# DETECTION OF WATER PIPELINE LEAKAGE USING TIME AND FREQUENCY SIGNAL

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**A project report submitted in partial fulfilment of the**
**requirements for the award of Bachelor of Engineering**
**(Hons.) Mechanical Engineering**

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**Universiti Tunku Abdul Rahman**

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# DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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# APPROVAL FOR SUBMISSION

I certify that this project report entitled **“DETECTION OF WATER PIPELINE LEAKAGE USING TIME AND FREQUENCY SIGNAL”** was prepared by **TING LING LING** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Mechanical Engineering at Universiti Tunku Abdul Rahman.

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# ABSTRACT

A statistic from Malaysia National Water Services Commission (SPAN) showed that 5.69 million litres of water losses from pipe daily and the major cause are due to water leakage. Therefore, several water leakage detection systems had been developed. Acoustic Emission (AE) technique is proven as an effective method that is widely and commonly used to help water utilities to locate leaks. AE is a phenomenon that high frequency stress wave generated due to rapid release of energy in the leak or discharge event. These waves will emit sound that can be measured by AE sensors which mounted on the pipe. The measured data are collected as signal and transmitted to a computer to proceed with signal processing by using Matlab software. The main objective of this project is to detect the location of water leakage through a series of signal processing methods. The methods involved are filtering, wavelet de-noising, spectral analysis and cross correlation. The key to the effectiveness of detection of water leakage by using time and frequency signal relies on the proper signal processing methods applied. The obtained results depicted that collected signals were consisted of interfering noise. Leakage event and its location were successfully detected in this project. In addition, leakage signals are enhanced after undergoing filtering and de-noising by suppressing and removing noise exists. Thus, filtering and de-noising on the signal can offer a better result with improved accuracy. A comparison was made between the results before and after band-pass filtering with wavelet de-noising applied and it showed a reduction of percentage error from 38.46 % to 2.31 %. This finding is significant that leak location of water pipeline can be detected and located accurately. Thus, water loss or water demand problems can be mitigated as well as the impacts caused by water leakages.

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| | |
|---|---|
| $D$ | total distance between two measuring points, m |
| $f_s$ | sampling frequency, Hz |
| $f_{min}$ | minimum interested frequency, Hz |
| $L_1$ | leak location relative to first measuring point, m |
| $n$ | decomposition level of wavelet de-noising |
| $t$ | time delay, s |
| $v$ | propagation velocity, m/s |

| | |
|---|---|
| AE | Acoustic Emission |
| DWT | Discrete Wavelet Transform |
| FAP | Fast Affine Projection |
| FEDS | Fast Euclidian Direction Search |
| FFT | Fast Fourier Transform |
| FT | Fourier Transform |
| GI | Galvanized Iron |
| LMS | Least Mean Square |
| MSE | Mean Square Error |
| NDT | Non Destructive Testing |
| NLMS | Normalized Least Mean Square |
| NRW | Non Revenue Water |
| PC | personal computer |
| RLS | Recursive Least Square |
| RTTM | Real Time Transient Model |
| SHM | Structural Health Monitoring |
| SNR | Signal Noise Ratio |
| SPAN | Malaysia National Water Services Commission |
| SURE | Stein’s Unbiased Estimated of Risk |
| WT | Wavelet Transform |

# CHAPTER 1

# INTRODUCTION

## 1.1 General Introduction

Water is a necessary and depleting resource on Earth. It is an essential element for human and other living organisms to thrive. Water is being transported to residential areas, industrial areas or other water consumers through the water distribution system. Unfortunately, water loss had grown into a critical problem. Abundant amount of water lost in every day even every second. A statistic conducted by Malaysia National Water Services Commission (SPAN) showed that supplied water consists of 36.6 % of non-revenue water (NRW) in 2013. It is about 5.69 billion litres of water loss from pipes in a single day. This large amount is sufficient to keep Perlis going for 53 days. The major cause of water loss is due to water leak from aging pipe systems (Lee, 2014). Similarly, as mentioned by Hunaidi (2000), leakage is the major contribution to water loss while other causes are metering errors, poor workmanship, pressure fluctuations, public usage and theft. Figure 1.1 shows the percentage of NRW at each state of Malaysia in year 2013.

