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Improvement of acoustic water leak detection based on dual tree complex wavelet transform-correlation method

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Abstract. Water leakage is one of the important agendas across the globe thus several effectual systems for leakage detection had been developed with the aim to improve sustainable use of water. Among the methods, acoustic leak detection technique had been proven as a promising approach to detect and localize leaks in water or gas pipeline. However, existence of noise in acoustic signals complicated the leak detection practices. Traditional de-noising methods like filtering and wavelet de-noising are not suitable for non-stationary and broadband acoustic signals. Therefore, Dual Tree Complex Wavelet Transform (DTCWT) is applied in this paper to reduce acoustic noise and decompose signals into several frequency bands. DTCWT decomposition is intended to resolve the problem encountered by the typical correlation-based leak localization method. Due to dispersive and frequency-dependent nature of wave propagation, correlation-based method normally assumes constant wave velocity which results in inaccurate leak source localization. In this paper, signal will be de-noised and decomposed by employing DTCWT. Wave velocity is evaluated based on the dominant frequency and dispersion curve. Then, time delay can be estimated via comparison study among cross correlation, CWT localization and convolution. CWT localization and convolution are proposed as new time-delay estimation method attributable to enhance localization accuracy. Experimental results validated that the proposed method, DTCWT-correlation outperforms other methods with a localization error of 4.67 %. Both CWT localization and convolution are also capable to pinpoint the location of leaks. Besides, leaking and non-leaking condition can be differentiated after multilevel decomposition of DTCWT.

1. Introduction

Water is a precious natural resource that essential for human and other living organisms to thrive. Unfavourably, water distribution networks are susceptible to leakage and results in substantial amount of water lost. According to statistics by National Water Services Commission (SPAN), the amount of non-revenue water (NRW) in Malaysia is 35.2% of supplied water which is equivalent to 5846 million litres per day [1]. NRW is water that is lost before it reaches consumers due to leakages, pipe bursts and theft. Water leakages are mainly due to aged and faulty pipes. Other causes are stress corrosion, manufacturing errors and external effects. Leakages account for loss of money and natural resources. They also pose a public health risk because contaminants may enter the pipe when there is pressure drop in the pipe system [2]. Consequently, pipeline monitoring had arisen as prime concern in many countries with a view to improve sustainability of the water resource.

Acoustic leak detection system is one of the effective and popular ways among water leakage detection techniques. When a leak occurs in a pipe, sudden change of pressure will induce pressure waves propagate along the pipeline. These waves measured by acoustic sensors which mounted on the pipe at different location. The arrival time of the signals at each sensor would be different. Therefore, leak location is able to be identified by computing time delayed [3]. In such manner, time delay computation plays a key role in the processing of acoustic leakage signals. Nonetheless, presence of noise in the signals will reduce the precision of time delay estimation and lead to missed or false detection. In fact, the major encumbrances of employing acoustic leak detection are occurrence of false alarms [4]. To this end, it is compelling to eliminate or reduce noise so as to avoid false trips and optimize usage of acoustic system in leak detection practices [3, 5, 6].

Digital filtering is a conventional way to remove noise out of interested signal. Examples of filter are low pass, high pass and band pass. To detect leaks in pipeline network, low pass and band pass filtering had been applied [2, 7]. However, filtering method is designed based on prior knowledge of both signal and noise so it is only applicable when a desired signal and noise occupy different frequency bands. Filter is not effective to extract signal information from broadband noisy acoustic signals as the signals and noise might exist in same frequency band [5].

Another noise reduction method is wavelet de-noising, which is a noise suppression method through wavelet analysis. It performs by decomposing the signals into several scales and applying thresholding on the wavelet coefficients. Thresholding aims to eliminate those coefficients which are smaller than the threshold prescribed [8]. Wavelet de-noising is capable to show satisfactory results in gas or water leakage detection events. This method enhanced the accuracy of the leak positioning by improving signal to noise ratio (SNR) [3, 9]. Nevertheless, there are few indispensable challenges would be encountered, which are selection of mother wavelet function [6, 10], number of decomposition level [6, 9], threshold method [9] and threshold value [3]. All the selections made can greatly affect the performance of de-noising.

Hence, DTCWT is introduced to provide a promising approach to suppress acoustic noise while preserving characteristics of the signal [11]. Furthermore, it is designed for non-stationary acoustic signals analysis.

