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Real-time Leak Localization of Pipeline by Acoustic Emission and Variational Mode Decomposition

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Keywords: acoustic emission, variational mode decomposition, leak detection, leak localization

ABSTRACT

This paper proposes a real-time water pipeline leak detection system using acoustic emission (AE) signal and Variational Mode Decomposition (VMD) for accurate leak detection and localization. The leak generated AE signal is often masked by background noise presence in the pipeline, causing difficulty in locating leak. The leak information in the signal can be effectively extracted by VMD. However, this technique requires a lengthy processing time, which poses a challenge for real-time leak localization. To overcome this, the system incorporates a hit-based leak event recognition technique to capture the segment of signals that contain leak information so that only these small segments of data are needed to be processed as such it enables VMD to be implemented in real-time. In conjunction with VMD, a more reliable wave velocity selection technique is introduced to achieve a better accuracy in leak localization as compared to the traditional method.

INTRODUCTION

Water distribution pipelines are generally buried underground and susceptible to leakage over time due to corrosion, ground movement and poor construction quality. Leakage often remain undetected until a sizable crack is formed which lead to the collapse of surrounding structures due to soil erosion caused by the gushing leaking water. This has resulted in enormous loss of revenue and detrimental to the environment. In Malaysia, the percentage of non-revenue water (NRW) is almost 36% of the total water supplied which cause a loss of US$ 1.85 million per day (Lai, Chan and Roy, 2017). The saving from the loss is more than enough to sustain a pipeline leakage monitoring system.

Acoustic Emission (AE) technique is a Non-Destructive Testing (NDT) technique that has been used for pipeline leak detection and localization (Miller *et al.*, 1999). AE is a transient elastic stress wave generated during pipeline leakage due to high velocity discharge of water from the crack. These waves can propagate along the pipe and detected by AE sensors attached on the pipe surface without halting the pipeline operations. Leak detection utilizes the kinematics law of motion to derive the position of leak based on the relationship of time delay of arrival (TDOA) of AE wave at the sensors, wave propagation velocity and the positions of the sensors on the pipeline. The TDOA of AE wave is commonly determined by employing cross-correlation technique (Gao *et al.*, 2004). However, the presence of noises in the pipeline such as flow-induced noise, pump noise and pipe fittings noise can mask the leak generated signal which cause enormous difficulty in determining the peak of the cross-correlation function.

Leak generated signal is non-linear and non-stationary. As such the characteristic of the signal is not consistent and subjected to change due to the fluctuations of pipeline operating conditions and the interaction of water from the crack with the surrounding medium. Thus, an adaptive non-stationary signal decomposition technique is needed to extract the leak information from the signal. One of the common adaptive techniques is Empirical Modes Decomposition (EMD). EMD has been used

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for adaptive noise cancellation in water pipeline due to its data driven nature and does not require any base function for the decomposition process (Guo *et al.*, 2016). It can decompose a given input signal recursively into a number of low to high frequency modes. However, it has several disadvantages, such as the lack of mathematical models for its decomposition process and has mode mixing problem. A new technique known as Variational Mode Decomposition (VMD) is proven to be more superior than EMD and is recently been applied to leak localization of natural-gas pipeline (Xiao *et al.*, 2018). This research study the decomposition results by both VMD and EMD techniques and demonstrates the effect of mode mixing problem for accurate leak localization. Unlike EMD, VMD does not have mode mixing problem and the improvement on accuracy of leak localization using VMD is verified in the study.

Most leak localization techniques developed in the past are not for implementation in real-time. This poses a risk of water leak not identified in time until the offline data are analysed in the laboratory. Thus, this paper focuses on developing a real-time leak localization technique utilizing the recent proven effective VMD signal processing technique.

VMD is usually performed in the post-processing stage due to its lengthy processing time. The processing time of VMD is significantly affected by the sample length of the input data. AE based leak detection application often uses high frequency AE sensor which requires high sampling rates during acquisition. Thus, the number of collected data sample per unit time is often large. This poses a challenge for real-time leak localization if every segments of data have to be processed.

A common method used to counter this challenge is to employ hit-based event recognition technique. This technique captures the AE burst signal known as a hit by comparing the envelope of the signal with a detection threshold which can be derived from the moving root mean square (RMS) of the signal (Jiang and Xing, 2012). The segment of signals that contain leak information is known as a leak event. A leak event is recognized when the hit timing of all the sensors are in correct sequence and are within the expected maximum event duration based on the minimum wave velocity and the sensor positions. Signal processing, analysis and leak localization are only performed when a leak event is recognized. This enables leak localization based on VMD to be implemented in real-time because only a small segment of data is needed to be processed which provides sufficient time for signal processing to be performed before the next event is recognized. The location of leak will be determined using probability histogram and based on the cumulative results of the histogram.

Most AE leak localization techniques assume that the wave propagation velocity is constant and only dependent on the pipe geometry and material. However, wave velocity is often not constant due to the wave dispersion phenomena and it is dependent on the mode and the frequency of the wave (Wang *et al.*, 2016). A more reliable velocity selection method has to be developed because the accuracy of leak localization can be affected by wrong selection of wave velocity.