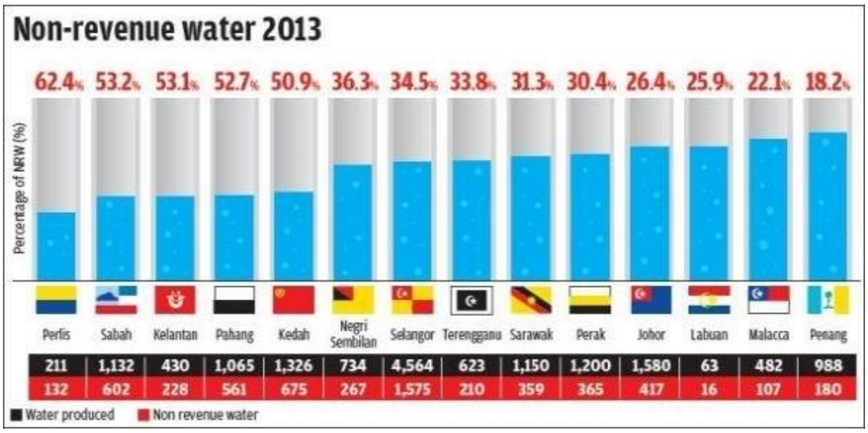


Figure 1.1: Distribution of NRW at Different States of Malaysia (Lee, 2014)

The latest statistic from SPAN had concluded that NRW percentage is 35.6 % and 35.5 % in 2014 and 2015, respectively. The result of this statistic is showed in Table 1.1.

Table 1.1: Non-Revenue Water (NRW) in 2014 and 2015

| **State** | **2014 (MLD)** | | | **2015 (MLD)** | | |
|---|---|---|---|---|---|---|
| | **System Input** | **NRW** | **NRW (%)** | **System Input** | **NRW** | **NRW (%)** |
| Johor | 1640 | 426 | 25.9 | 1702 | 436 | 25.6 |
| Kedah | 1294 | 596 | 46.1 | 1316 | 614 | 46.7 |
| Kelantan | 445 | 220 | 49.4 | 454 | 222 | 49.0 |
| Labuan | 69 | 20 | 29.5 | 71 | 22 | 30.9 |
| Melaka | 478 | 102 | 21.4 | 481 | 93 | 19.3 |
| N. Sembilan | 744 | 267 | 35.9 | 757 | 264 | 34.8 |
| Penang | 995 | 182 | 18.3 | 1014 | 202 | 19.9 |
| Pahang | 1108 | 588 | 53.1 | 1128 | 596 | 52.8 |
| Perak | 1237 | 379 | 30.6 | 1260 | 382 | 30.3 |
| Perlis | 216 | 121 | 55.8 | 220 | 124 | 56.3 |
| Sabah | 1196 | 618 | 51.7 | 1229 | 677 | 55.1 |
| Sarawak | 1192 | 381 | 32.0 | 1268 | 423 | 33.3 |
| Selangor | 4593 | 1545 | 33.6 | 4675 | 1497 | 32.0 |
| Terengganu | 605 | 188 | 31.0 | 621 | 192 | 31.0 |
| MALAYSIA | 15809 | 5633 | 35.6 | 16195 | 5743 | 35.5 |

According to Fiedler (2014), leaks may cause by fatigue cracks, stress corrosion, hydrogen indexing, material defects, material manufacturing errors, faulty installation and external influences. Water leakages attribute to loss of money and natural resources. Economic losses are in term of raw water cost, its treatment, transportation and damage to the pipe system itself. Besides, water leakages bring environmental effects like soil erosion, damages to the foundations of roads or buildings. Leakage issues also create public health risk due to contamination. Therefore, several effective water leakage detection systems had been developed (Hunaidi, 2000).

Acoustic leak detection technique is effectively and widely used to detect water leakage. It was employed to detect leaks or wear of oil and gas pipeline (Lin, Wu and Tan, 2015). The basis of Acoustic Emission (AE) method lies in Kaiser-effect which developed by German Professor J. Kaiser in 1950. He identified that ultrasound is emitted when cracks formed and propagating. Subsequently, this method is employed to detect leaks, propagating cracks and monitoring the manufacturing process (Aastroem, 2008).

## 1.2 Importance of the Study

The result of this present study may have significant impact on saving water from leakage. Defected pipes will be repaired or replaced once leakage is detected. As a result, raw cost of water being lost can be recovered and cost spent on NRW may greatly reduce.

