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Pipeline Fault Identification using Synchrosqueezed Wavelet Transform based on Pressure Transient Analysis

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ABSTRACT

Brand modern technology of leak detection by using pressure transient analysis has been developed and interested to research due to its advantages such as low cost, simplicity and convenient to use. This technology uses the concept of signal reflections which identify pipeline features. The method used in this study was using a pressure transducer (piezoelectric pressure sensor) to obtain pressure transient respond generated by rapid opening and closing of solenoid valve. However, such reflections are very difficult to determine the pipe characteristic most probably because of excessive noise from other sources. Therefore, this paper proposed a method called Empirical Mode Decomposition (EMD) to decompose the reflection signal to its Intrinsic Mode Function (IMFs) and further analysis using continuous wavelet transform (CWT) to transform the signal into Time-Frequency domain and spectrum diagram. From the spectrum diagram, the characteristic of the pipe can be clearly display. From the finding results, it proves that this method not only useful for leak detection but also can determine the location of leak and its magnitude with error less than 10%.

1. Introduction

Non-revenue water is described as water that does not make it from point A (the source of the water delivery device) to point B (the end user) due to pollution, wastage, or thief along the way using pipeline system. A pipelines system is utilised for the purpose of transporting purified water from the water treatment plant to the homes and other structures in the neighbourhood for human consumption [1]. However, both real and actual losses (due to leaks, cracks, spills, and so on) and merely apparent losses (due to defective or tampered meters, incorrect meter readings, poor record keeping, or overt water theft) are possibilities. Leaks and breaks that cause water to escape

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frequently allow impurities into the delivery system, reducing water quality. It is difficult to do maintenance work since there is little information available regarding the location and depth of the subterranean pipe [2]. According to the National Water Services Commission (SPAN), non-revenue water accounted for 35.2 percent of gross water use in 2016 and 35.7 percent in 2017. The government and water service companies have been fighting NRW for decades with little success. Between 1996 and 2010, the Malaysian government spent roughly USD 600 million to reduce the nation's NRW rate, relating to the Eighth, Ninth, and Tenth Malaysia Plans. Such high NRW prices jeopardize Malaysia's long-term water survival, potentially harming the country's social (unfair water supply bills), environmental (power supply losses), and economic well-being (water business revenue losses) [3]. Pipeline leaks not only damage property and money, but they also deplete the planet's energy supply, putting humans and marine life at risk [4].

Nowadays, there are a number of solutions accessible to detect pipe leakage, which can be split into two categories: hardware detection and software detection. Very specialized technology utilized in hardware identification includes leak noise correlators, leak noise loggers, ground penetrating radar, and infrared imaging. Some of these methods also used the principle of wave such as ground penetrating radar that based on reflection of wave amplitude and velocity of electromagnetic wave [2]. This hardware, however, is expensive, labour-intensive, and slow to run, and it can necessitate the suspension of pipeline operations for a prolonged period of time. Therefor software detection had become widely used to overcome the shortcomings of hardware detection since they enable a vast volume of data to be obtained in a relatively limited period of time [5]. The subterranean pipes present even another obstacle when attempting to locate the source of the leak; hence, the in-line sensor, despite its little size, should be useful [6]. By using this new invented sensor, water industries may enhance their detection of water leaks and reduce the overall cost of both inspection and prevention [7].

Years ago, reflections in basic pipe networks were identified using cross-correlation analysis by Beck *et al.,* [8]. This strategy worked, although it was cumbersome and time-consuming. Later, Al-Shindani *et al.,* [9] used wavelet transformations on experimental and simulated pipe transients. While the simulated data analysis was effective, when the same analysis was applied to the real data, no relevant results were obtained. This is because in actual systems, waves spread out due to dispersion making the outgoing and incident waves less acute [10]. Sabir *et al.,* [11] introduced a paradigm based on WPD and signal kurtosis to study the bearing signals. The authors Džakmić *et. al,* [12] introduced a combination of a Fourier transform (FFT or STFFT) and a Mexican-hat wavelet for transmission and distribution networks signal. It first detects the harmonics of the fault using a Fourier diagram, and then, after calculating the scale factor, it applies the Mexican-hat wavelet. Another study employed bagged decision trees to locate faults in microgrids utilising FFT and Windowed Wavelet Transform characteristics [13].

Continuous wavelet transform (CWT) was brought into the field of mechanical fault diagnosis to compensate for the shortcomings of orthogonal wavelet transform in the application of mechanical fault diagnosis [14]. However, wavelet analysis possesses particular advantages for characterising signals at different localisation levels in time as well as frequency domains [14]. Therefore, continuous wavelet transform is the technique to analyse the reflected signal from the pipeline features and removing the noise with Morlet as mother wavelet.