This paper proposes a real-time water pipeline leak localization system using acoustic emission signals by incorporating threshold-based hit detection, leak event recognition, VMD and probability histogram. The hit-based event recognition algorithm is implemented in Field Programmable Gate Array (FPGA) and the performance of the entire leak localization system is evaluated by a leak simulation experiment. A more reliable wave velocity selection method is also developed and the improvement on the accuracy of leak localization is evaluated and compared with traditional wave selection method. Based on real-life experiment, the developed system is capable of achieving an accuracy of within 3.29% in leak localization.

At this moment, the developed system is limited for the detection and localization of leak on steel pipeline. The application on other pipe materials has yet to be tested and will be conducted in future research.

This paper is arranged with an introduction of the motivation of this work in Section 1. The theories of leak localization mechanism using AE, Variational Mode Decomposition (VMD) and wave dispersion effect are described in Section 2. In Section 3, the algorithm of the proposed real-time leak localization system is presented which include the hit-based leak event recognition technique, signal processing and the details of the leak localization algorithm. In Section 4 the experimental setup of the research is described. In Section 5, the results of the threshold-based hit detection, leak event recognition and modes pair selection technique of the developed system, followed by the study of the effect of wave dispersion on wave velocity and the performance results of the leak localization algorithm and the developed real time leak localization system are presented. Lastly, the conclusion of the research and the planned future work are presented.

THEORY

Leak Localization Mechanism using Acoustic Emission

In the event of a leak, AE waves are generated due to unstable turbulence pressure field around the crack caused by the high velocity of discharge water from the pipe (Anastasopoulos, Kourousis and Bollas, 2009). These waves propagate along the pipe and can be detected by AE sensors attached on the pipe surface as shown in Figure 1.

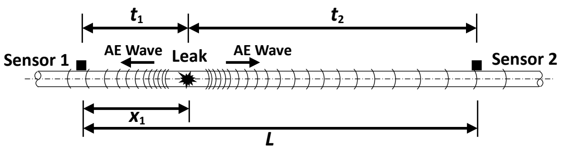


Fig. 1. Relationship of leak and AE wave propagation.

Leak localization can be done by placing two AE sensors on the pipeline, one at the upstream and the other at the downstream of the pipeline. The position of leak can be determined by knowing the TDOA of AE waves at the two AE sensors, wave propagation velocity in the pipe and the positions of the AE sensors on the pipeline. Assume that the leak is located in between these two sensors, the distance of leak from one of the sensors, x_1 can be expressed by:

$$x_1 = \frac{L - v\Delta t}{2}, \tag{1}$$

where L denotes the distance between the two AE sensors, v denotes wave propagation velocity in the pipe and $\Delta t = t_2 - t_1$ denotes the TDOA of AE waves at the two AE sensors.

Leak generated AE wave tends to attenuate and distort when it propagates down the pipeline (Guo *et al.*, 2016). The waves received by the sensors located at the upstream and downstream of the pipeline are different because the propagation paths of the wave are different. The presence of defects along the pipeline such as corrosion, pipe fittings and welded connection joint will cause distortion to the propagating wave. Thus, the signals received by the two sensors, $y_1(t)$ and $y_2(t)$ are different and can be expressed by

$$\begin{aligned} y_1(t) &= \alpha s(t-\tau_1) + \delta_1(t) \\ y_2(t) &= \beta s(t-\tau_2) + \delta_2(t) \end{aligned}, \tag{2}$$

where $s(t)$ is the leak generated signal, α and β are the attenuation factors of respective propagation paths, τ_1 and τ_2 are the time delays of the leak signal at both sensors, δ_1 and δ_2 are the distortion components caused by the defects along the respective path.

The TDOA of AE waves at the two sensors is commonly determined by employing cross-correlation technique which is expressed by:

$$R_{y1y2}(\tau) = \mathrm{E}\left[y_1(t)y_2(t+\tau)\right], \tag{3}$$

where $R_{y1y2}(\tau)$ is the cross-correlation function of the signal $y_1(t)$ and $y_2(t)$, E denotes expectation and τ denotes time delay. However, the cross-correlation function can be affected by the amplitudes of the signals. The correlation of both similar waveform signals is not perfect if the amplitudes of the two signals are not matched. Thus, a normalized cross-correlation is commonly used when comparing two signals with different amplitudes (Gao *et al.*, 2004). A normalized cross-correlation, $\rho_{y_1y_2}(t)$ has a scale between -1 to 1 and can be expressed by:

$$\rho_{y_1y_2}(t) = \frac{R_{y_1y_2}(t)}{\sqrt{R_{y_1y_1}(0)R_{y_2y_2}(0)}}, \tag{4}$$

where $R_{y_1y_2}$ is the cross-correlation function of the signal $y_1(t)$ and $y_2(t)$, $R_{y_1y_1}$ and $R_{y_2y_2}$ are the autocorrelation functions of signals $y_1(t)$ and $y_2(t)$. The time corresponds to the highest peak of the normalized cross-correlation function will be the TDOA of the AE wave.

In real life, with the presence of noises in the pipeline the leak generated signal is often masked, causing the peak in the cross-correlation function undistinguishable. This can cause difficulty in determining the TDOA of the AE waves. Thus, the signal has to be processed to extract the information of leak from the noisy signal.

