Wave velocity selection for leakage localization of water pipeline by Variational Mode Decomposition

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Abstract. Water pipelines are susceptible to leakage due to deterioration over time, pipe corrosion, water hammer and soil movement. Water leakage results in losses of revenue and can cause devastating consequence to the environment. Water leakage often happens below ground and remains undetected until a sizable crack has been developed on the pipeline. In the event of a leak, water from the pressurized pipeline expels through the crack at high velocity and generates acoustic waves which propagate along the pipeline. These waves can be picked up by acoustic emission (AE) sensors attached on the surface of the pipe without interfering with the operation of the pipeline. To pinpoint the location of a leak, it requires at least two sensors to be placed on each side of the leak along the pipe. The location of the leak can be located by knowing the time delay of arrival (TDOA) of the acoustic waves at both sensors by employing cross-correlation technique. Leak location is commonly calculated using a constant wave velocity which corresponds to the pipe material. However, the localization error is often large because acoustic wave does not travel along the pipeline at a fixed velocity due to wave dispersion phenomena. The velocity of the acoustic wave is dependent on the frequency and mode of the wave. This paper proposes a leak localization method with an innovative wave velocity selection method based on mode separation by Variational Mode Decomposition (VMD). The proposed method is validated by a leak simulation experiment and it achieves an accuracy of within 7.72% in leak localization.

1. Introduction

Water is a vital and depleting resource around the world. In some countries, the scarcity is so severe that policies are needed to be implemented to preserve this vital resource. Water transmission pipelines are susceptible to leakage as it deteriorates naturally with time due to corrosion, water hammer, soil movement and poor construction quality. Water leakage not only results in loss of revenues but also causes devastating consequence on the environment such as soil erosion, nearby physical asset damage and water contamination. In Malaysia, the amount of non-revenue water is nearly 36% of the total water supplied [1]. Considering the average water rates of about US$0.33 per cubic meter, the cost due to non-revenue water is about US$1.85 million per day. The saving from the loss is more than enough to sustain a leakage monitoring system.

Acoustic emission (AE) is commonly used for leak localization. In the event of a leak, water from the pressurized pipeline will expel through the crack with a high velocity [2]. The unstable turbulent pressure field at the crack due to the rapid discharge of water generates acoustic waves which propagate along the pipeline in both directions from the leak. These acoustic waves can be picked up by acoustic emission (AE) sensors attached at both sides of the leak without interfering the water flow in the pipeline.
The times of arrival of AE waves at both sensors can be used to localize the position of the leak. The distance of the leak from one of the sensors, \( x \) can be calculated by:

\[
x = (D - v\Delta t) / 2
\]

where \( D \) is the distance between AE sensors, \( v \) is the wave propagation velocity in pipe and \( \Delta t \) is the time delay of arrival (TDOA) of the AE waves at the two sensors [3]. One of the most common techniques used to estimate the TDOA of the AE waves is to employ cross-correlation function to the signals measured by the two sensors \( s_1(t) \) and \( s_2(t) \), which is expressed by:

\[
R_{12}(\tau) = E[s_1(t)s_2(t + \tau)]
\]

where \( R_{12}(\tau) \) is the cross-correlation function of the measured signal \( s_1(t) \) and \( s_2(t) \), \( E \) denotes expectation and \( \tau \) denotes time delay. The \( \Delta t \) in equation (1) is estimated by the value of \( \tau \) which corresponds to the highest peak in the cross-correlation function.

The leak signal in the measured signal is often masked by the background noises such as flow induced noise, pump noise and valve noise. These noises can cause the peak in the cross-correlation function becomes undistinguishable, consequently increase the difficulty of identifying the TDOA of the AE waves. The leak signal is a non-linear and non-stationary signal. The characteristic of the leak signal and noises are inconsistent and subject to change with the pipeline operating conditions. Thus, an adaptive non-stationary signal processing method has to be employed to extract the leak information.