Pressure transient analysis is the analysis of pressure changes over time, especially those associated with small variations in the volume of fluid. In most well tests, a limited amount of fluid is allowed to flow from the formation being tested and the pressure at the formation monitored over time. For this analysis, the signal reflection is an important element to study the characteristic of pipeline. Any of the discontinuities signal is reflected out from the grid owing to piping machine irregularities such as blockages or leaks. As a consequence, the reflected signal is analysed to determine if the pipeline has leaks or characteristics, as the pressure wave represents those irregularities. Transient wave-based technologies were utilised to deliver active waves, gather data from field equipment, and mathematically or theoretically analyse information in order to assess pipeline system weaknesses [15-19]. Several years ago, the analysis of the transient behaviour of pipelines in networks for the purpose of leak detection was developed and perfected due to this method's potential to produce a significant amount of data in a single test, the ability to locate leaks at a very long distance from a measurement point, low cost, simplicity, and environmental friendliness. Despite the method's appealing advantages, there is one drawback: the leak signal obtained is distorted by other computer noise. Therefore, Empirical Mode Decomposition (EMD) is used to decompose those signals without leaving it in the time domain. The basic principle behind EMD is to identify suitable time scales that exhibit signal physical properties, then decompose the signal into intrinsic mode functions (IMFs) [20]. From the IMFs based on amplitude versus time, it is necessary to convert into frequency domain in order to observe the consequence of the signal pulse.

This paper proposed a CWT-based technique to leakage diagnostics. The benefit of CWT is also used to localise the leak that is present along the pipeline system, as it is in other CWT-based applications. This method will be explained detail in this paper and the error will be analyse between the analyse location and measured location.

2. Wave propagation in pipes

A wave is a disturbance that travels across a medium. A slight displacement of the medium molecules between these two points creates variations in energy and momentum from one end to the other. In the case of pipelines, opening or closing a valve, or starting and stopping pumps, may cause a hydraulic transient wave to circulate through the pipeline as illustrated in Figure 1. The higher the duration of the occurrence of the hydraulic transient, the quicker these operations are carried out, resulting in a situation known as water hammer [21]. Water hammer phenomena are a well-known technique for producing waves using the hydraulic transient process. The wave then travels through the pipeline serving as a mechanism for identifying any features such as leakage and blockages, as a leak happens in a tube, the leak induces a reflection of the pulse in the speed of light returns to the measuring point, culminating in the leak-reflected signal at a certain moment, and the signature of the signal is the interest to be further process.

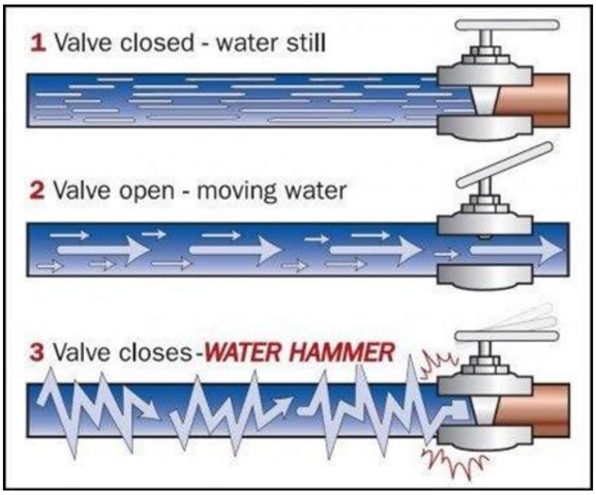


Fig. 1. Phenomena of water hammer

Wave propagation inside the pipeline network, will relay different signals depending on the size of the leak and the distance of the leak according to the following equation,

$$Distance, s = \frac{Time, t \times Speed\ of\ sound, c}{2} \quad (1)$$

3. Theoretical background

3.1 Continuous Wavelet Transform

If $\psi(t) \in L^2(R)$ and the Fourier transform $\hat{\psi}(\omega)$ fulfils the admission requirement

$$C_\psi = \int_{-\infty}^{\infty} \left|\hat{\psi}(\omega)\right|^2 / \left|\hat{\psi}(\omega)\right| d\omega < \infty \quad (2)$$

It describes $\psi(t)$ as mother wavelet or wavelet function, which $L^2(R)$is the space of square integrable complex functions. The related wavelet family consists of a sequence of son wavelets formed by dilation and translation from the mother wavelet, as illustrated below

$$\psi_{a,b}(t) = |a|^{-1/2}\, \psi\left(\frac{t-b}{a}\right) \quad (3)$$

where a represent the scale vector and b is time location, $|a|^{-1/2}$ used to guarantee energy preservation. Assume $x(t)$ as signal, defined the product in the Hilbert space L^2 norm as below

$$W_b(a) = < \psi_{a,b}(t), x(t) > |a|^{-1/2} \int x(t)\psi_{a,b}^*\ dt. \quad (4)$$

The asterisk here denotes complex conjugate. Scale factor a and time location b are always changing. In term of discrete sequence x_m , let $t = m\delta t$ and $b = n\delta t$, where m, n = 0, 1, 2, ..., *N-1*, *N* represent sampling point number and δt as the sampling interval. So, CWT of x_m is defined as follows

$$W_n(a_j) = \sum_{m-o}^{N-1} x_m \psi^* \left[\frac{(m-n)\delta t}{a_j}\right]. \quad (5)$$

By altering the indexes j and n, which correspond to scale factor a and time location b, one may create an image that shows both the amplitude of any features versus the scale and how this amplitude evolves over time. Review researcher for the details reference of CWT method.