Variational Mode Decomposition (VMD)

VMD is an adaptive non-stationary signal decomposing technique proposed by (Dragomiretskiy and Zosso, 2014). It can decompose a given input signals into a number of bandlimited modes with distinct center frequency through a process of seeking optimal solution for a variation problem via an iterative manner. The constrained variational model can be expressed by

$$\min_{\{u_m\},\{\omega_m\}} \left\{ \sum_m \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_m(t) \right] e^{-j\omega_m t} \right\|_2^2 \right\}, \tag{5}$$

$$\sum_m u_m = y(t), \tag{6}$$

where $\{u_m\}$ and $\{\omega_m\}$ represent the set of decomposed modes and their respective center frequencies, and the summation of decomposed modes will be the input signal. Throughout the demodulation process, the set of modes and center frequencies are constantly updated in each iteration until the solution of the demodulation process meets the convergence criteria. The complete algorithm of VMD are explained in the literature (Dragomiretskiy and Zosso, 2014). The self-adaptive nature of VMD is essential because the characteristic of leak generated signal and noises present in the signal are not consistent due to the fluctuation of pipeline operating conditions and the interaction of water from the crack with the surrounding medium. The decomposition process of VMD will adapt to the characteristic of the input signal and the signals will be decomposed into set of modes with different center frequencies adaptively.

Wave Dispersion Effect

Leak generated AE wave that propagates along the pipeline is classified as multimodal wave (Li *et al.*, 2016). The wave is dispersive in nature and its velocity is dependent on the frequency and mode of the wave. They usually propagate in three different modes, namely flexural, longitudinal and torsional mode. The relationship of the wave velocity, mode and frequency are illustrated in the pipe dispersion curve in Figure 2. The dispersion curve is simulated using PCDISP package which is an open source tool developed for the simulation of wave propagation in cylindrical waveguides (Seco and Jiménez, 2012). The simulation is for steel pipe with an inner diameter of 80 mm and an outer diameter of 88 mm.

AE sensors attached on the pipeline surface are usually unidirectional and sensitive to radial displacement of the pipe surface. Some wave modes can cause more pipe radial displacement than the other modes. Figure 3 shows the simulation of the pipe radial displacement caused by different wave modes. The simulation is done by using pcwaveform tool available in the PCDISP package with a frequency step size of 5 kHz for the same pipe used in the simulation of pipe dispersion curve.

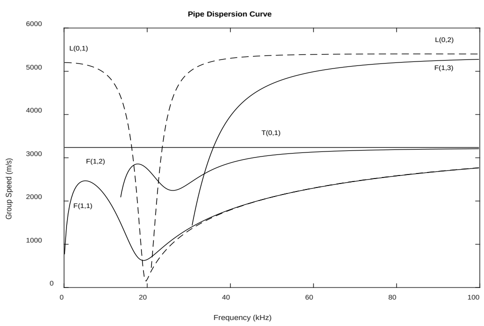


Fig. 2. Pipe dispersion curve.

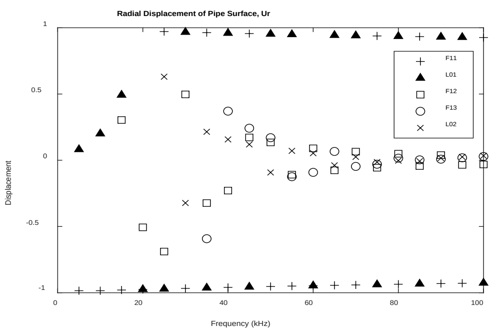


Fig. 3. Radial displacement of pipe surface caused by different modes.

It can be seen that the dominant modes which cause pipe radial displacement are F(1,1) and L(0,1) modes. However, L(0,1) mode only becomes the dominant mode when it is above 20 kHz and its velocity curve is almost similar to F(1,1) mode after 20 kHz. Thus, the wave velocity will be selected based on the velocity curve of F(1,1) mode according to the frequency of the wave.

PROPOSED REAL-TIME LEAK LOCALIZATION SYSTEM

This section discusses the algorithm of the proposed real-time leak localization system based on acoustic emission which incorporates techniques such as hit detection, event recognition, VMD and probability histogram. The algorithm of the system is divided into two sections, real-time section and event driven section. Real-time section consists of operations that will be executed continuously in real-time such as signal acquisition, signal conditioning, hit detection and leak event recognition. This section constantly monitors the signals and recognizes the leak event by comparing the AE hit sequences of all the sensors. The event driven section contains the rest of the algorithm of the system such as signal processing, signal analysis, leak localization and probability histogram that will only be executed if a leak event is detected. The schematic of the proposed algorithm is illustrated in Figure 4 below.

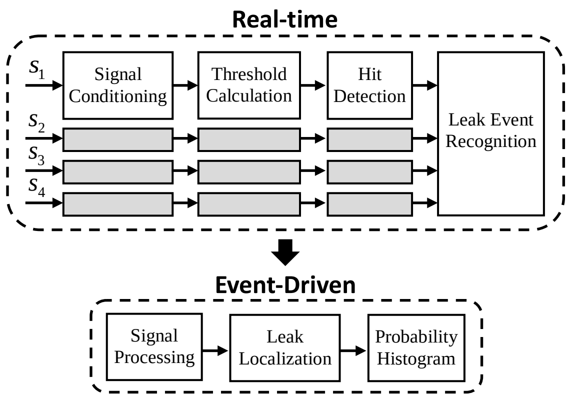


Fig. 4. Algorithm layout of the proposed real-time leak localization system.

