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Leak detection through wavelet analysis of pressure measurement for injected pressure for a simple pipeline system

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ABSTRACT

An effective leak detection method is one of the most demanding techniques for the management of water distribution systems. A leak detection scheme with pressure wave analysis using a rapid manipulation of hydraulic boundary conditions is not always suitable owing to substantial pressure variation, which can result in undesirable consequences for pipeline systems. The introduction of a relatively small pressure pulse through a regulated pressure generator can substantially diminish the potential damage of high- or low-pressure surges. Wave reflection due to the leakage boundary condition can be useful for predicting the leak location based on the time-domain reflectometry of the pressure signal. Further elaborate analysis for leak detection can be performed using wavelet analysis of the pressure signal, which provides leak response features in the time/frequency domain. Two distinct experimental conditions were employed to illustrate the impact of resonance on the hydraulic structure, such as a pressurized tank. The developed method demonstrates the potential of leak detection in a laboratory-scale pipeline system.

Keywords: Pipeline system; Leakage detection; Pressure generator; Wavelet analysis

1. Introduction

Proper management of water distribution systems is important to satisfy the increasing demand for drinking water. Most urban infrastructures for water distribution are located underground, which often suffer from leakage due to various reasons, such as excessive internal or external forces and natural disasters. Water loss from leakage can deteriorate the quality of drinking water and reduce the efficiency of water distribution systems. Furthermore, water leaked from the water supply system can result in the creation of sinkholes and ground subsidence. Therefore, leak detection in water distribution systems has been a demanding research topic in the field of pipeline management.

Depending on the method of analyzing the pressure data, the leakage detection method has evolved into three distinct approaches (e.g., time domain, frequency domain, and time-frequency domain). Inverse transient analysis in the time domain to match the measurement and prediction pressure has been widely recognized for predicting leakage locations in pipe networks [1]. The enumeration of pipe networks into smaller parts enabled the determination of leak size and location through inverse transient analysis [2]. The intensity of the transient can be important in improving leakage prediction accuracy for either single or multiple leakages in pipe network systems [3]. The uncertainty issue in data acquisition for the application of inverse transient analysis has also been investigated in both a laboratory pipeline system and a quasi-field system [4].

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Alternatively, the detection of pipeline abnormalities in the frequency domain through pressure wave variation has been studied using the transfer matrix method [5]. Wave oscillation harmonics were used for abnormality detection and a method for comparing wave-forms via their impulse response was proposed [6,7]. The implementation of the unsteady friction model substantially improves the predictability of pressure variation under a transient event, which improves the predictability of leakage in pipe networks [8].

To analyze the pressure wave features in both the time and frequency domains, we employed the wavelet transform as a signal processing technique. Leak edge detection was performed through the wavelet transform analysis for pressure variation by the valve maneuver [9]. Parameters for leakage, such as size, location, and number of leakages, can be determined via numerical modeling. It is known that the uncertainty in leak detection affects responses in both the time and frequency domains of the pressure signal [10]. The transient introduced through an abrupt valve maneuver or pump shutdown can damage the pipeline owing to the surge associated with the rapid variation in flow velocity. In particular, the difficulty in fast valve closure tends to be pronounced for a pipeline system with a large diameter. Therefore, an alternative method to generate transients has been explored using a controllable pressure wave generator, which can reduce the risk of potential damage due to excessive pressure variation.

Leak detection in the time and frequency domains has been studied using injected pressure waves and pressure measurements [11]. The injected pressure and its reflected pressure signal were analyzed through a coupling between wavelet transform analysis and the Lagrangian model [12]. The pressure wave generator can be used to detect various abnormalities, such as illegal side branch, partial blockage, partially closed valve, and leakage along the pipeline system [13]. Pipeline branches and pipe ends can be detected through pressure wave analysis, using a pressure wave generator for a pipeline system with a length of 1,324.8 m and a diameter of 506.6 mm [14]. Therefore, a combined approach between the pressure injector for controllable transient and comprehensive signal processing techniques (e.g., the wavelet transform) can provide an alternative method for pipeline leak detection, considering system security from abrupt pressure variation and uncertainty in the time and frequency domains. The difference in pressure signals between leakage and no leakage can be characterized through time/frequency domain representation, which can be used to determine both the existence of leakage and location.

The analysis of the leakage signal is further substantiated through unexplored signal process techniques, such as decomposition and reconstruction of leakage features. The enhanced signal processing of the pressure date can facilitate the identification of leakage through the regulated pressure measurement of pipeline systems.