The objective of this paper is to improve time delay estimation and enhance the accuracy of leak localization through DTCWT noise reduction. Different delay estimation methods are proposed in this study in order to verify their accuracy and feasibility in leak localization. Detailed descriptions of DTCWT and time delay estimation methods are presented in the following sections.

2. Dual Tree Complex Wavelet Transform

DTCWT is proposed by Kingsbury [12] and further improved by Selesnick [13]. DTCWT decomposes and reconstructs a signal via two parallel real wavelet transforms. Two transforms with different groups of filters aimed for real and imaginary of the complex coefficients [11]. Figure 1 describes the decomposition process of DTCWT where *x(t)* is signal that going to be decomposed, low pass filter (a_0 and b_0) and high pass filter (a_1 and b_1). Low pass and high pass filter will decompose signal into approximation and detail coefficients, respectively. Approximation coefficients will be decomposed further at each decomposition level.

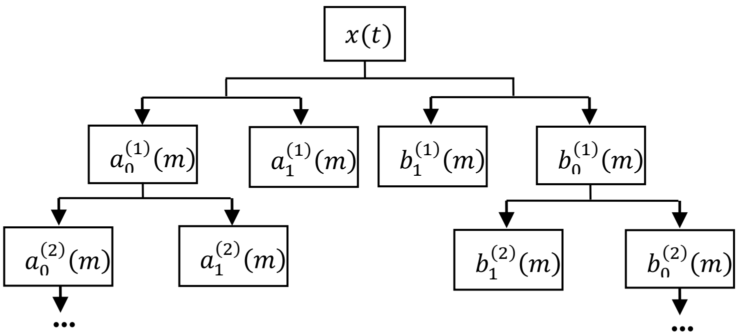

Figure 1: Decomposition of 2-levels DTCWT.

Superiority of DTCWT over traditional Discrete Wavelet Transform (DWT) is its shift invariance and this indicates that DTCWT coefficient gives accurate measure of spectral energy [12, 13]. On the contrary, distribution of energy will be greatly disturbed due to minor shifts in signal when using

DWT. Besides, DWT will cause frequency aliasing yet DTCWT has a strong anti-aliasing property. Therefore, it will extract correct information from the signal and not to induce artificial frequency peaks which can lead to errors.

3. Leakage Localization

When a leak occurs in a pipe, acoustic signals generated at the leak source propagate upstream and downstream along the pipe. As long as the leak is located asymmetrically between two measurement points, there would be a difference of arrival time between two signals [2]. Thereafter, leak might be located by applying knowledge regarding wave velocity in the pipe and estimation of time delay. Equation 1 is used to calculate the location.

$$x = 0.5(L + vt) \tag{1}$$

where x is leak location relative to the first measuring point; L is distance between two measuring points; v is wave propagation velocity and t is an estimated time delay.

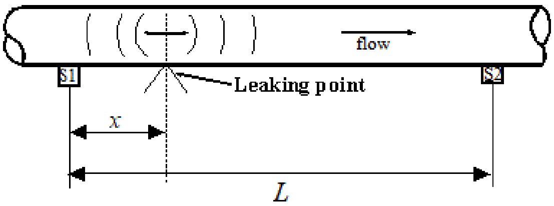

Figure 2: Illustration of Leak Localization.

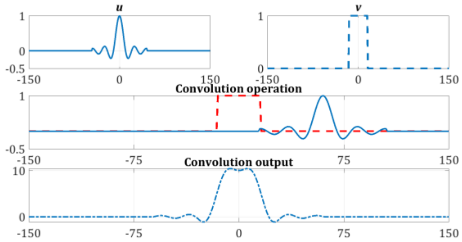

Figure 3: Convolution Process.

Cross correlation is a common method used to estimate the time delay. It performs by measuring the similarity between two signals and time delay can be evaluated based on the time instant that gives a highest correlated coefficient. Convolution is another method that can be applied to compute delay. It shares the similar concept with the cross correlation. By referring to an illustration in Figure 3, overlapping waveform represents convolution of two inputs, *u* and *v*. It will give a largest output when both inputs have the highest similarity.

Apart from cross correlation and convolution, time delay can be estimated through time-frequency analysis method like Continuous Wavelet Transform (CWT). CWT is able to analyse signals jointly in time and frequency so it is suitable to be used for analysis of non-stationary and time-variant signals [14]. Therefore, CWT is able to perform localization of transients such as leakage event. Its basic philosophy is that any time signal can be decomposed into a self-similar series of dilation and translation of mother wavelet. CWT of a signal, *x(t)* is defined as:

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} \psi\left(\frac{t-b}{a}\right) x(t)dt \tag{2}$$

where ψ is mother wavelet, a is scale or dilation parameter and b is shift or translation parameter. CWT has superior precision, better features extraction and detection. However, its disadvantage is owing to the redundant computation [6].

