absorption and relaxation equipment on the upstream or downstream side of the valve and increases the period of one side. An air chamber and a surge tank are used as the water-hammer absorption and relaxation equipment. The air chamber absorbs the inertial force of the water by compressing air in the chamber, which constrains the water hammer. The surge tank is a free surface tank that protects the pipe by raising the water level.

6.2 Inhibitory effect of pressure oscillation

The water hammer energy is absorbed by the water-hammer absorption and relaxation equipment. Energies, which are distributed to pipeline, decrease. Hence, the water-hammer pressure decreases. Consequently, the entire oscillation period increases as the apparent elasticity of the pipeline increases and the water hammer energy of the pipeline and the absorption equipment is redistributed (Mitsuno, 1981, Mitsuno, 1982).

Eq. (21) gives the frequency equation of the system, which includes a surge tank on the pipeline as shown in Figure 11. The oscillation period is expressed as shown in Eq. (20).

\[
\frac{\cos \alpha_1}{a} - \frac{\cos \alpha_2}{a} - K \cos \omega - \frac{\alpha_1}{a} - \frac{\sin \alpha_1}{a} - \frac{\sin \alpha_2}{a} = 0 \quad (21)
\]

where \( l_1 \) and \( l_2 \) are the length of the pipe, \( a \) is the propagation speed of the wave and \( K \) is the relative absorption coefficient.

The relative absorption coefficient is the proportion of the absorption property of the pressure absorption equipment to the pressure absorption property of pipe, as shown in Eq. (22).

\[
\bar{k} = \frac{k_a}{g(4a) / a^2} = \frac{k_a}{g(l_1 + l_2) \pi D^2 / 4 / a^2} \quad (22)
\]

where \( k_a \) is the absorption ability (coefficient) of the pressure energy of the pressure absorption equipment.

In the case of the surge tank, the pressure energy absorption ability is equal to the cross-sectional area of the surge tank, as shown in Eq. (23).

\[
k_a = \frac{\pi d^2}{4} \quad (23)
\]

where \( d \) is the diameter of the surge tank.

In this study, it is assumed that the pipeline in the upstream and downstream sections, has a diameter \( D = 200 \) mm, the propagation speed of the pressure wave is \( c = 320 \) m/s and the total length of the pipeline is \( L = 1,200 \) m. Figure 11 indicates the oscillation period for various location and diameters of the surge tank.

A part of the pressure wave is absorbed, and its residue propagates toward the upstream side when the pressure variation occurs at the end of the pipeline and the water hammer propagates toward the absorption equipment.

The intrinsic oscillation period of 15–17 s is amplified by approximately two and a half times if the surge tank, which is equivalent to the pipeline and whose relative absorption coefficient is 8.7, is installed on the upstream and the downstream ends of the pressure-reducing valve. In addition, the oscillation of the pipeline is equivalent to the case where there is no absorption equipment, i.e., when the ab-
sorption equipment is installed at the upstream end.

Hence, the synchronization of the oscillation period of the pipeline can be prevented if the effect of the location and scale of the surge tank on the pressure oscillation period of the pipeline can be fully comprehended. The surge tank of an appropriate scale can thus be installed at the appropriate location on the upstream and downstream sides of the pressure-reducing valve.

In addition, the air chamber can be used as the water-hammer absorption and relaxation equipment. It is an equipment which just replaced the air to the compressed air, and its function is the same as that of the surge tank. Its relative absorption coefficient is 0.1–100 owing to the scale of the equipment.

In a practical pipeline such as that of a dam and power station, the open-type surge tank is primarily used. A installing the open-type surge tank on the downstream section of the pipeline is difficult owing to its descending slope toward the downstream end. Hence, installing a closed-type surge tank is also an option. However, it is not often used in gravity-flow pipelines but just in the pump station as the scale and the facility of devices are complex, and thus managing it becomes complicated.

6.3 Effect of air stick on downstream side of pressure-reducing valve

The open type surge tank is subject to a restriction on the installation position because of the altitude of the pipeline and the static level. Hence, the small-scale air stick, which includes \( \phi 75\)-mm and \( \phi 200\)-mm polyvinyl chloride pipes, is installed on the downstream side of the pressure-reducing valve as the provisional surge tank, as shown in Figure 12.

The air stick is generally installed in order to reject and provide air in the pipeline and to prevent the destruction of the pipeline due to the rapid pressure variation. The air stick does not affect the oscillation period of the downstream section of the pipeline as it is installed in the upstream end of the downstream section of the pipeline. The surface of the water in the air stick is open to air when the pressure oscillation that occurs at the downstream end reaches the downstream side of the pressure-reducing valve. Hence, the objective of the air stick is to convert the pressure oscillation into the vibration of the water surface and to reduce the pressure variation on the secondary side of the pressure-reducing valve.

The effect of the air stick was verified by opening the gate valve S7 after starting the flow in the condition wherein the gate valve S7 of the air stick is closed. Figure 13 shows the temporal variation in the pressure at the upstream and downstream section of the pressure-reducing valve and the upstream section of the constant flow valve. The end valve S5 in branch line 2 is opened and closed four times. The air stick is closed from 3,600-3,800 s and from 4,700-4,800 s, and the pressure variation occurs. In addition, the gate valve S7 of the air stick is opened from 3,850-4,650 s. When the end valve S5 is opened and the air stick is operated, the pressure on the downstream side of the pressure-reducing valve oscillates temporarily. However, it disappears in a short time and the pressure oscillation does not occur on the downstream side. In addition, the pressure oscillation also does not occur in the upstream side when the pressure in the downstream side of the pressure-reducing valve is stabilized.