The key concern is that drawbacks of water leakage especially water shortage problem can be resolved. Water resources can be conserved so that the depleting process of water would be decelerated. Other aftermaths caused by water leakage such as impacts on human health and environment can be mitigated (Fiedler, 2014).

## 1.3 Problem Statement

Water is a vital and precious resource around the world. Unfavourably, water is lost through pipeline leakage in every moment. There is more than 32 billion cubic meters of water leaks from urban distribution systems per year which is shown in Table 1.2.

Table 1.2: Estimates of Worldwide NRW Volumes (Kingdom, 2006)

| | | | | **Volume (billions of $m^3$ / year)** | | |
|---|---|---|---|---|---|---|
| | **Supplied Population (millions, 2002)** | **System Input (l/capita/day)** | **Level of NRW (% of System Input)** | **Physical Losses** | **Commercial Losses** | **Total NRW** |
| **Developed countries** | 744.8 | 300 | 15 | 9.8 | 2.4 | 12.2 |
| **Eurasia** | 178.0 | 500 | 30 | 6.8 | 2.9 | 9.7 |
| **Developing countries** | 837.2 | 250 | 35 | 16.1 | 10.6 | 26.7 |
| | | | Total | 32.7 | 15.9 | 48.6 |

Public or government were disregarded about water leakage issues in past times. They put less effort on solving water leakage problems because they thought the water tariff is very cheap so monetary amount attributed by water leakage is inconsiderable. They might think that the water resource is abundant and unlimited. In addition, impacts of water leakage are not significant or critical enough. Water leakage is unlike gas leakage which can cause catastrophic failure, severe financial and environmental impacts. As a result, leak detection of oil and gas pipeline is more growing concern (Karkulali et al., 2016). Moreover, traditional field survey methods used to detect water leaks are costly and time-consuming. Those methods are highly depending on the experience of the users (Khulief et al., 2012).

There are several challenges faced by Asian water utilities on water leakage management which including outdated infrastructure, poor operation and maintenance, inadequate technical skill, technology and financial constraints.

Despite the rate of water tariff is low, public shall not ignore water leakage problems because the cost caused by water leakages may contribute to a large amount in the long run. Table 1.3 shows about US$ 14 billion is lost through water utilities annually.

Table 1.3: Estimated Value of NRW and Its Components (Kingdom, 2006)

| | | | **Estimated Values (billions of US$/year)** | | |
|---|---|---|---|---|---|
| | **Marginal Cost of Water (US$ / m$^3$)** | **Average Tariff (US$ / m$^3$)** | **Cost of Physical Losses** | **Lost Revenue resulted from Commercial Losses** | **Total Cost of NRW** |
| **Developed countries** | 0.30 | 1.00 | 2.90 | 2.40 | 5.30 |
| **Eurasia (CIS)** | 0.30 | 0.50 | 2.00 | 1.50 | 3.50 |
| **Developing countries** | 0.20 | 0.25 | 3.20 | 2.60 | 5.80 |
| | | Total | 8.10 | 6.50 | 14.60 |

Besides, the rise of water demand is in parallel with population growth. For instance, more than 36 states in United States will experience the water shortage in next 10 years and 400 out of 600 cities in China are suffering from water shortage (Tai, 2004). Thus, proper water demand management and water leakage reduction emerged as foremost goals for many countries.

To resolve doubt of public on the effectiveness of leak detection methods, a new, low cost and easy to use which is acoustic system had been introduced to locate leak source (Hunaidi et al., 2004). In past researches, existence of system noise is a major barrier in acoustic leak detection method. Hence, de-noising technique is required in signal processing method (Rashid et al., 2014).

## 1.4 Aims and Objectives

The main aim of this study was to detect the location at where the water leaked from the pipeline.

In order to achieve the aim, the specific objectives of this study are defined:

1. To employ signal processing techniques in order to suppress pipeline background noise, identify spectral characteristics of the leakage signal and determine the leak location.
2. To study characteristics of different signal processing methods and identify efficient methods that can be applied to increase precision of the result.
3. To evaluate accuracy of AE method by comparing with actual leak location.

## 1.5 Scope and Limitation of the Study

The working scope of the current study is to detect leakage of water pipeline by using signal processing method. This study consist some limitations:

- Propagation velocity, $v$ used in the equation is crucial to determine location of the leak source. Hence, it should be calculated or identified accurately. However, $v$ is depending on pipe material, pipe thickness and frequency (Hunaidi and Chu, 1999).
- Amplitude of the leak signal will vary with pressure and affects the collected raw signal. Hence pressure shall be kept constant when collecting results (Yalcinkaya and Ozevin, 2013).
- Effectiveness of cross correlation function would be limited if reflected waves are included in waveforms obtained (Yalcinkaya and Ozevin, 2013).