2. Material and methods

2.1. Unsteady analysis

The flow velocity and pressure in the pipeline are spatially and temporally varied, which can be widely explained by sequential generation and transient decay. The generation of hydraulic transients often results in damage to the pipeline structure, such as rupture and burst, due to significantly higher or lower pressure than the steady pressure head. The pressure variation can be generally described using the Joukowsky equation as follows:

$$\Delta h = -\frac{c\Delta V}{g} \tag{1}$$

where Δh = head difference, ρ = flow density, c = wave speed, ΔV = flow velocity, and g = gravitational acceleration.

The wave speed can be evaluated by Wylie and Streeter [15]:

$$c = \sqrt{\frac{K/\rho}{1+\left(K/E\right)\psi}} \tag{2}$$

where K is the bulk modulus of the fluid, E is the elastic modulus of pipeline materials, and ψ is the ratio of the inner diameter to the pipe wall thickness.

2.1.1. Continuous wavelet transform

The frequency characteristics of the time series data can be interpreted using a more generalized function than that of the Fourier transform through the introduction of a wavelet transform with the additional feature presentation in the time domain; that is, the wavelet transform can provide simultaneous information of data in both the time and frequency domains. Furthermore, the strengths of the wavelet transform, flexibility, and high applicability to non-stationary signals can be useful for analyzing the pressure data obtained in this study. The continuous wavelet transform (CWT) can be expressed as follows [16]:

$$W_n\left(s\right) = \sum_n x_n \frac{1}{\sqrt{s}} \varphi^*\left(\frac{n-\delta t}{s}\right) \tag{3}$$

where x_n = Morlet wavelet transform of time series, $n = 1,2,\ldots,N$ (total length of data), s = scale, which is a factor that controls the mother wavelet, and φ^* = the mother wavelet in which the wavelet was used. The Morlet wavelet can be expressed as $\varphi^*(\eta) = \pi^{-0.25}e^{i\omega\eta}e^{-0.5\eta^2}$, where ω = the dimensionless periodic factor and η = time factor.

In this study, the leakage detection approach was explored using the CWT with the Morlet mother wavelet basis. Furthermore, considering the high recovery feature of the Morlet basis, a reconstruction of key wave features from the transformed CWT can be performed to obtain the identifiable signal for leakage, as follows:

$$x_t = \frac{\delta_j \cdot \delta t^{1/2}}{C_\delta \cdot \varphi\left(0\right)} \sum_{ns} \frac{\mathrm{Re}\left(W_n\left(s\right)\right)}{\sqrt{s}} \tag{4}$$

where δ_j = spacing of scale, C_δ = reconstruction factor as 0.776, which was suggested empirically for full reconstruction [17], $\varphi(0)$ is the standardized wavelet base function in the initial time step, and $\mathrm{Re}(W_n(s))$ is the real part of the wavelet transform.

Eq. (4) enables the reconstruction of CWT for a designated frequency range. The reconstruction can be executed on a statistically significant scale in the frequency domain, which can be transferred back into the time domain for comparative analysis [18].

2.1.2. Unsteady flow laboratory

A schematic of the laboratory pipeline system is shown in Fig. 1. The pipeline system is composed of an upstream reservoir (tank A), a supplying pipeline, an upstream air chamber (tank C), a main pipeline, a downstream air chamber (tank D), a drainage pipeline, and a downstream reservoir (tank B). The total length of the pipeline extension is 151 m and the length of the experimental pipeline segment is 90 m, which is located on the ground floor. The pipeline material is stainless steel, and the inner diameter of the pipeline is 0.0272 m, with a wall thickness of 0.0021 m. The estimated Darcy–Weisbach friction factor was 0.0244. The steady flow rate between the upstream and downstream reservoirs can be controlled by the head difference between tanks A and B, which are located on the 5th floor. Two air chambers (tanks C and D) in the experimental pipeline section secure the pressure wave path at the ground floor.

A pressure transducer (AEP: TPUSB, 0.05 %) with a high data acquisition rate (4,800 Hz) was installed adjacent to the downstream control valve. To represent a leakage boundary condition, controllable orifices were made at constructed at 27 and 72 m from the downstream control valve. Pressure injection and monitoring had been performed under three distinct leakage conditions, with leakage rates of 13 mL/s (Leakage 1), 39 mL/s (Leakage 2), and 65 mL/s (Leakage 3). The total flow rate was 90 mL/s and respective leakage rates were 14.4% (Leakage 1), 43.3% (Leakage 2), 72.2% (Leakage 3). The experiments were conducted under two conditions; first, that the valve at tank D was closed, indicating no resonance between pressure injection and downstream air chamber. Second, the valve at tank D was open, introducing resonance between the injected pressure and downstream air chamber. The laminar steady flow condition with a flowrate of 90 mL/s can be controlled by the pressure head difference of 0.25 m between tank A and tank B.