Hit-Based Leak Event Recognition

Leak signal is a mixture of burst and continuous types signal (Miller *et al.*, 1999). Burst type signal is generated by the leak due to the unstable turbulence pressure field at the crack and the interaction of the gushing water with the surrounding medium. Continuous signal is generated when multiple burst type signals overlapping each other, forming a uniform amplitude signal envelope. The burst type signal can be discriminated from the continuous signal by using threshold-based hit detection technique which is commonly used in commercial AE parameter-based techniques (Anastasopoulos, Kourousis and Bollas, 2009; Juliano, Meegoda and Watts, 2012). The signals acquired from the sensors are continuously compared to a detection threshold. The segment of signal that has a magnitude higher than the detection threshold and satisfy the detection criteria will be recorded as an AE hit. The detection threshold level can be either fixed or floated. For pipeline leak localization application, a floating threshold is usually preferred because the pipeline operating condition is not consistent due to the fluctuation of water demands. The threshold level has to be adjusted over time adaptively based on the real-time signal level.

One of the methods to derive the floating detection threshold level is based on the moving RMS of the signal (Jiang and Xing, 2012). The moving RMS is less sensitive to the transient of the signal because it is an average value calculated over the data in a moving window. Since the moving RMS is always lower than the amplitude envelope of the signal, it has to be multiplied by a bias factor so that the derived threshold level is above the envelope of the signal. The derived threshold level v_t can be expressed by:

$$v_t = A\sqrt{\frac{1}{t_n - t_0}\int_{t_0}^{t_n} y(t)^2\,dt}\ , \tag{7}$$

where *y(t)* is the measured signal, *A* is the bias factor, t_0 and t_n is the first and last n value of the time window. The derived threshold level will not rise at the instance when a burst type signal is detected, thus making it a good parameter for hit detection.

One thing to be noted is the assumption made on the derivation of Equation 1. The leak position is assumed to be in between the two AE sensors as illustrated in Fig. 1. When the two AE sensors are placed at the same side of the leak, the position of leak cannot be calculated as the TDOA of similar velocity AE wave is always the same no matter how far is the leak from the sensors. Thus, leak localization equation can only be used if the leak is located in between the two AE sensors.

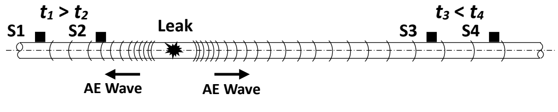


Fig. 5. Schematic of hit-based leak event recognition.

To ensure the leak source is detected within the sensors bounded region, a hit-based leak event recognition algorithm based on 4 AE sensors is proposed. The AE sensors are arranged in pairs at the upstream and the downstream of the pipeline as shown in Figure 5. In order for a leak event to be recognized, the signals of the sensors have to meet two criteria. First, the AE source must be originated from the region bounded by the two outermost guard sensors, S1 and S4. Any extraneous sources from outside of the region bounded have to be rejected to avoid false detection. The rejection is done by evaluating the hit sequence of the sensors. As can be seen in Fig. 5, the sensor located nearer to the leak such as sensor S2 has to detect the AE hit first before it is detected by the guard sensor S1. The same goes to the other pair of sensors, sensor S3 has to detect the hit before it is detected by the guard sensor S4. Any event with the wrong hit sequence will be discarded.

Second, the time difference between hits of the 4 sensors must be within the expected maximum event duration calculated based on the minimum wave velocity and the position of the sensors using equation of motion shown below:

$$\begin{aligned} \Delta t_{12\max} &= L_{12} / v_{\min} \\ \Delta t_{34\max} &= L_{34} / v_{\min}\ , \\ \Delta t_{14\max} &= L_{14} / v_{\min} \end{aligned} \tag{8}$$

where $\Delta t_{\max}$ is the maximum time between hits of the sensors, L is the distance between the sensors with subscripts represent the distance between the two respective sensors and $v_{\min}$ is the minimum wave propagation velocity in the pipeline. Leak event will only be recognized if the above conditions are met. Since leak localization only requires the hit signal from one of the sensors at the upstream of the pipeline and one of the sensors at the downstream, only the signals from either S1 or S2 and S3 or S4 will be recorded as a leak event and be used for further processing in the event driven section.

Signal Processing & Leak Localization Algorithm

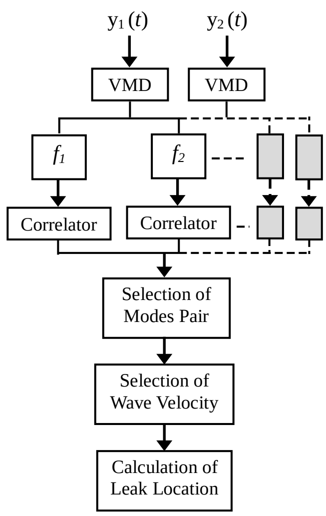


Fig. 6. Proposed Signal Processing & Leak Localization Algorithm

The algorithm of event driven section of the system is illustrated in Figure 6. The hit signals of two AE sensors from the leak event will be first decomposed by VMD individually into respective sets of modes with distinct center frequencies. Since the wave propagation paths between the leak and both sensors are different, both set of decomposed modes will have different set of center frequencies. The sensor located further from the leak will receive less high frequency wave because higher frequency waves tend to attenuate sooner than the lower frequency waves. Also, the noise present in the signals of both measured signals $y_1(t)$ and $y_2(t)$ are different as both sensors are physically located in different part of the pipeline where the amount of noises from the surrounding medium, pump and pipe fittings are different. Furthermore, the signals received by each sensor are distorted differently due to the difference in wave propagation paths between the leak and the two sensors. Since the decomposition process of VMD is data driven, the signals of both sensors will be decomposed adaptively into different set of modes with different center frequencies.