## 1.6 Contribution of the Study

The contribution of this project may help to locate leaks in the water distribution system thus can save water from leakage and reduce water demand problem through acoustic leak detection system. Besides, the theory behind and techniques involved can also be applied in detection of pipeline corrosion or oil and gas pipeline leakage.

## 1.7 Outline of the Report

In this report, literature review found will be discussed and commented in Chapter 2. Methodology and methods involved in this study will be explained in Chapter 3. Meanwhile, collected results and some discussions will be presented in Chapter 4. In Chapter 5, conclusions and recommendations are made.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Acoustic Emission Technique

AE method is a non-destructive testing (NDT) which is used for structural health monitoring (SHM) for engineering structures (Kaphle and Tan, 2015). It was applied to detect fracture, property change in materials and bearing defect (Lin, Wu and Tan, 2015). AE method offers advantages such as fast response and able to provide high sensitivity (Yughay, Gribok and Volov, 1997). This was confirmed by Juliano, Meegoda and Watts (2013) in their paper that AE system is capable to detect leaks in fluid-filled metal pipes and the localization of leak source is faster than other conventional methods. AE method is able to detect small leakages for on-going pipeline without interfering its operation (Kadri, Yaacoub and Mushtaha, 2014).

At the leak point, there will be a turbulent jet. High turbulent pressure fluctuations and sound will produce when jet interacts with the pipe wall. The pressure at the leak point will fall below vapour pressure and creates vapour bubbles if velocity is high. Vapour bubbles will implode due to high downstream static pressure. As a result, all energy will concentrate on a very small region and create minute shock waves. These shock waves will also emit sound (Khulief et al., 2012). Generally, AE is a phenomenon that high frequency stress wave created due to rapid release of energy in a leak or discharge event (Kaphle and Tan, 2015).

The working mechanism of AE technique is relying on AE sensors that mounted on the pipe to measure noise level along the pipe (Fiedler, 2014). Figure 2.1 shows how AE sensor works. The noise level at leak location is higher.

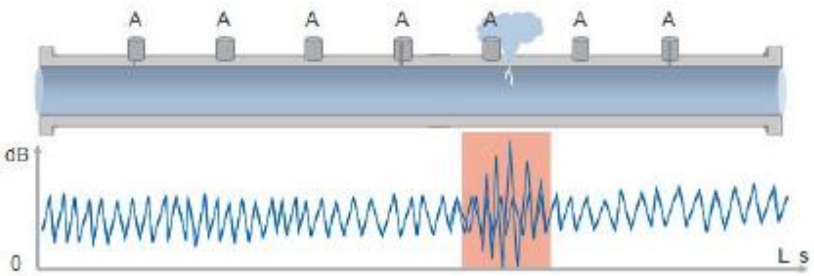


Figure 2.1: Acoustic Sensor Mounted on Pipe (Fiedler, 2014)

Once the signals are detected from AE sensors, they will be transmitted to a computer to proceed with signal processing (Hunaidi et al., 2004). Signal represents any physical quantity that changing with time, distance, position, temperature, pressure or other parameters (Proakis and Manolakis, 1996). Salivahanan (2015) mentioned that signal processing refers to the operations that modify, analyse or manipulate the signal in order to extract useful information. Therefore, signal processing is related to represent signals in a mathematical way and extracting information by performing algorithmic operations.

Collected raw signals are in the time domain, which means their amplitudes vary with time. Signal in frequency domain basically is converted from the time function into a sum of sine functions. Frequency domain analysis is able to figure out the frequency spectrum composition exists in the signal. Typically, high frequency occurs when the signal changes rapidly.