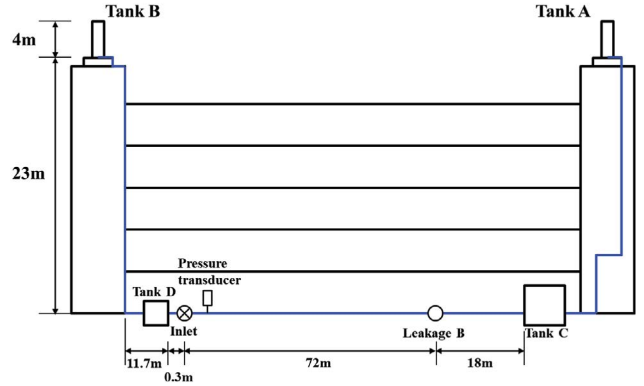

Fig. 1. Schematic of unsteady flow laboratory pipeline system.

2.1.3. Pressure wave generator

The pressure wave generator is shown in Fig. 2. The pressure of the wave generator can be regulated via the injected gas and its pressure gauge, with a control valve facilitating the injected pressure. To control the pressure impulse from the wave generator into the pipeline system, a solenoid valve is installed at the connecting portion of the main pipeline. The water level in the pressure injector can be checked using an externally installed manometer. The travel time of the pressure reflection can be calculated as $\tau = 2L/c$ (L = length of pipe, c = wave speed), which allows evaluation of the wave propagation speed.

3. Results and discussion

3.1. Pressure wave analysis

3.1.1. Condition without a pressure resonance between pressure wave injector and hydraulic structure

The pressure injection experiment was performed under the condition of no pressure resonance between the water tank (25 m pressure head) and pressure generator. The pressure from the wave generator was injected with a pressure head of 30 m, which is 5 m higher than the steady pressure head. Three different leakage conditions were used for the pressure wave experiment: no leakage, leakage 1 (relatively small), and leakage 2 (relatively large). While a pressure wave can be bounced back from tank C

Fig. 2. A picture of a pressure wave generator.

for the no-leakage condition, that of a leakage condition additionally addressed the reflection from the leakage.

Fig. 3 shows the pressure responses under no leakage and two different leakage conditions. The pressure wave appeared to bounce back at 0.13 s, indicating the reflection from tank C. As shown in Fig. 3a, the pressure rises to 0.01 s and vibration can be observed until 0.05 s, indicating the opening of the solenoid valve. The pressure reflection from Tank C can be seen at 0.13 s in all conditions. The impact of leakage on the falling pressure can be noted at 0.14 s, which exhibited greater damping for the larger leakage. The pressure time series were amplified between 0.10 and 0.12 s as shown in Fig. 3b. The difference between no leakage and leakage conditions showed an apparent pressure damping difference between leakage 1 and leakage 2 of 0.3 and 0.7 m, respectively. The wave speed was assumed to be 1,346 m/s and the distance to the leakage was 72 m, indicating that the round travel distance of the pressure wave was 144 m. This means that the travel time for the pressure wave is 0.107 s, using $\tau = 2L/c$, where L and c are the round travel distance and wave speed, respectively. The travel times for leakages 1 and 2 were 0.1089 s and 0.1092 s, respectively, indicating that the errors were 0.0019 s and 0.0022 s, respectively. The predicted leakage locations for leakage 1 and 2 were 73.29 and 71.49 m, indicating errors of 1.79% and 2.07%, respectively.

3.1.2. Condition of pressure resonance between pressure wave injector and hydraulic structure

There can be a repeated wave oscillation between the pressure wave injection point and tank B, which can be characterized as a high-frequency resonance. The pressure reflection damping from the leakage cannot be observed under the resonance condition, as shown in Fig. 4. While Fig. 3 shows the limited pressure variation at 0.02 s under the no-resonance condition, the pressure resonance condition increases up to 0.25 s and stabilizes at 1 s. The pressure time series in Fig. 4a presents the wave reflection from the pressurized tank between 0.01 and 0.03 s, which resulted from the abrupt opening of the solenoid valve. The reflected wave from tank C can be also observed at 0.13 s and that from the leakage can be found between 0.10 and 0.11 s, as shown in Fig. 4b. No reflected wave oscillation can be found for leakage 1 but the apparent wave impact can be detected for leakages 2 and 3 at 0.1062 and 0.1021 s, respectively. Using $\tau = 2L/c$,