Due to wave dispersion phenomena, different frequency modes will propagate along the pipeline with different wave velocity. Wave velocity is dependent on the frequency of the wave which changes according to the pipe dispersion curve. In order to avoid causing ambiguity in the selection of wave velocity, the modes with similar center frequency will be grouped in pair so that modes with different wave velocity are not mixed. The modes of sensor 1 will be paired with modes of sensor 2 based on their center frequency. The modes that are successfully paired will be used for further analysis whereas the modes that are unsuccessfully paired will be discarded.

After modes pairing, each modes pair will be analysed by cross-correlation function. Based on Equation 2, the signals received by the sensors contain leak signals which are correlated and also distorted components which are mutually uncorrelated if the wave propagation path between the leak and each sensor are very different. Through the cross-correlation analysis, the pair of modes that are correlated and contain leak information will have an obvious peak shown in the cross-correlation function. In other word, the absence of an obvious peak indicates that the pair of modes are not correlated and does not contain leak information. These modes are not useful for the analysis and will be discarded. The pair of modes with an obvious peak will be selected to be used for leak localization. The time corresponds to the highest peak of the cross-correlation function will be the TDOA of mode at both AE sensors.

The selection of wave velocity will be based on the frequency of the selected modes pair according to the velocity curve of the dominant F(1,1) mode on the dispersion curve of pipe. Each different frequency modes pair has its own unique velocity and the location of leak is calculated based on the selected wave velocity and the TDOA of modes obtained in cross-correlation analysis. The results of the leak localization are analysed by a probability histogram. The calculated leak location of all the individual selected modes pairs are plotted in the histogram. The histogram will accumulate all the results of the subsequence leak events and the final predicted leak location is based on the cumulative results of the histogram. The effectiveness of the proposed leak localization system will be evaluated by leak simulation tests with different sensor positions.

EXPERIMENTAL SETUP

The leak simulation tests are carried out on a 3inch galvanized iron pipeline with an operating pressure of 1.5 bar. Water leakage is simulated by allowing pressurized water to expel through a 10mm hole at the test section of the pipeline. The sensors used for the tests are Soundwel SR40M AE sensors with an operating frequency between 15 kHz to 75 kHz. The sensors are connected to a NI-9223 C-series voltage input module via Soundwel PAS preamplifier and Thorlabs EF504 240 kHz analog low-pass filter. The signals of the sensors are sampled at a rate of 1 MHz and then digitally downsampled to 100 kHz to reduce the computational time of the program.

There are four AE sensors magnetically attached on the pipe surface and are positioned in such a way that one pair of sensors are attached at the upstream of the pipeline and the other pair are attached at the downstream as shown in Figure 7. A total of 3 tests with different sensor positions were carried out. The position of leak is defined as 0m and is located in between the two pair of sensors. The coordinates of the four AE sensors are defined relative to the position of the leak.

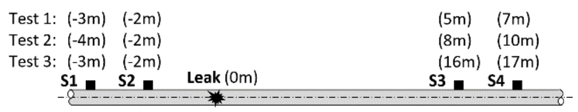


Fig. 7. The position of AE sensors for the leak simulation test

The proposed real-time leak localization program runs on a NI cRIO-9030 chassis which features a FPGA chip, and on a host PC. The real-time section of the program which involve 4 channels simultaneous operations such as data acquisition, data conditioning, hit detection and event recognition are running on FPGA whereas the event-driven algorithm which involve signal processing, leak localization and probability histogram are running on host PC. The host PC will receive the recognized leak event signals from the

FPGA via the Direct Memory Access (DMA) First-In-First-Out (FIFO) buffer. The effectiveness of the proposed system and the developed wave velocity selection method are evaluated by the 3 leak simulation tests with different sensor positions.

RESULTS

Threshold-Based Hit Detection

Figure 8 shows the floated threshold derived from the moving RMS of the input signal of sensor S1 and S2 based on Equation 7. The moving RMS of the signal is calculated over a sliding window with the size of 30000 samples and has its trailing edge aligned to the last element of the signal. The threshold is derived with a bias factor of 5 to raise the moving RMS to a suitable level above the envelope of the input signal. It can be observed that the computed threshold has a minimal sensitivity to the sudden transient of the signal but still response to the trend of the average signal level well. The threshold level only rises slightly in response to the spike in the signal and it drops back to normal in a very short time after the spike. This characteristic is good for hit detection because the leak generated burst signal can

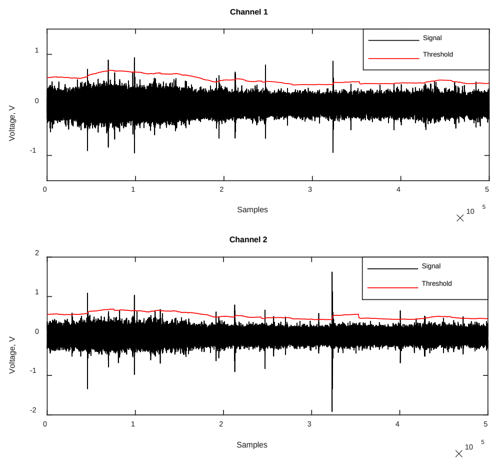


Fig. 8. Floating thresholds derived based on the RMS of the input signals S1 and S2.