4. Methodology

The test rig was setup at fluid mechanic lab at Faculty of Mechanical and Automotive Engineering Technology, University Malaysia Pahang. In Figure 2, an artificial leak was manually created 47.9 m from the point of analysis using a hand drill. The point of analysis in this experiment is a fire hydrant with an improved cap that includes a solenoid valve and a single pressure sensor, as seen in Figure 3. The most command approach method involves making use of two sensors that are positioned in a manner that is opposite between the leaks. The disadvantage of taking this strategy is that it requires using two sensors to perform the required action. In addition, in order to identify leakage, both sensors need to be able to hear the noise; hence, the distance that separates the sensors is a significant consideration [22]. The point of analysis was also located 10 meters away from the electric pump to reduce noise during data processing This is due to the high velocity and pressure of the turbulent water flow caused by the electric pump, which causes friction between the water flow and the inner wall of the vessel. The solenoid valve used in this experiment is normally closed type, Water hammer is triggered by the sudden closing of a solenoid valve, and the intermittent shock flows at the speed of sound down the piping.

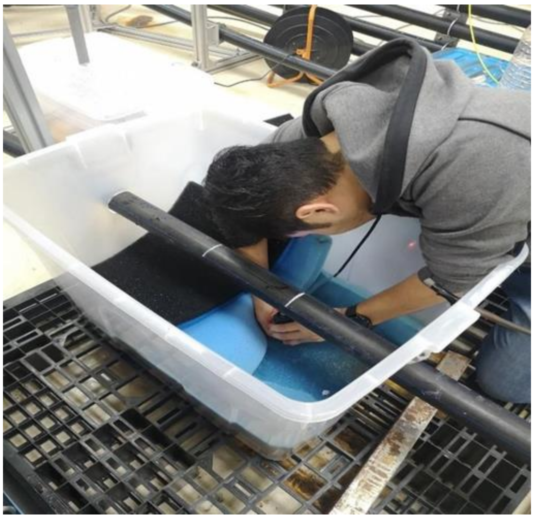


Fig. 2. Create artificial leak

Based on theory of wave propagation, if there is a leak, blockage, or pipe function, the wave may be divided into three classes (a) the wave is absorbed, (b) the wave is released, and (c) the wave is reflected. Since the pressure sensor measures the mirrored pulse, the latter was the subject of this study. Both of the findings were recorded using the DASYLAB software. The test rig design is same as the actual situations in pressure condition for underground pipe.

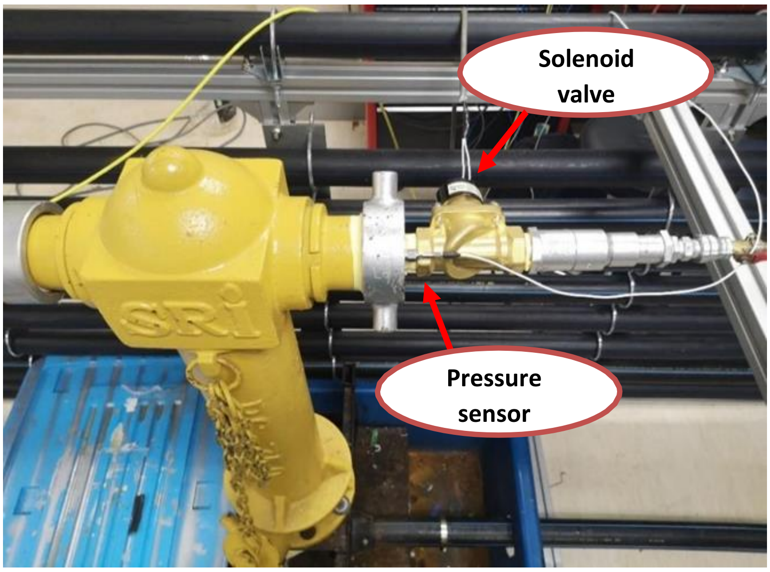


Fig. 3. Improved fire hydrant with solenoid valve and pressure sensor

The experiment was carried out in the form of a 100-meter-long rotating loop pipeline system as shown in Figure 4. The pipeline network is constructed of Medium High-Density Polyethylene (MDPE) tubing with internal diameters of 60 mm and outer diameters of 63 mm. The pipeline design fabricated using aluminium profile to make sure that the pipeline steady and avoiding from vibration that can disturbed the signal collected. The properties of MDPE pipe and pressure sensor used in the experiment listed in Table 1.