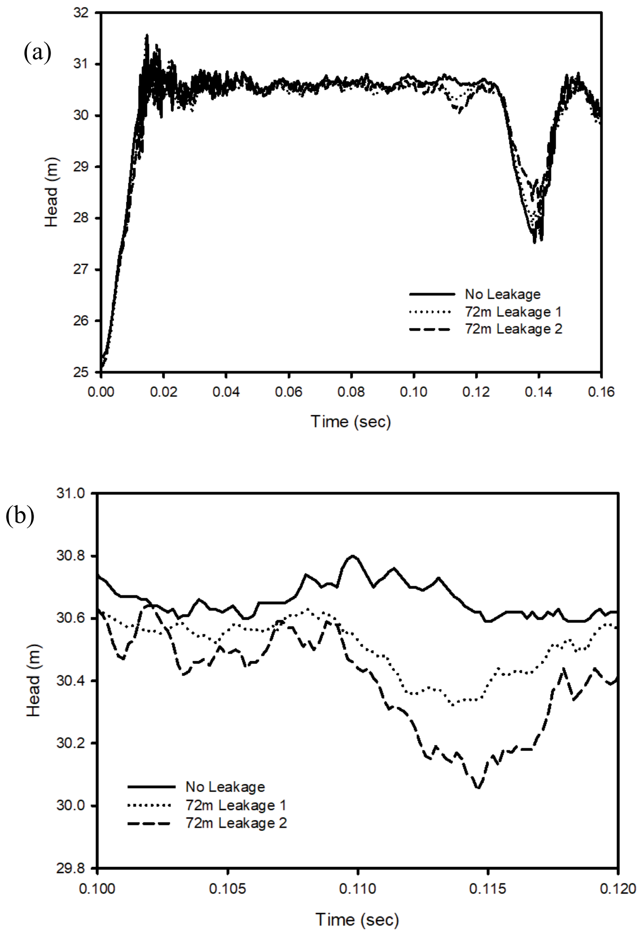

Fig. 3. Pressure responses under no leakage and two different leakage conditions without pressure resonance condition (a) 0–0.16 s and (b) 0.10–0.12 s.

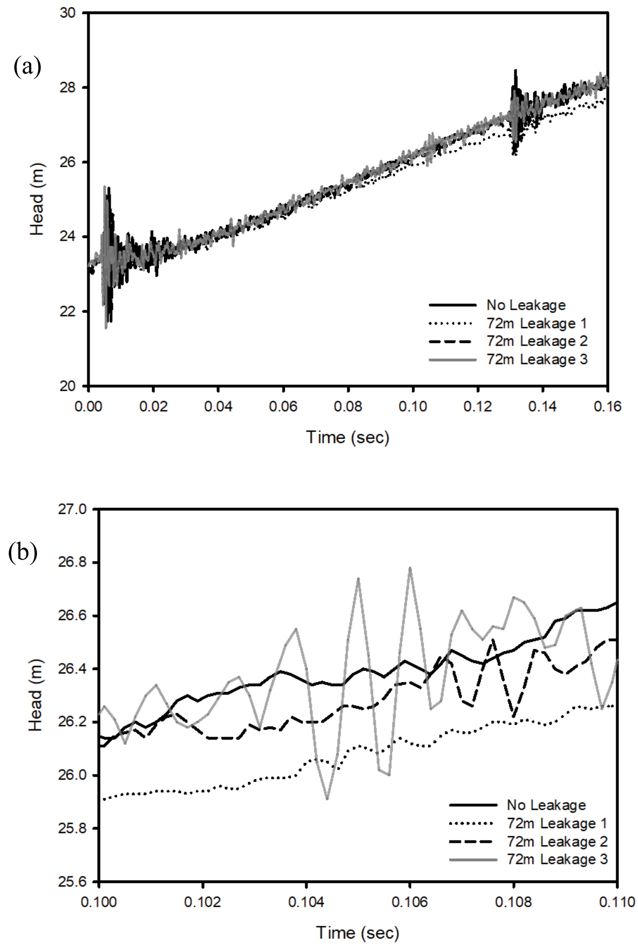

Fig. 4. Pressure responses under no leakage and three different leakage conditions with pressure resonance conditions (a) 0–0.16 s and (b) 0.10–0.11 s.

where L is the distance to the leakage and c is the wave speed, which depends on pipeline features, the predicted leak locations for leakages 2 and 3 were 71.47 and 68.72 m indicating 0.73% and 4.56%, respectively. The wave speed can be changed for dimensions (e.g., pipeline diameter and thickness) and material (e.g., elastic modulus) by Wylie and Streeter [15]. This means that leakage can be detected by the pressure damping impact under the no-resonance condition while the reflection wave from leakage addresses the oscillatory pressure reflection under a resonance condition.

3.2. Wavelet analysis

Depending upon the size of the leakage, the feasibility of leak detection via visual inspection can be limited. Wavelet analysis can be applied to detect leakage location through further investigation of the time/frequency domain. Considering the difference in the wave response feature between the no-resonance and resonance conditions, wavelet analysis employing the Morlet basis function was performed for 1 and 0.16 s, respectively.