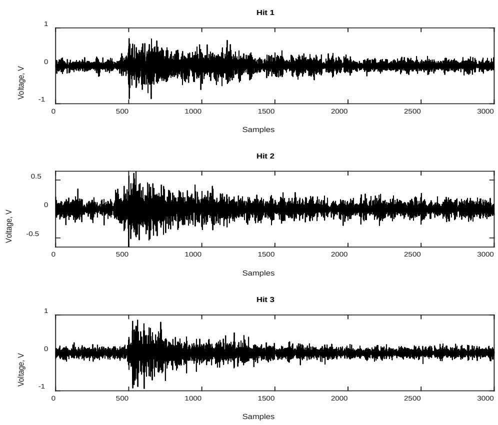
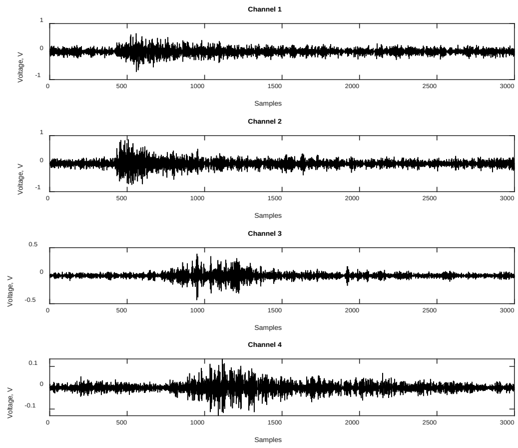


Fig. 9. Hit signals detected from the signal S1 based on the derived threshold.

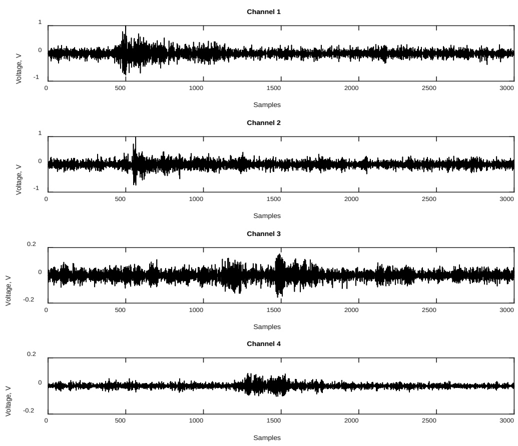
be detected effectively and the threshold level does not need manual adjustment as it will adapt to the input signal during the fluctuation of pipeline operating condition. The segment of signal that has a magnitude exceed the threshold level will be extracted as a hit signal. Figure 9 shows some of the extracted hit signals from the signals of sensor S1 using the hit detection algorithm based on the derived threshold.

Leak Event Recognition

Figure 10 shows the characteristic of the hit signals of a recognised leak event compared to the hit signals of a non-recognised event. It can be observed that for a recognised event shown in Fig. 10(a), sensor S2 will receive the signal first before receiving by sensor S1. Same goes to the sensors on the other side, sensor S3 will receives the signal first before receiving by sensor S4. Based on Figure 7, this hit sequence makes sense as sensors S2 and S3 are installed nearer to the leak. On the other hand, the hit signals shown in Fig. 10(b) are not recognised as a leak event because the hit sequence is wrong. In this case, sensor S1 receives the signal before sensor S2



(a)

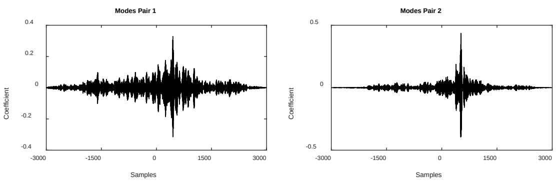


(b)

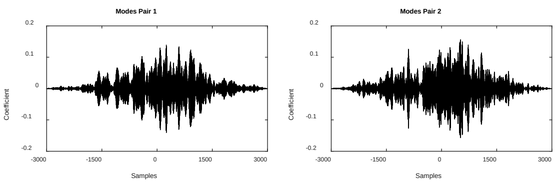
Fig. 10. Hit signal patterns of (a) recognised leak event & (b) non-recognised leak event.

which indicates that the detected AE wave is from outside the region bounded by the sensors S1 and S4. As mentioned in previous section, leak localization equation is based on assumption that the position of leak is within the region bounded by two AE sensors. Any AE source that is not originated from this region has to be rejected to avoid false detection. Thus, the hit signals shown in Fig. 10(b) are rejected and not recognised as a leak event.

Modes Pair Selection



(a) Coefficient > 0.25



(b) Coefficient < 0.25

Fig. 11. Cross-correlation of different modes pairs.