Fig. 4. Overview of the experiment test rig

Table 1
Test rig parameter properties

Item	Parameter	Value
Medium Density Polyethylene (MDPE) pipe	Pipe length (m)	100
	Inner diameter (mm)	60
	Outer diameter (mm)	63
	Tensile strength (Mpa)	12.4-19.3
	Density (g/cm3)	0.926-0.940
	Young modulus (Mpa)	172-379
Piezoelectric pressure sensor	Voltage sensitivity (mV/kPa)	7.611
	Output bias level (VDC)	8.1
	Output voltage (V)	0-5
	Pressure range (bar)	0-10
	Span (bar)	4.992

5. Result and Discussion

The experimental results analysis was divided into two parts by which are constant pressure with different leak size and constant leak size with different pressure. Some examples of raw signal pressure as shown in Figure 5 obtains from piezoelectric pressure sensor with different pressure. From the raw signals shown, it fails to detect clear reflection signal generates from the leak and any disturbance in the pipes.

Therefore, further action to filter out or decompose the signal by Empirical Mode Decomposition (EMD) respond into 12 level of Intrinsic Mode Function (IMFs) based on amplitude level versus time as shown in Figure 6. Basically, noise with a significant amplitude may be found in IMF levels 1, 2, and 3. IMFs 8 and above often include both the fundamental network response as well as the residual. Therefore, all of these levels of IMFs are going to be withdrawn for further investigation. It is generally agreed that IMF levels 5 through 7 provide the optimal range from which to choose and utilise IMF data for further analysis using CWT [21]

The signal showed a spike at the 10000 sample which represents the point when the solenoid valve opened. Thus, the pressure inside the pipe drops gradually until the solenoid valve closed. At this point, the pressure begins to raised again until it reached the level of pressure manipulated inside the pipeline. The raw signal is contaminated with all types of noise such as pump noise, pipe vibration noise, surrounding noise, and others. The true signal is hidden inside the signal that contains noise. Thus, signal processing is used in this article to remove all unwanted signals captured by the pressure sensor.

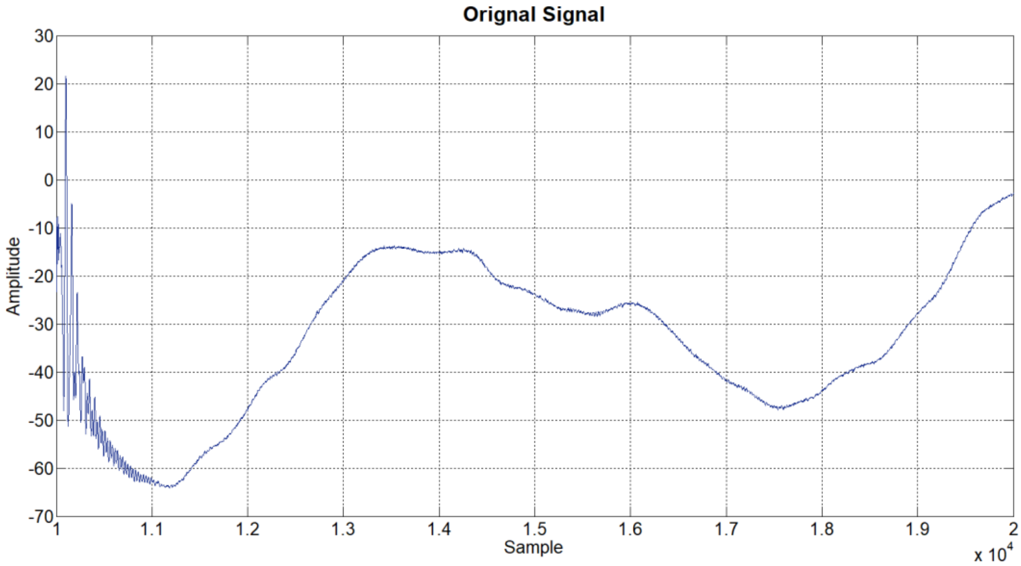


Fig. 5. Original signal gained from pressure sensor

The chosen IMFs is then further analysed by CWT which combined with mother wavelet (Morlet) for every data set and then represented by time-frequency chart representation and time-frequency spectrum. The characteristics time of the pipe, t can be calculating by using the formula since the leak distance from measuring point is known (47.9m). We obtain the respond time is 0.18 s. Since the time start of the solenoid valve to generate shock wave is at 1 second as shown in Figure 5, therefore the total time measured time was 1.18 seconds, which means there was a respond in every leak situation at 1.18s of the time-frequency spectrum diagram. This is in order to make sure that the pressure inside the pipeline maintained at 4bar because the artifial leak created can led to decrease in pressure [23].