The pressure vibration during the operation of the pressure-reducing valve is caused by the temporary locking owing to the anchoring of the piston of the pilot valve. The result of the suppression of the pressure vibration through the operation of the air stick on the downstream side of the pressure-reducing valve indicates that the pressure oscillation is not caused by the internal mechanism of the pres-
sure-reducing valve. Moreover, this result supports the hypothesis that the transmission mechanism involves the pressure variation on the downstream side being detected by the pressure-reducing valve and propagated toward the upstream side.

Figure 13: Temporal variation in pressure in the sections upstream and downstream of the pressure-reducing valve and the section upstream of the constant flow valve

7 Method for evaluation of the occurrence of the self-excited pressure vibration using the oscillation periods of pipeline

The position of installation of the pressure-reducing valve is determined from the boundary of the government-, prefecture-, or corporation-managed project, the economy of the pipeline, and the hydraulic factor such as the required diverted water level. Hence, there can be a variety of combinations of the intrinsic oscillation period of the pipeline and the installation position of the pressure-reducing valve.

In addition, practical pipelines include complicated lines such as arborescent lines and pipe networks, which include divergences and junctions. The pipe diameter and pipe material are varied, and the control equipment include valves and the transitional facilities include surge tanks. Therefore, a substantial change in the oscillation period corresponding to the structure of the system cannot be avoided. Hence, a reliable method for predicting the occurrence of the pressure oscillation required.

This study proposes a method for predicting the occurrence of a self-excited pressure vibration in the following flow by using the dimensions of the facilities along the pipeline. The general flow used for predicting the occurrence of the pressure oscillation is described below.

1. The dimensions of the pipeline on the upstream and downstream of the pressure-reducing valve (pipe length \( l \), pipe diameter \( D \), pipe thickness \( b \), elastic coefficient \( E \), connection of the pipe, etc.) are defined.
2. The propagation speed \( a \) of the pressure wave of the pipeline is determined.
3. The transfer matrix \( T \) of the overall pipeline is developed.
4. The intrinsic oscillation frequency is calculated by solving the frequency equation.
5. The intrinsic oscillation period \( T_0 \) is calculated.
6. The intrinsic oscillation periods of the upstream \( T_{01} \) and downstream \( T_{02} \) sides of the pressure-reducing valve are compared, and it is determined that the self-excited pressure vibration occurs if \( T_{01} \approx T_{02} \).

8 Conclusions

This study involved an analysis of the pressure waveform of the self-excited pressure vibration that occurs in a low-pressure system comprising a pressure-reducing valve. The analysis was based on field measurement data that was collected under the following conditions.

1. The pressure-reducing valve is placed in the middle of the pipeline.
2. The direct-acting constant-flow valve is placed at the end of the pipeline.

Consequently, the following results were obtained.

1. Intrinsic oscillation period from the transfer matrix
   The intrinsic oscillation period \( T_0 \) of the upstream and downstream sides of the pressure-reducing valve, which is obtained from the transfer matrix of the pipeline, is \( T_{01} = 16.9 \text{ s} \) in the upstream section of the pressure-reducing valve and \( T_{02} = 15.3 \text{ s} \) in the downstream section.
2. Oscillation period obtained from the spectral analysis of the pressure waveform based on field measurements
   The shortest oscillation period of the measured data, which is obtained from the spectral analysis of the pressure waveform based on field measurements, is approximately \( 15 \text{ s} \), and the amplitude of the primary pressure is the maximum at this point. The theoretical value of the intrinsic oscillation period of the pipeline is similar to the shortest oscillation period obtained based on the measured data. Hence, this is an indicator of the periodicity of the pipeline.
3. Cross-correlation function and phase-shift time of the primary and secondary pressures
   The cross-correlation function of the pressure oscillations on the upstream and downstream sides (primary and secondary side) of the pressure-reducing valve is the maximum and the phase-shift time is the minimum near the intrinsic oscillation period. The primary and secondary pressure of the pressure-reducing valve are independent, and the secondary pressure propagates as the primary pressure via the pressure-reducing valve.
4. Oscillation period of the pipeline and installation position of the pressure-reducing valve
   The self-excited pressure vibration could occur in
the low-pressure system on using the pressure-reducing valve when the pressure-reducing valve is placed in the middle of the pipeline and the oscillation periods of the pipeline on the upstream and downstream sides of the valve are the same.

5. Inhibitory effect of the pressure oscillation using the surge tank and the air stick

If a surge tank of the appropriate scale is installed at the appropriate point of the upstream and downstream sides of the pressure-reducing valve, the synchronization of the pressure oscillation period of the pipeline can be prevented. When the air stick is placed on the downstream side of the pressure-reducing valve, the pressure oscillation is converted into the vibration of the water surface and the pressure variation on the secondary side of the pressure-reducing valve is reduced.

6. Evaluation method of the occurrence of the self-excited pressure vibration

In this study, a method that can be used to determine the occurrence of a self-excited pressure vibration by using the dimensions of the facilities along the pipeline is proposed. In the future, the authors intend to conduct the verification of the generation mechanism of the self-excited pressure vibration using a numerical model, which simulates the case wherein the pressure-reducing valve is placed at any point of the pipeline, and the analysis of the pressure waveform of the field measurement data. In addition, the authors will verify the validity of the method used for determining the occurrence of the self-excited pressure vibration based on the intrinsic oscillation period of the pipeline, which is defined by the position of installation of the pressure-reducing valve.

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