Figure 11 shows the cross-correlation analysis of different modes pairs from different leak events. This analysis is used to select the modes pair that contain leak information by comparing the maximum absolute coefficient of the normalized cross-correlation function with a threshold value. Based on the analysis of large amount of experimental data, the suitable threshold to be used to discriminate the correlated modes pair with non-correlated modes pair is 0.25. From Fig. 11(a), it can be seen that these modes pairs have a maximum absolute coefficient more than 0.25 and have a define peak in the cross-correlation function. The existing of peak shows that the pair of modes contain leak information and the TDOA of the modes are defined by the sample lag correspond to the highest peak in the cross-correlation function. On the other hand, the modes pairs shown in Fig. 11(b) have a maximum absolute coefficient less than 0.25 and do not have a distinguishable peak in the cross-correlation function. The absence of the distinguishable peak shows that the pair of modes are not correlated and cannot be used to determine the TDOA of the modes. These modes pairs will be discarded and only the modes pairs with strong correlation and define peak in the cross-correlation function will be used for leak localization.

Effect of Wave Dispersion on Wave Velocity

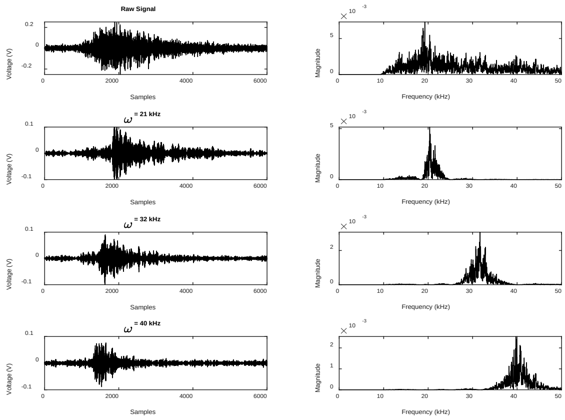


Fig. 12. Decomposition of a hit signal by VMD.

Figure 12 shows the decomposition of a leak event signal using VMD technique. The signal is decomposed into modes with distinct center frequency. VMD can maintains good separation of frequency spectrum between modes which makes it suitable to be used for the study of wave dispersion effect. From the figure, the signal is decomposed into low to high frequency modes where ω indicates the center frequency of the mode. The right side of the figure shows the Fast Fourier Transform (FFT) of the raw signal and modes. It can be observed that higher frequency mode has a higher wave velocity as it arrives sooner at the sensor compared to the lower frequency modes. This is the results of wave dispersion effect which cause the wave to have different velocity in different frequency.

The other observation is the decomposed mode has a significant narrower waveform as compared to the raw signal. The reason is that all the components of the mode arrive at the sensor almost at the same instance as the mode has a smaller wave velocity range due to having a narrower frequency bandwidth. In contrast, the raw signal is the summation of all the modes with wave velocity ranging from low to high. Thus, the range of the time of arrival of all the signal components is larger, causing the raw signal to have a broader waveform.

The effect of wave dispersion can also be visualized through the cross-correlation analysis of different frequency modes pairs shown in Figure 13. It can be seen that the TDOA of different frequency modes pairs are different. This implies that different wave velocity has to be selected based on the

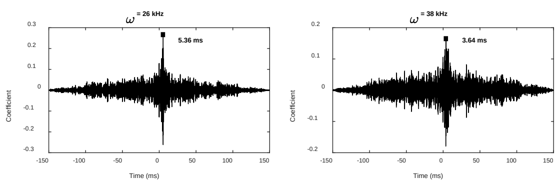


Fig. 13. Cross-correlation of different frequency modes pairs.

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, leak localization should be based on the TDOA of individual modes pair with the wave velocity selected based on the frequency of the individual modes pair from the dispersion curve of the pipe.

Performance of Leak Localization using VMD and Developed Wave Velocity Selection Method

This section shows the comparison of the newly developed wave velocity selection method versus the traditional wave velocity selection method. The comparison results are shown in Table 1. The location of leak, *d* is calculated based on the TDOA of different frequency modes pair and the wave velocity selected using the proposed and traditional methods. For proposed method, leak location will be calculated using the wave velocity selected from the velocity curve of F(1,1) mode on the pipe dispersion curve according to the frequency of the modes pair. For traditional method, wave velocity is assumed to be constant for all different frequency mode pairs and the leak location is calculated just based on a single constant wave velocity.

It can be observed that the leak localization based on proposed method has significantly lower percentage error compared to traditional method. This is because wave velocity is dependent on the frequency of the wave and simply can't be accurately represented by an average velocity. Leak localization application is sensitive to minor changes in wave velocity. The actual wave velocity can be as low as 800 m/s at 20 kHz up to 1800 m/s at 40 kHz. By

Table 1. Results of leak localization using selected wave velocity versus fixed velocity.