3.2.1. Condition without a pressure resonance between pressure wave injector and hydraulic structure

Fig. 5 presents the wavelet transform of the pressure series under no leakage and leakage 2 conditions. Wavelet transforms for two distinct conditions both demonstrated that high ranges of wavelet power tend to decrease in later time steps; this can be explained by the repeated pattern

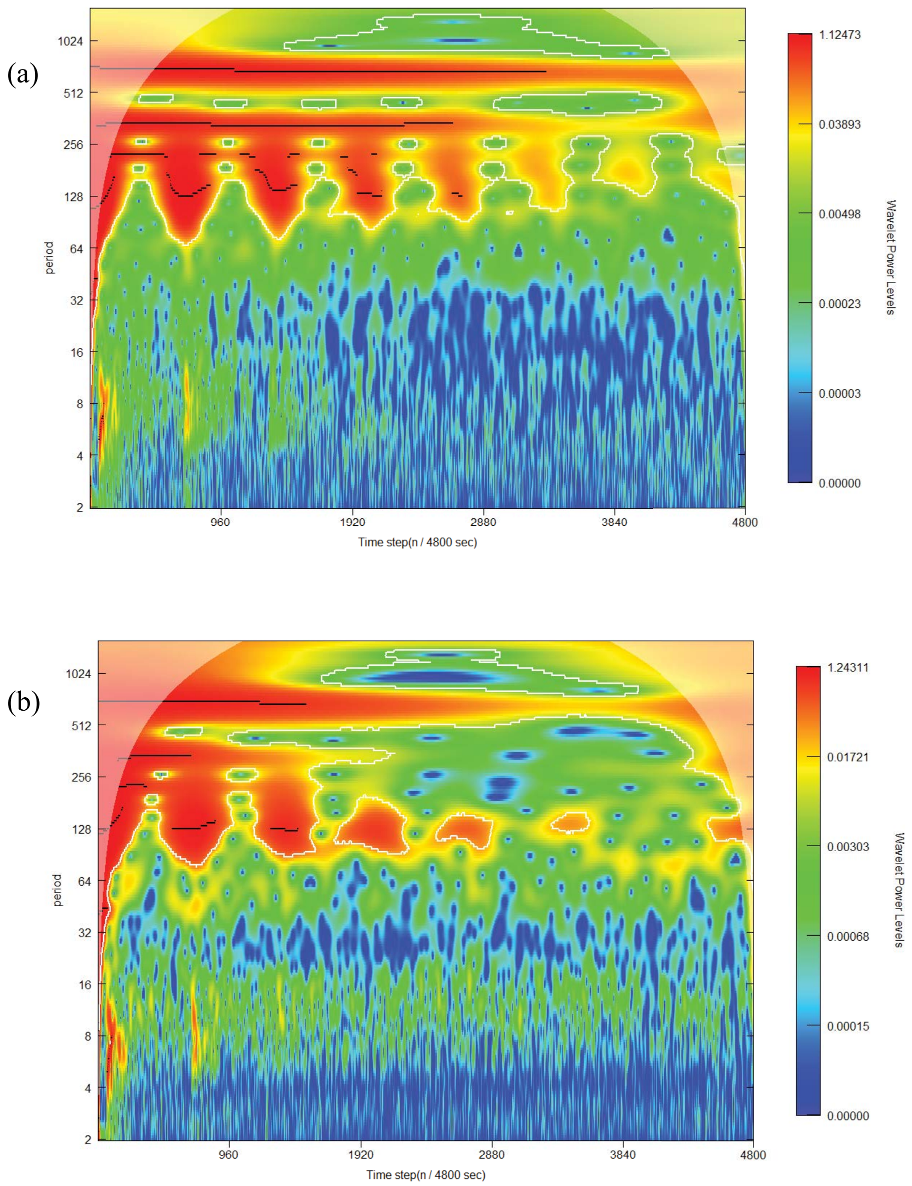

Fig. 5. Wavelet transform of pressure series under no leakage and leakage 2 conditions without pressure resonance condition (a) no leakage and (b) leakage 2.

of pressure wave interaction with the pressurized tank under the no-resonance condition. However, the wave power between periods 256 and 512 demonstrated a more apparent reduction in the higher leak quantity condition, which can also confirm the reduced black line, indicating a statistically significant range. This means that the feasibility of leakage presence detection can be obtained through frequency domain analysis under the no resonance condition. The pressure signal used in Fig. 5 can be decomposed and reconstructed for a designated period. Considering the distinctive leakage feature between periods 256 and 512, the pressure signal was reconstructed within the corresponding period for a p-value of less than 0.05 (Fig. 6). Compared to Fig. 6a for the no-leakage condition, Fig. 6b for the leakage 2 condition shows an apparent stagnant signal from the time domain of 2000 in the reconstructed signals, which confirmed the presence of leakage.