4. DTCWT-Correlation Method

The state-of-the-art leak positioning method is correlation-based location algorithm which is presumed that the wave speed is known and constant. In practice, waves will encounter distortion as they propagate along the pipe so as the velocity. This is known as dispersion which refers to the phenomenon of velocity varies with frequency due to transmit structure and geometric size. The key question is that dispersion phenomenon has not been address in state-of-the-art approach and this may cause inaccuracy of leak localization. Therefore, the goal of this paper is to introduce pre-processing of signals via DTCWT decomposition before cross correlation process. In such wise, dispersion phenomenon will be taking into consideration by evaluating wave speed based on frequency. Relationship between frequency and velocity can be expressed by the dispersion curve shown in Figure 4 which is plotted using PCDISP software [15]. There are three fundamental modes which are longitudinal, flexural and torsional modes. Pipeline leakage acoustic wave will mainly dominate by $F(1,1)$ mode [16]. Figure 5 illustrates the procedures of the proposed method to position leaks.

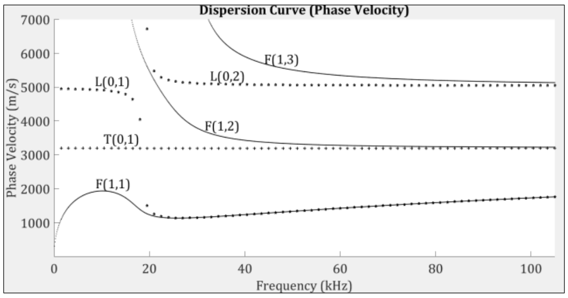

Figure 4: Phase Velocity Dispersion Curve for 3 inches Pipe.

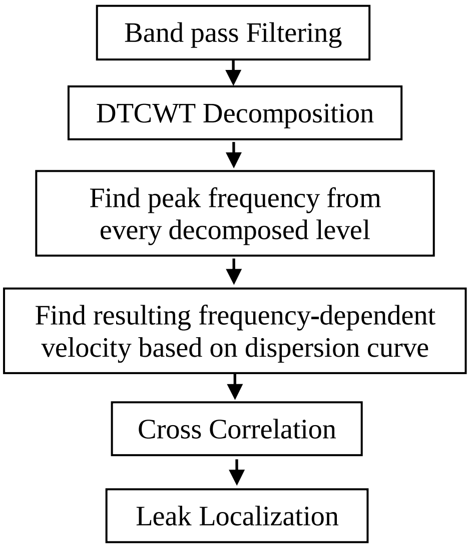

Figure 5: Procedures of DTCWT-Correlation.

5. Experimental Design

The experiment is conducted on a test rig which is constructed with 46 m long galvanized iron pipeline of 80.4 mm inner diameter and 4 mm thickness (Figure 6). A hole is threaded to simulate as a leak. Eight identical AE sensors are mounted on the pipe and located in the mounting positions shown in Figure 7. The signals were acquired by LabView software and amplified using pre-amplifiers with a gain set at 60 dB. Each signal acquired is segmented at 20 milliseconds with sampling frequency of 1 MHz for duration of 5 seconds. Signals are collected for both normal and leaking condition at 1 bar operating pressure. AE sensors specifications used in the experiment are shown in Table 1.

Figure 6: Physical Test Rig Setup.

Table 1: Specifications of Sensors.

Sensor Model	SR 40M
Dimension OD × H (mm)	22 × 36.8
Operating Frequency Range (kHz)	15-70
Resonant Frequency (kHz)	40
Peak Sensitivity	> 75 dB

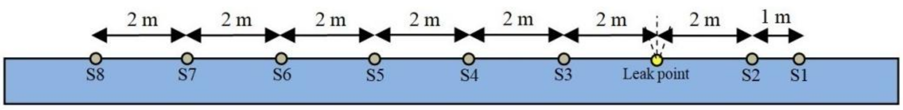

Figure 7: Schematic Diagram of Experimental Setup.