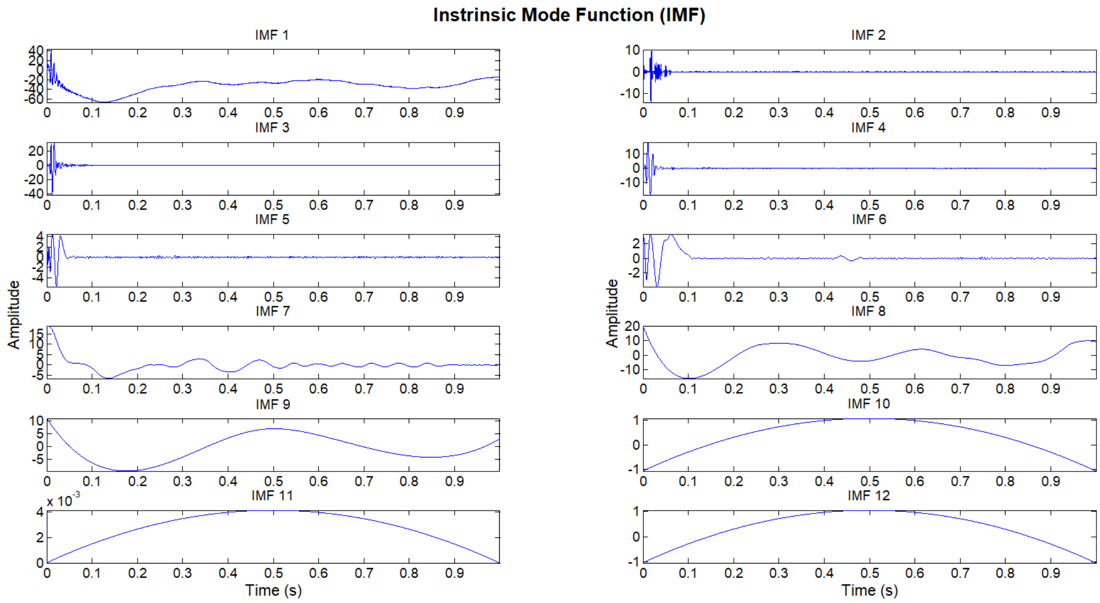


Fig. 6. Component of IMFs extracted using EMD method

5.1 Analysis for Constant Pressure with Different Leak Size

The repetitive pattern and the rapid changes in the signal are obvious in the wavelet spectrum where absolute intense values are almost consistently located using CWT analysis. Analyses from the wavelet spectrum was carry out to compare the different between leak size 1mm until 5mm with constant pressure of 4 bar. Based on the result from [24] the magnitude of the velocity is strongly influenced by the diameter of the leak hole size. Wavelet spectrum diagram in Figure 7 shows the results of a healthy no leak pipeline with 4 bar pressure. From the observation, there is no high amplitude and instant frequency change absent to represent any features inside the pipeline network.

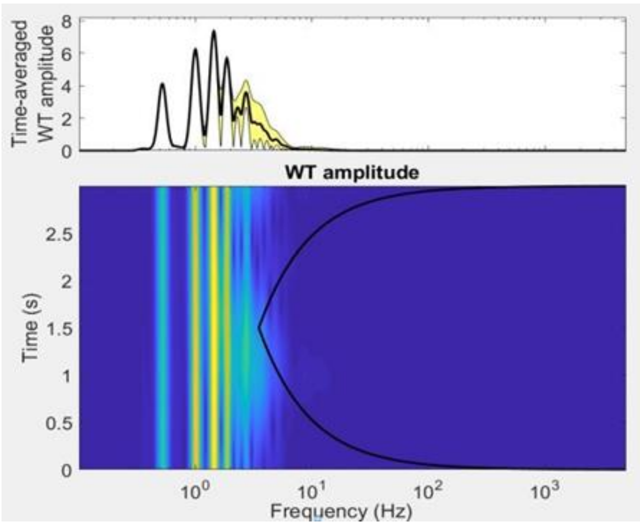


Fig. 7. No leak features absent

As we can see in Figure 8, the result shows the result of analysis of 1mm leak feature that present in the pipeline network. Refer to the spectrum, the observation shown that the high frequency signal occurs at 1.192s. In the setup of experiment, the data was captured one second earlier for the solenoid valve to open and the closed after one second later. So, the observe data need to be minus one second because the main part to be observe when the solenoid valve closed.