3.2.2. The condition of pressure resonance between pressure wave injector and hydraulic structure

High-frequency oscillations can be found in the pressure response for all resonance conditions. The injected pressure introduces both an increase in pressure and oscillatory behavior; the increasing trend can be removed to delineate the reflected wave with vibration. The differenced signal during 0.16 s was analyzed through the wavelet transform. The common feature of the wavelet transform under resonance conditions is an increase in the wavelet power between periods 4 and 8 at time steps 30 and 670 (Figs. 7a and b). The wavelet power level rises at time step 540, as shown in Fig. 7b. If leakage is generated at 72 m, the effect of the leak is seen after step 512 by calculation of $\tau = 2L/c$. Including the first injection point at 30, the wavelet power level rises at step 540. The higher the leak quantity, the greater the oscillatory behavior in the wave response.

The wavelet transform was statistically significant ($p < 0.05$) between periods 4 and 8, and the corresponding reconstruction can be performed. The pressure signal showed the initial injection point and reflection from the tank through the reconstructed signal, as shown in Fig. 7. Furthermore, a notable vibration can be found at time step 540 in the reconstructed signal (Fig. 8b), which can be attributed to the higher oscillation in the greater leakage. The degree of leak identification can be modulated as the p-value constraint is relaxed ($p < 0.3$), as shown in Fig. 9a and b.

The identification capability of leak location was confirmed at a time of 0.16 s under the resonance condition (Fig. 10a and b). The pressure injection experiment under resonance conditions demonstrated that the wavelet analysis

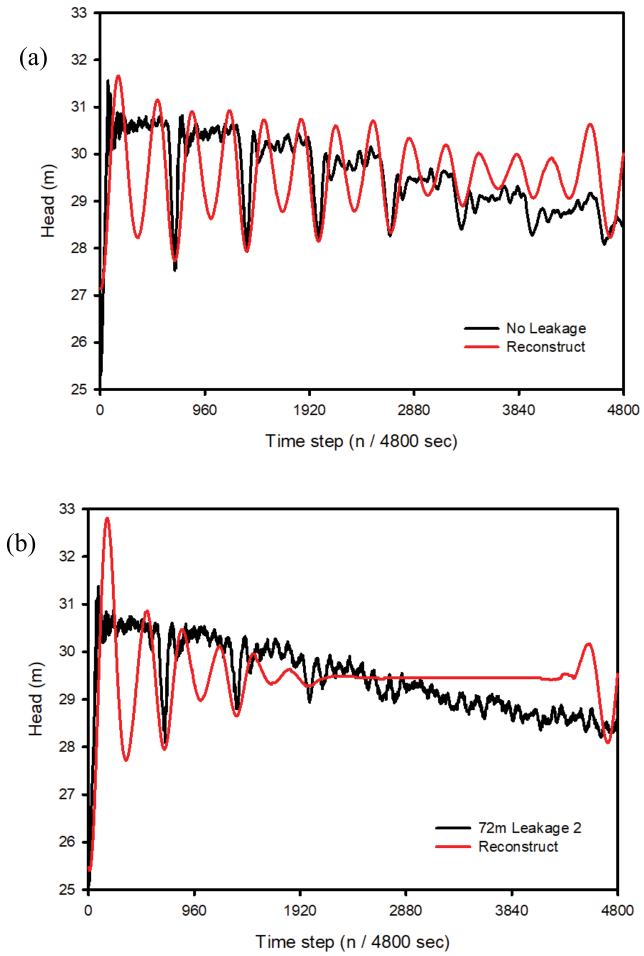

Fig. 6. Reconstruction of pressure series between period 256 and period 512 under no leakage and leakage 2 conditions without pressure resonance condition (a) no leakage and (b) leakage 2.