6. Results and Discussion

Both normal and leaking conditions signal are processed with 5-levels DTCWT to decompose into different bandwidth. Figure 8 shows the comparison of frequency spectra between leaking and non-leaking signals after DTCWT decomposition. Spectra of level 1 and 2 which ranged from 125 to 250 kHz are neglected because their frequency bands are beyond sensor operating frequency range and mostly consist of noise. Detail and approximation coefficients are decomposed via high pass and low pass filters, respectively. DTCWT analysis results show that leak signal has higher amplitude compared to no-leak signal, especially when the frequency is more than 50 kHz.

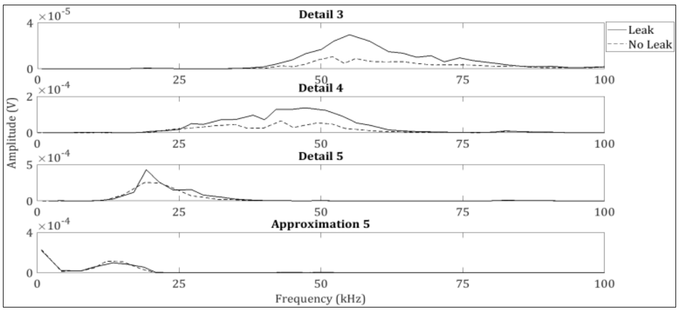

Figure 8: Results after signals decomposed with 5-layers DTCWT.

In this study, location of the leak source is evaluated based on the probabilistic approach. The leak is most likely to occur at the position which gives the highest probability. Figure 9 and Table 2 show the statistical comparison of leak localization results using the proposed method, DTCWT-correlation with other methods for 250 samples. The methods are cross correlation, CWT localization, convolution and wavelet de-noising before cross correlation. The velocity is evaluated based on the peak frequency when applying DTCWT-correlation method. In contrast, the velocity is assumed as 1226 m/s at 40 kHz during the application of other methods because the resonant frequency of the sensor is 40 kHz.

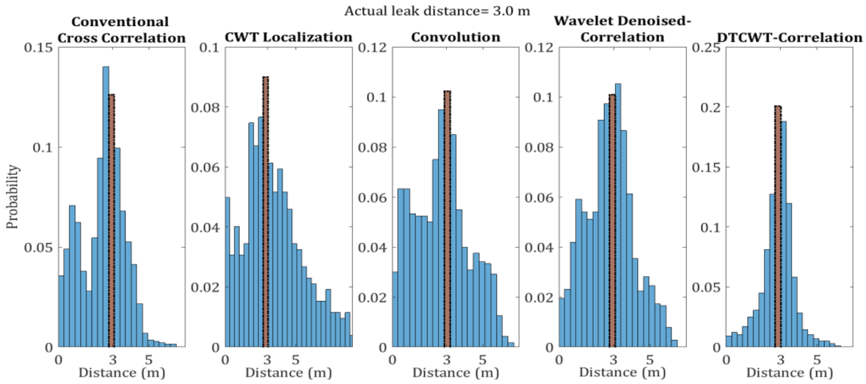

Figure 9: Comparison among different Localization Methods

Table 2: Results among different Localization Methods (actual leak location 3 m)

Methods	Mean (m)	Standard Deviation (m)	Percentage Error (%)
Conventional Cross Correlation	2.46	1.19	18
CWT Localization	3.44	2.05	14.67
Convolution	2.73	1.50	9
Wavelet Denoised-Correlation	2.80	1.31	6.67
DTCWT-Correlation	2.86	0.89	4.67

From Figure 9, each method is shown to locate the leak at 3 m with high probability. Nevertheless, the probability of DTCWT-correlation is highest with lowest missing rates. It is able to obtain the highest localization accuracy with lowest percentage error and standard deviation (Table 2). Hence, the application of DTCWT prior to cross correlation can significantly increase the leak positioning accuracy. In real life, two sensors can be mounted on a pipe with a maximum gap of 15 m to detect leak accurately according to our experimental setup. More sensors can be utilised to increase the accuracy.

7. Conclusion

In summary, the DTCWT-correlation method is demonstrated without the assumption of constant wave velocity. DTCWT decomposes signal into several levels with different frequency bands. Then, the peak frequency from every level is used to evaluate wave velocity in reference to pipe dispersion curve. Thereafter, frequency-dependent velocity is used to locate water leak source. Experimental results have confirmed DTCWT-correlation method gives superior localization results than conventional cross correlation method by showing 4.67 % localization error. Thus, DTCWT-correlation is more feasible to improve pipeline leak localization by using the frequency-varying velocity instead of constant speed.

8. Acknowledgments

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