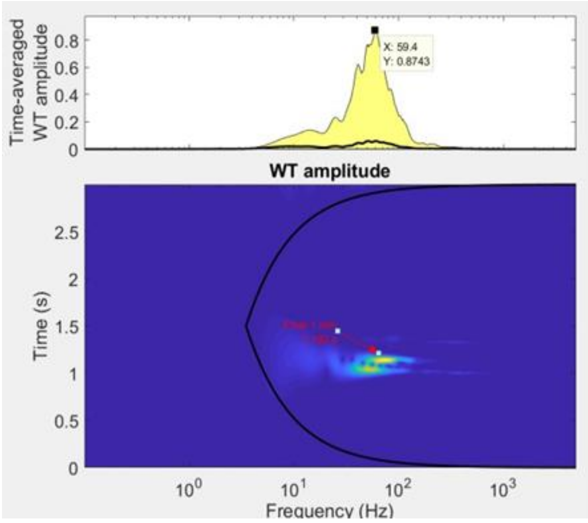


Fig. 8. Leak size of 1 mm

Later on, the artificial leak of 2mm created and the signal was analysed using CWT method. The result is shown in Figure 9 with the occurrence of high-density spectrum at 1.171s. While in Figure 10, it is shown the result of analysis for 3mm leak size created in the pipeline network. The spectrum show that leakage was identified at 1.168s based on the fluctuated frequency and the high amplitude appear after the analysis.

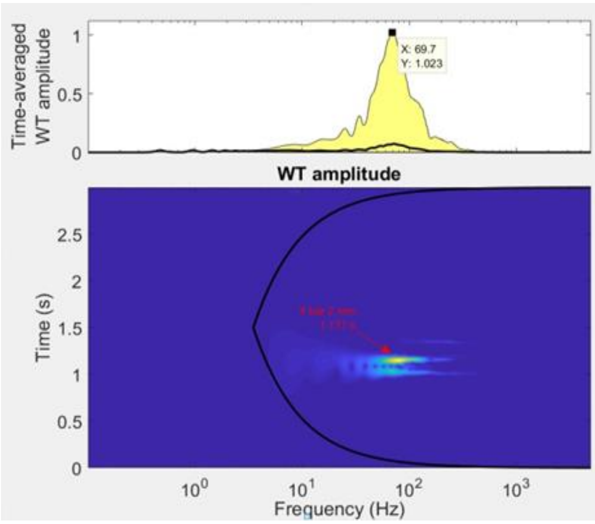


Fig. 9. Leak size of 2 mm

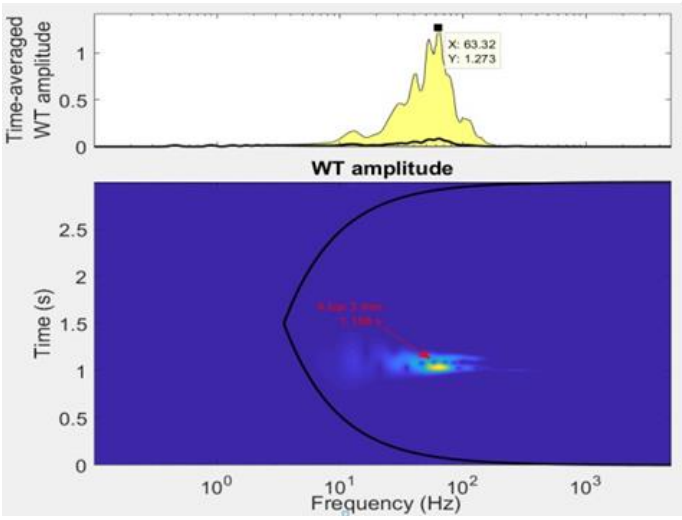


Fig. 10. Leak size of 3 mm

Based on the observation of TF spectrum, if there is an instant frequency and energy (amplitude) appear, the value of amplitude slightly increases when leak size increases. Figure 11 shown the spectrum of wavelet analysis for 4mm leak size. The result shown that the high amplitude of frequency appears at 1.173s that justified as leakage. Meanwhile, Figure 12 the signal analysis of 5mm leak size that artificially created at the pipeline network. The high frequency of spectrum signal show that the features was identified at 1.195s based on the time-frequency domain of continuous wavelet analysis.