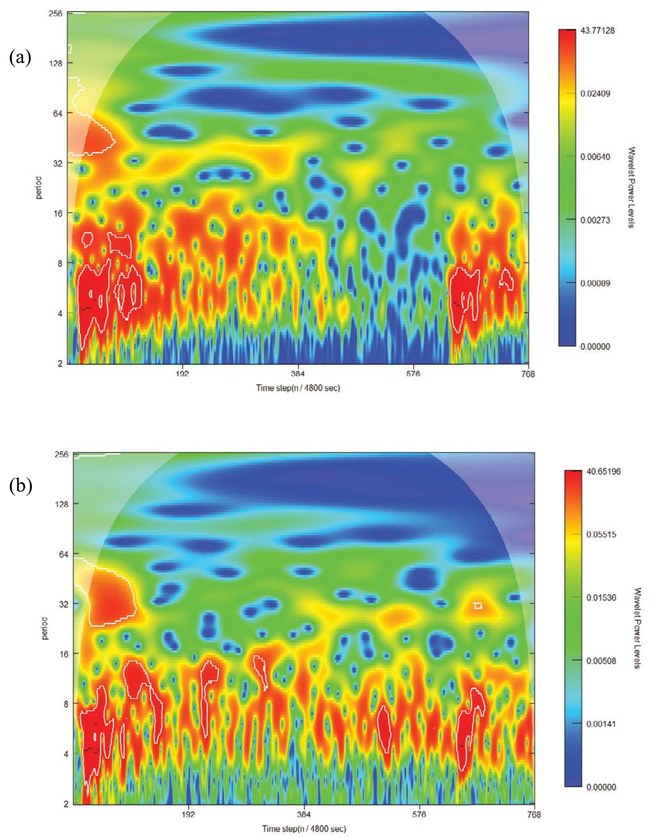

Fig. 7. Wavelet transform of pressure series under no leakage and leakage 3 conditions with resonance condition (a) no leakage and (b) leakage 3.

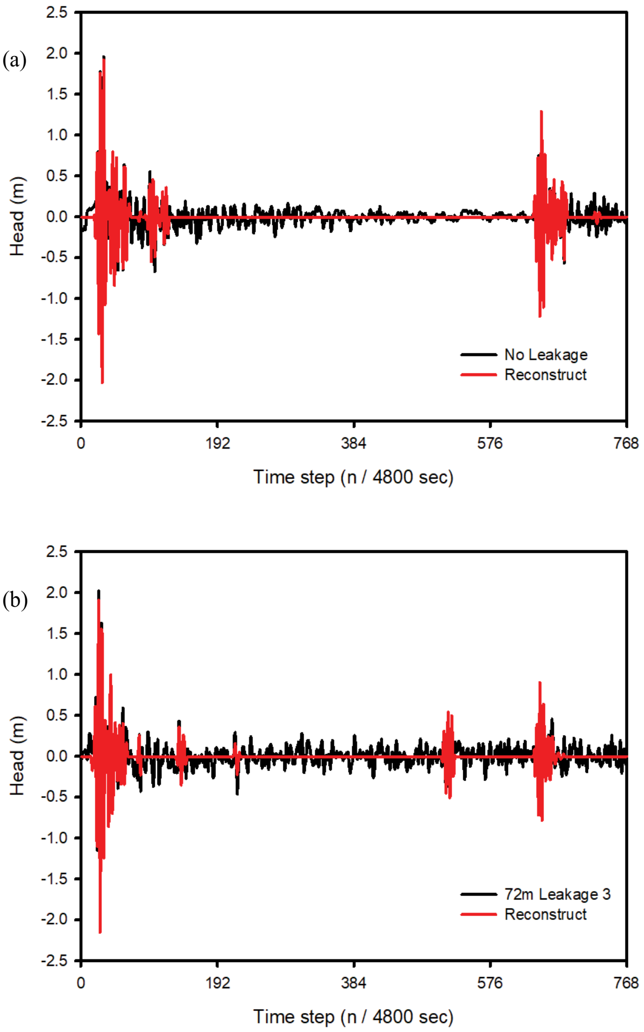

Fig. 8. Reconstruction of pressure series between period 4 and period 8 under no leakage and leakage 3 conditions with resonance condition (a) no leakage and (b) leakage 3.