One of the common methods is Empirical Mode Decomposition (EMD). EMD has been used for pipeline leak detection because it is a data driven technique where no base function is required for the decomposition process [4]. EMD works by recursively screening and decomposing a given signal into a number of high to low frequency modes. However, it has several drawbacks, such as mode mixing problem and lack of exact mathematical model for the decomposition process [5]. Variational Mode Decomposition (VMD) is a new self-adaptive non-stationary decomposition technique [6]. It can adaptively decompose a signal into a number of modes with a limited bandwidth that dense around their center frequencies. Unlike EMD, VMD has a solid mathematical foundation and it can non-recursively decompose a signal and control its decomposition convergence condition reasonably well. VMD has been used for leak localization on natural-gas pipeline and is proven to be superior to EMD [7].

Leak location is commonly calculated using a constant wave velocity which corresponds to the pipe material. However, wave velocity is not constant due to wave dispersion phenomena. Wave velocity is dependent on the mode and the frequency of the wave. Most decomposition methods decompose a given signal into a number of modes with different frequency bands. Signal de-noising is done by eliminating the unwanted modes and reconstructing the signal with the remaining modes. These methods tend to mix the modes with different wave velocity and causes ambiguity in the selection of wave velocity.

This paper proposes a water leak localization algorithm with an innovative wave velocity selection method based on mode separation by VMD. The effectiveness of VMD in separating the modes with different wave velocity and the necessity of selecting wave velocity based on the frequency of the mode are examined. The accuracy of the proposed algorithm is validated by a leak simulation experiment and is compared with the common leak localization technique using a constant wave velocity.

2. Proposed Leak Localization Algorithm

![Figure 1. Proposed leak localization algorithm.](image-url)
In this section, the mode separation algorithm using VMD and the method of selecting wave velocity are discussed. The overall algorithm is illustrated in figure 1. In the event of a leak, acoustic wave will be generated due to the high discharge pressure of water from the crack which propagates along the pipeline in both directions (downstream and upstream) from the leak. At the time when the acoustic wave reaches the sensors, the wave energy attenuation had occurred. Due to the difference in distance of the sensors from the leak, each sensor will receive the wave with different attenuation and time delay. The acoustic wave received will also been distorted because of the presence of defects along the pipeline caused by corrosion and welded connection joint along the propagating path [4]. Since the paths between the sensors on each side of the leak are different, the signals received by the two sensors are different and it can be expressed by:

\[ s_1(t) = \alpha x(t - \tau_1) + \delta_1(t) \]  
\[ s_2(t) = \beta x(t - \tau_2) + \delta_2(t) \]

where \( s_1(t) \) and \( s_2(t) \) are the received signals, \( x(t) \) is the leak signal, \( \alpha \) and \( \beta \) are the attenuation factors of the leak signals in their respective paths, \( \tau_1 \) and \( \tau_2 \) are the time delays of the leak signal at the respective sensors, \( \delta_1(t) \) and \( \delta_2(t) \) are the distorted components including noise.

The acoustic wave generated from the leak is a multimodal wave which is dispersive in nature [8]. The wave usually propagates along the pipeline in three different modes, namely, longitudinal, flexural and torsional modes. Knowing the wave mode is important because these waves travel in different velocity at different mode and frequency. The relationships of wave velocities, modes and frequencies are illustrated by the pipe dispersion curve shown in figure 2 which is plotted using PCDISP software in Matlab [9]. The waveform of the acoustic wave will change and broaden when it propagates along the pipeline because each distinct wave mode possesses different propagation velocity. As a consequence, it affects the performance of the cross-correlation function as the peak becomes undistinguishable. This effect will be more severe when the sensors are located further away from the leak.

The selection of wave velocity is important as it has serious impact on the accuracy of leak localization. The AE sensor attached on the pipe surface is usually sensitive to the radial displacement of the pipe surface. Figure 3 illustrates the radial displacement of pipe surface caused by different modes in different frequency range. Some wave modes cause more radial displacement than the other modes. It can be observed that F(1,1) and L(0,1) modes are dominant in causing radial displacement of the pipe surface. However, L(0,1) mode only becomes a dominant mode starting from 20 kHz and it has almost same velocity as F(1,1) mode. Thus, the selection of wave velocity in this study will be based on F(1,1) mode which ranged from 800 m/s to 2800 m/s. A method for selecting the correct wave velocity is essential and it will be discussed in the following sections.