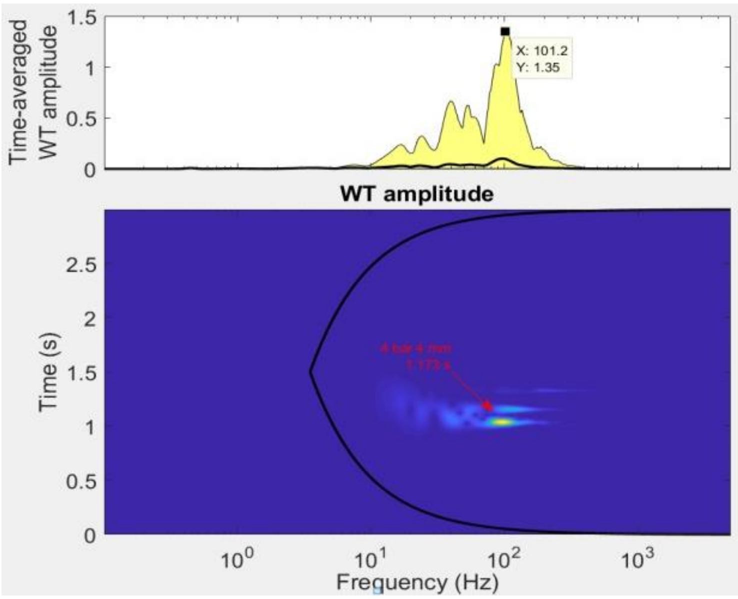


Fig. 11. Leak size of 4mm

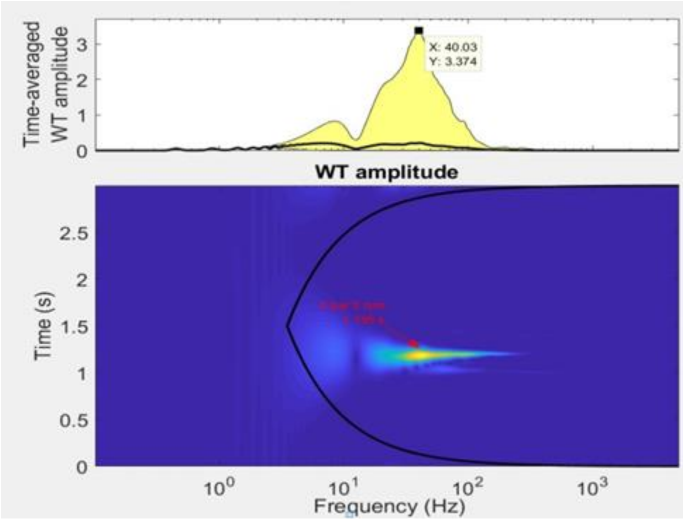


Fig. 12. Leak size of 5mm

To conclude the analysis for different leak size and constant pressure part, all the result gathered in Table 1 which contain analyzed time, measured distance and analyzed distance. The analyzed time was converted into distance by using Eq. (1). The percentage of error for all the leak size variant calculated by comparing the measured and analyzed distanced. After calculating and comparing the result, it is proved that the error of leak location was less than 10% for each feature.

Table 1
Percentage of error for all features

Leak size	Analyzed time (sec)	Measured distance (m)	Analyzed distance (m)	Percentage error (%)
1 mm	0.192	47.9	50.33	4.83
2 mm	0.171	47.9	44.83	6.85
3 mm	0.168	47.9	44.04	8.76
4 mm	0.173	47.9	45.35	5.62
5 mm	0.195	47.9	51.11	6.28

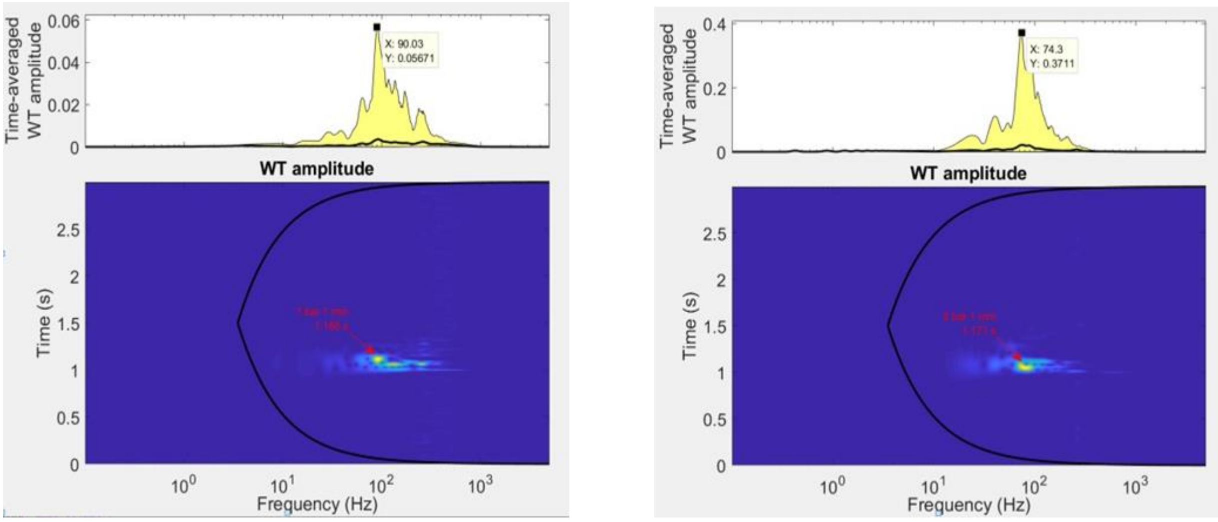
5.2 Analysis for Variant Pressure with Fixed Leak Size

The wavelet spectrum analysis was conducted for leak size 1mm with different pressure range that were 1bar until 4bar. At the beginning, the raw signal which gathered from piezoelectric pressure sensor have no important features are available since the reflection signal is masked in the signal noise. Therefore, further signal analysis is required to be carry out to obtain the pipeline information. Empirical Mode Decomposition used to decompose the signal into 12 level of Intrinsic Mode Function (IMFs) in the form of amplitude level versus time.