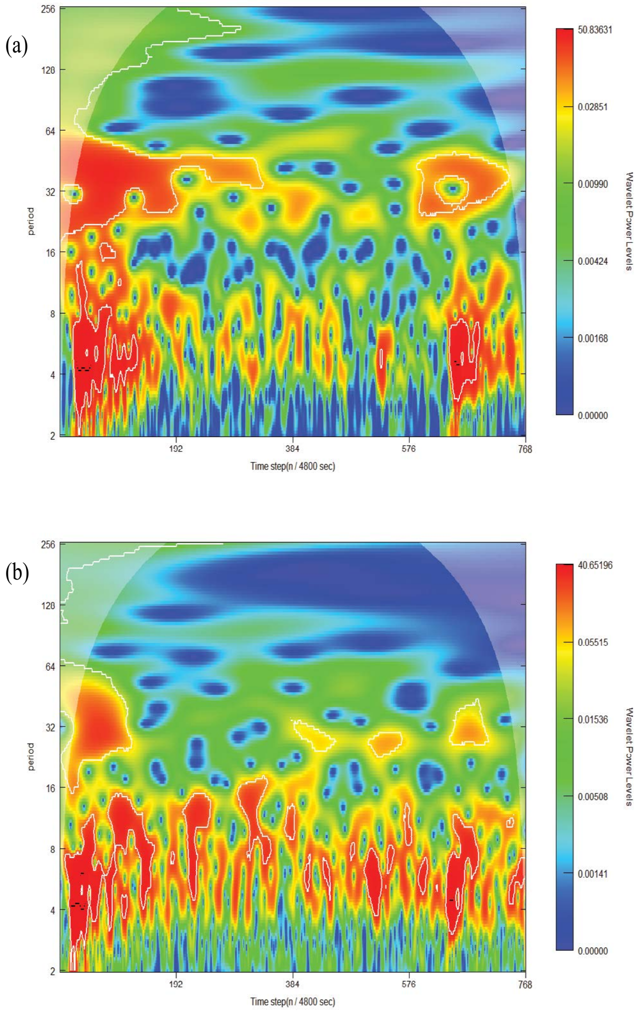

Fig. 9. Wavelet transform of pressure series under leakage 2 and leakage 3 conditions with resonance condition, the constraint of p-value relaxed as $p < 0.3$ (a) leakage 2 and (b) leakage 3.

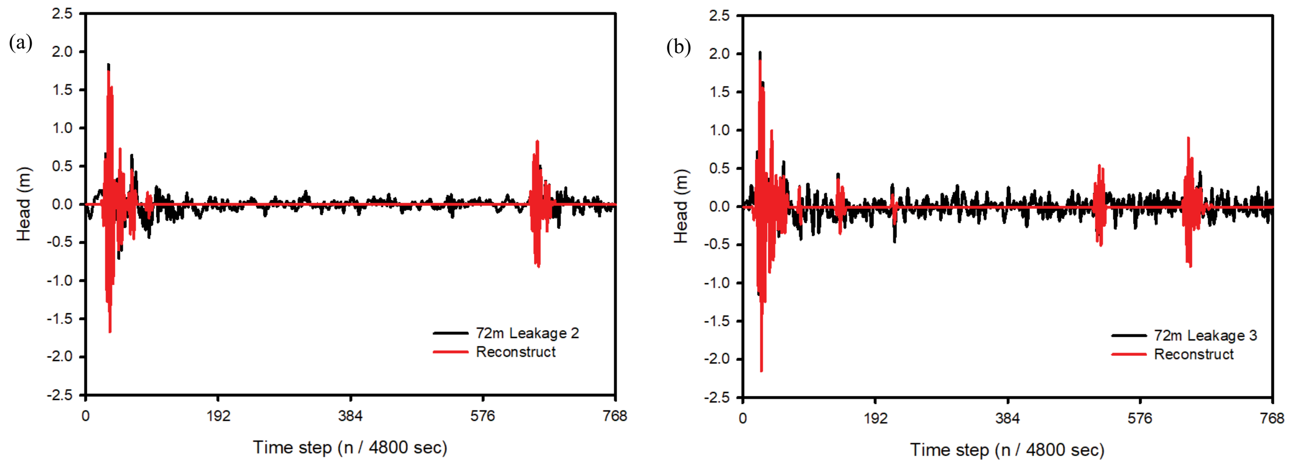

Fig. 10. Reconstruction of pressure series between period 4 and period 8 under leakage 2 and leakage 3 conditions with resonance condition, the constraint of p-value relaxed as $p < 0.3$ (a) leakage 2 and (b) leakage 3.

in the pressure signal provides improved predictability in leak presence and quantity.

4. Conclusions

A regulated pressure injection device was introduced to generate a controlled transient event as an alternative for the valve maneuver, which can minimize the impact of a surge in pipeline systems. Experimental results indicated that the manipulated pressure pulse can be useful for identifying the leakage location, both under resonance conditions with a supplementary pipe device and no resonance condition. The presence of leakage can be identified through the damping of the reflected pressure wave from the hydraulic boundary of leakage under the no-resonance condition but the reflected vibration wave can be found for the resonance condition, which can be explained by the high-frequency interaction with an adjacent pressurized tank. Time-domain reflectometry can be applied in leakage identification for a pressure time series of 0.16 s for the no-resonance condition. A CWT for 1 s provides a notable difference in wavelet power in the frequency range of 256 and 512 periods owing to the presence of leakage, which can also be substantiated by the leak quantity. A reflected wave with vibration can be found for a pressure time series of 0.16 s under resonance conditions. Wavelet analysis for the pressure time series demonstrated a notable difference in the high-frequency range from 4–8 periods under resonance conditions. Considering the carefully planned experimental conditions in this study, further study is required for up-scaled and complicated pipe networks to improve the applicability of the developed method to real-life systems.

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Symbols

Δh — Head difference
ρ — Flow density
c — Wave speed
g — Gravitational acceleration
K — Bulk modulus of the fluid
E — Elastic modulus of pipeline materials
ψ — Ratio of the inner diameter to the pipe wall thickness
x_n — Morlet wavelet transform of time series
s — Scale, which is a factor that controls the mother wavelet
φ^* — Mother wavelet in which the wavelet was used
ω — Dimensionless periodic factor
η — Time factor
δ_j — Spacing of scale
C_δ — Reconstruction factor

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