Sensor Positions		Based on wave velocities of F(1,1) mode selected based on the respective frequencies, *f*					Based on fixed wave velocity of F(1,1) mode in 30 kHz		
1	2	*f*, kHz	Δ t (ms)	v (m/s)	d (m)	Error (%)	v (m/s)	d (m)	Error (%)
-3m	7m	22	4.79	900	7.16	2.29	1400	8.35	19.29
		26	3.64	1100	7.00	0.00	1400	7.55	7.86
		38	2.08	1700	6.77	3.29	1400	6.46	7.71
-4m	10m	26	5.43	1100	9.99	0.10	1400	10.80	8.00
		32	4.14	1500	10.11	1.10	1400	9.90	1.00
		40	3.62	1800	10.26	2.60	1400	9.53	4.70
-3m	17m	26	11.84	1100	16.51	2.88	1400	18.29	7.59
		32	9.21	1500	16.91	0.53	1400	16.45	3.24
		38	7.93	1700	16.74	1.53	1400	15.55	8.53

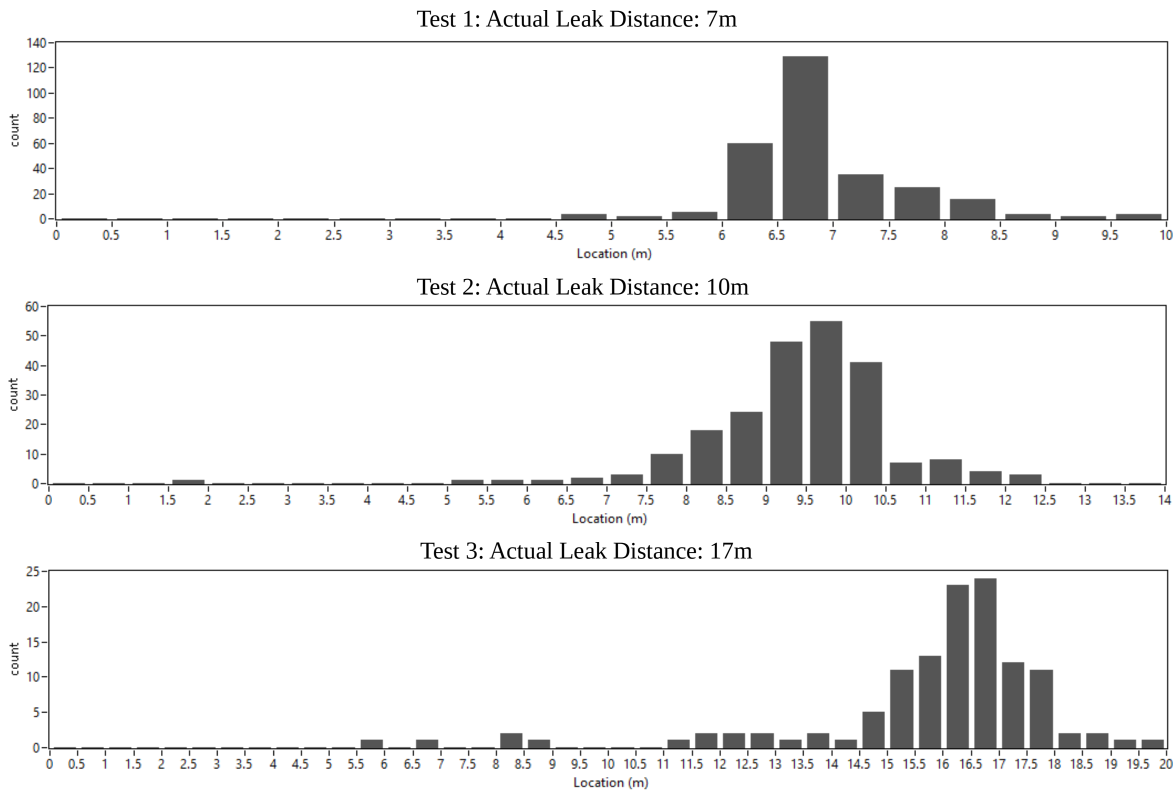


Fig. 14. Leak localization results of the 3 leak simulation tests.

selecting wave velocity based on the frequency of the modes pair, the accuracy of leak localization is able to achieve percentage error within 3.29%. Thus, the necessity of selecting wave velocity based on the frequency of wave is confirmed. The proposed wave velocity selection method can effectively increase the accuracy of leak localization.

Performance of Developed Real-Time Leak Localization System

Table 1 shows only the results based on a single leak event. In real life, the leak localization program will be running continuously in real-time. The calculated leak locations of all the selected modes pairs from an event and subsequence events are plotted in a probability histogram with a bin resolution of 0.5 as shown in Figure 14. The plotted leak locations are relative to sensor S4 and the detected leak locations are based on the cumulative result of the histograms. All the results of the 3 tests show the correct location of leak and this proves the consistency and accuracy of the developed real-time leak localization system.

CONCLUSION

In this research, a leak localization system based on acoustic emission signal and VMD that is capable of achieving an accuracy of within 3.29% in leak localization is developed. The system is implemented in real-time by incorporating technique such as threshold-based hit detection, leak event recognition and probability histogram into the algorithm. The consistency and accuracy of the developed real-time leak localization system is demonstrated by several tests with different sensor positions and all the results of the tests show the correct location of leak. The study of the effect of wave dispersion is conducted and it concludes that wave velocity is not only dependent on the pipe geometry and material, but also dependent on the frequency and mode of the wave. As a result, a more reliable wave velocity selection method is developed and achieves a better accuracy in leak localization comparing to the traditional method which assumes a constant wave velocity that is dependent solely on the pipe geometry and material. In future, the effect of different leak size and pipeline pressure on the performance of the leak localization system will be studied.

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