Then, the selected level of IMFs the used to further the analysis by using continuous wavelet transform (CWT), finally denoised signal then can be review by time-frequency representation and time-frequency spectrum. From the result obtained, there was respond at the time range from 1 to 1.5 seconds.

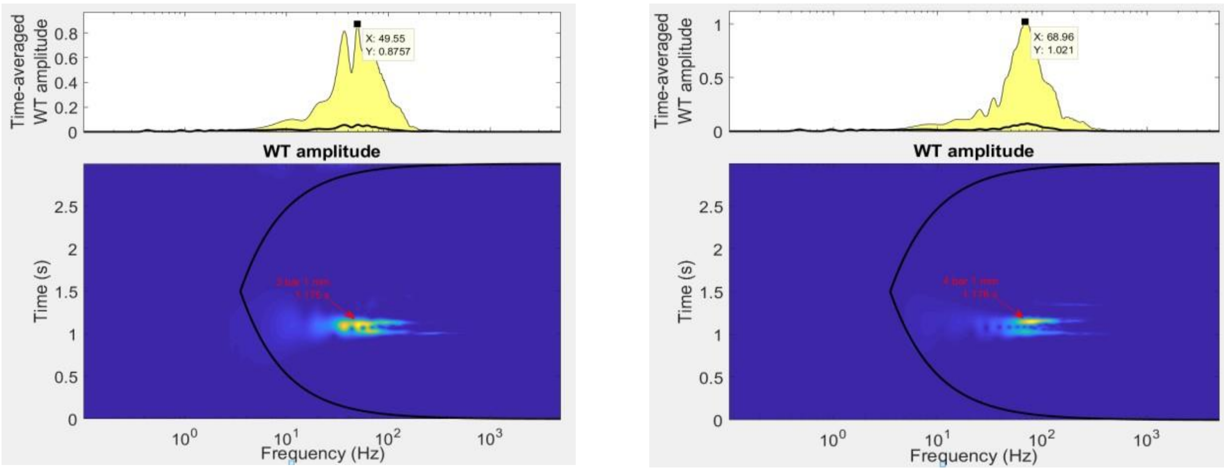
Figure 13(a) and (b) show the result of CWT for 1bar and 2bar of pressure respectively. As observed from the TF spectrum, for 1 bar pressure signal, it is show that the high frequency spectrum occurs at 1.168s. Meanwhile, for 2 bar analysis shown that the high-density spectrum observed at 1.171s.

Figure 14(a) show the result of CWT analysis for 3 bars analysis while Figure 14(b) show for 4bar of pressure level. It is shown that for 3bar analysis, the instant frequency occurs near 1.175s while for 4bar, it is observed at 1.178s. Ultimately, all the data for this part of analysis tabulated in Table 1 based on analyzed time, measured distance, and analyzed distance. The percentage of error calculated based on location of leak that measured directly from the pipeline network and the distance acquired from the analysis.



(a) (b)

Fig. 13. (a) 1 bar 1mm leak size, (b) 2 bar 1mm leak size



(a) (b)

Fig. 14. (a) 3 bar 1mm leak size, (b) 4 bar 1mm leak size

As we can see, the percentage of error from all four types of analysis shown Table 2 is still under 10%. So, it can be said that this method used in this paper able to identified the presence of leakage in pipeline system and localize the position of leak.

Table 2
Percentage error for four range of pressure

Pressure (bar)	Analyzed time (sec)	Measured distance (m)	Analyzed distance (m)	Percentage error (%)
1	0.168	47.9	44.04	8.76
2	0.171	47.9	44.83	6.85
3	0.175	47.9	45.88	4.41
4	0.178	47.9	46.66	2.65

6. Conclusions

As a conclusion, the identification of leaks from any water distribution should be practice by any method which is efficient and convenient as it will prevent waste and ensure everyone get the amount of water as billed. Based on all the work from the experiment, using transient analysis of water hammer for leak detection has proven for effectively detection of leak based on the findings results and compared. As mention before, water hammer occurs when a valve is opening and closing rapidly and then generate a transient pressure wave through the system. When it encounters any features along the pipe, reflection of the wave can be captured using piezoelectric pressure sensor and further analyze by signal processing. Both measured and analyzed data were used to evaluate the performance of this technique and results show that it can detect the location of leak with error less than 10%. Besides, the results also prove the ability of piezoelectric pressure sensor in detecting fast response frequency change in the pipeline system. Moreover, this report also proposed an effective method to eliminate noise that mask the signal called Empirical Mode Decomposition (EMD). EMD is useful to filtered out the raw signal into Intrinsic Mode Function (IMFs) then further analyze using continuous wavelet transform.

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