![Figure 2. Pipe dispersion curve.](image-url)  
![Figure 3. Radial displacement of pipe surface.](image-url)
2.1. Variational Mode Decomposition (VMD)

VMD is a signal decomposition technique proposed by Dragomiretskiy et al. [6]. It can adaptively decompose a given input signal into k numbers of amplitude-frequency modulated wave modes that has its components dense around their corresponding center frequency through an iterative process of finding optimal solution to a variational problem. The expression of the constrained variational model can be written as:

\[
\min_{\{u_n\}, \{\omega_n\}} \sum_n \left\| \int \left[ \left( \delta(t) + \frac{j}{\pi t} \right) * u_n(t) \right] e^{-j\omega_n t} dt \right\|^2 \quad (5)
\]

\[
\sum_n u_n = s(t) \quad (6)
\]

where \(\{u_n\}\) and \(\{\omega_n\}\) represent the set of modes and center frequencies of the components after decomposition. The summation of these \(u_n\) modes will be the original input signal, \(s(t)\). The modes and its center frequency are continuously updated through iteration of the decomposition process. For complete algorithm of VMD can be referred to [6]. The two most important input parameters of VMD are the K parameter which specify the number of modes after decomposition and the \(\alpha\) parameter which control the tightness of the band-limits of each mode.

VMD is suitable for leak detection because of its self-adaptive nature. The characteristic of the leak signal is not consistent as its intensity and frequency bandwidth are subjected to change with pipeline operating conditions and the turbulence flow at the crack. VMD is able to decompose the leak signal adaptively as the center frequency of the modes will change according to the bandwidth of the leak signal. As illustrated in figure 1, the measured signals \(s_1(t)\) and \(s_2(t)\) will be decomposed individually by VMD into their own respective modes. Since the paths from the leak to both sensors are different, the center frequency of the decomposed modes of \(s_1(t)\) and \(s_2(t)\) will be different. When the wave propagates along the pipeline, the high frequency components of the leak signal will attenuate faster than the low frequency components. The signal received by the sensor located further away from the leak will have less high frequency components and thus the signal will be decomposed to lower frequency modes. Due to the inconsistency, the modes of the signal of each sensor have to be matched and sorted into different frequency bands according to its center frequency.

2.2. Selection of wave velocity

Each mode travels in different velocities depending on its frequency as illustrated in figure 2. Thus, only the modes from each sensor that has the same frequency band will be correlated using cross-correlations function. The time delays of arrival of the modes of different frequency band are different. The wave velocity is selected from the pipe dispersion curve shown in figure 2 according to the frequency of the mode. Leak location can then be calculated using equation (1) with the time delay and its corresponding wave velocity.

The results of the cross-correlation function can also be used to identify whether the modes contain useful information. In general, the existing of a sharp peak in the cross-correlation function indicates that the pair of modes are highly correlated and contain the information of leak [4]. It also indicates that the SNR of the signals are high with low noise corruption. However, the absence of an obvious peak in the cross-correlation function indicates that the two modes are not correlated or contain a lot of noises. These modes of a particular frequency band will be discarded and only the pair of modes with a sharp peak in cross-correlation function will be used for leak localization. The effectiveness of the proposed method is validated by a leak simulation experiment on a pipeline test rig.
3. Experimental Setup
A 3 inch galvanized steel water pipeline test rig is used to validate the proposed algorithm for leak localization. The test rig consists of a 10 mm hole for leak simulation with an operating pressure of 2 bar. There are 4 AE sensors magnetically attached on the pipeline as shown in figure 4 and the sensors used are Soundwel SR40M with an operating frequency range between 15 kHz to 75 kHz. The signals are acquired by NI 9223 simultaneous analog input module. The location of the leak is defined as 0 m and the positions of the AE sensors are defined relative to the leak location as shown.

![Figure 4. Positions of leak and sensors on the pipeline](image)

4. Results
Figure 5 shows the decomposition of a leak pulse signal received by sensor 3 located 18m from the leak using VMD. The signal is decomposed into multiple modes with distinct frequency band. The waveform of the decomposed mode is narrower than the raw signal because it has a narrow frequency band, hence the range of the wave velocity is small. Each distinct frequency mode has a different wave velocity and it arrives at the sensor in different time. In figure 6, it can be observed that the TDOA of the modes in different frequency bands are different. This implies that different wave velocity has to be selected based on the frequency of the modes. The common de-noising methods by reconstructing the modes are less ideal because it results in ambiguity in the selection of wave velocity as the modes with different propagation velocity are mixed. Thus, the TDOA of the leak signal should only be determined by cross-correlation of the modes from each sensor that have a similar frequency band. The wave velocity can then be selected based on the frequency of the mode from the pipe dispersion curve in figure 2.

The results of the leak localization experiment with different pair of sensors are shown in Table 1. The accuracy of the proposed algorithm is within 7.72%. The wave velocity is selected based on the F(1,1) mode of the pipe dispersion curve according to the frequency of the mode. Leak localization using a constant wave velocity is also calculated. As a comparison, the error of the leak location with constant velocity is larger. Thus, the necessity of selecting wave velocity based on the frequency of the mode is confirmed.

![Figure 5. Modes of the decomposition of a leak pulse signal from sensor 3 (18m) using VMD.](image)  ![Figure 6. Cross-correlation function of modes in different frequency bands.](image)
Table 1. Results of leak localization using selected wave velocity versus fixed velocity.

| Sensor Positions | Based on wave velocities of F(1,1) mode in respective frequencies | Based on fixed wave velocity of F(1,1) mode in 40 kHz |
|------------------|-------------------------------------------------------------------|------------------------------------------------------|
|                  | f, kHz | Δt (ms) | v (m/s) | d (m) | Error (%) | v (m/s) | d (m) | Error (%) |
| 1 2              | 20     | 11.60   | 800     | 13.14 | 6.14      | 1800    | 18.94 | 35.29     |
| -3m 14m          | 35     | 7.35    | 1500    | 14.01 | 0.07      | 1800    | 15.12 | 8.00      |
|                  | 45     | 6.17    | 1900    | 14.35 | 2.50      | 1800    | 14.05 | 0.35      |
|                  | 25     | 13.75   | 1100    | 18.06 | 0.33      | 1800    | 22.88 | 27.11     |
| -3m 18m          | 35     | 11.12   | 1500    | 19.39 | 7.72      | 1800    | 20.50 | 13.89     |
|                  | 45     | 8.33    | 1900    | 18.41 | 2.28      | 1800    | 18.00 | 0.00      |
|                  | 20     | 24.88   | 800     | 22.45 | 2.05      | 1800    | 34.89 | 58.59     |
| -3m 22m          | 30     | 14.43   | 1400    | 22.60 | 2.73      | 1800    | 25.49 | 15.86     |
|                  | 45     | 9.66    | 1900    | 21.67 | 1.50      | 1800    | 21.19 | 3.68      |

5. Conclusion
The proposed water leak localization algorithm with an innovative wave velocity selection method based on mode separation by Variational Mode Decomposition (VMD) is verified and is capable of achieving an accuracy of within 7.72% in leak localization. Acoustic wave does not travel along the pipeline with a single constant velocity due to wave dispersion phenomena and its wave velocity is dependent on the mode and frequency of the wave. It is shown that the modes with different wave velocity can be separated by VMD and its frequency information can be used to select the wave velocity. The TDOA of the leak signal can be determined by the cross-correlation of modes from each sensor that have a similar frequency band. In future, the proposed algorithm will be implemented in Field Programmable Gate Array (FPGA) to form a real-time pipeline leakage monitoring system. The system will incorporate techniques that are commonly used in acoustic emission application such as hit-based technique, thresholding and event triggering.

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