## 2.2 Signal Processing Methodology

In few papers, basic steps involved in signal processing method had been introduced. Figure 2.2 shows methods used to detect leaks in plastic pipe. Signal is measured at two points that bracketed a leak. Anti-aliasing filter is a low-pass analogue filter. It is used to limit and reduce the amplitude of signals that having a higher frequency than the cut-off frequency. As the leak signals in plastic pipes are mostly consisted of low frequency components which less than 50 Hz. Hence, cut-off frequency is set at 200 Hz. After that, the signal will be sampled at 500 Hz or 500 samples per second (Hunaidi and Chu, 1999). Sampling refers to the process periodically measures signal at fixed intervals. According to Nyquist sampling theorem, sampling rate should be at least twice of maximum interested frequency (Silva, 2007). This indicates that the sampling frequency should be twice of the cut-off frequency of anti-aliasing filter. After that, signals will undergo digital filtering and spectral analysis (Hunaidi and Chu, 1999).

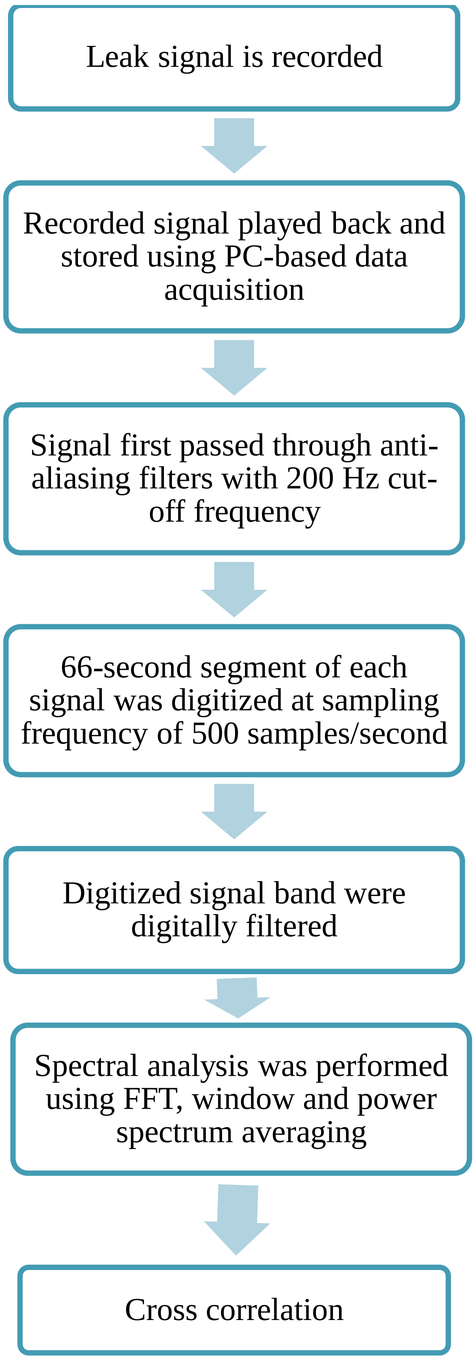


Figure 2.2: Steps Involved in Analysis of Leak Signal (Hunaidi and Chu, 1999)

Figure 2.3 shows procedures used to detect and locate transient pipe burst events by using wavelet analysis. Raw signals are pre-processed by applying wavelet de-noising and low-pass filtering. De-noised signals are decomposed through a few decomposition levels to identify signal features. Possible signal feature will be enhanced or retain when decomposition levels go higher. Finally, arrival times of burst transient at each measurement points are estimated to localize burst event (Srirangarajan et al., 2012).

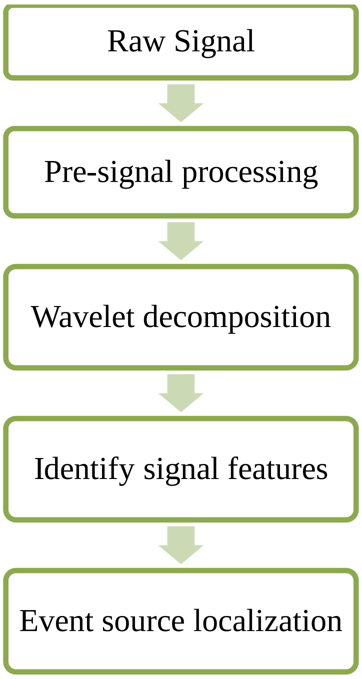


Figure 2.3: Wavelet-based Event Detection Scheme (Srirangarajan et al., 2012)

Figure 2.4 shows wavelet techniques used for damage detection of steel pipe. The signal will undergo wavelet decomposition before performing spectral analysis. Detail coefficients are resulted from high frequency components meanwhile approximation coefficients are resulted by low frequency components and will be further decompose to filter out noise and enhance the signal (Ying et al., 2013).

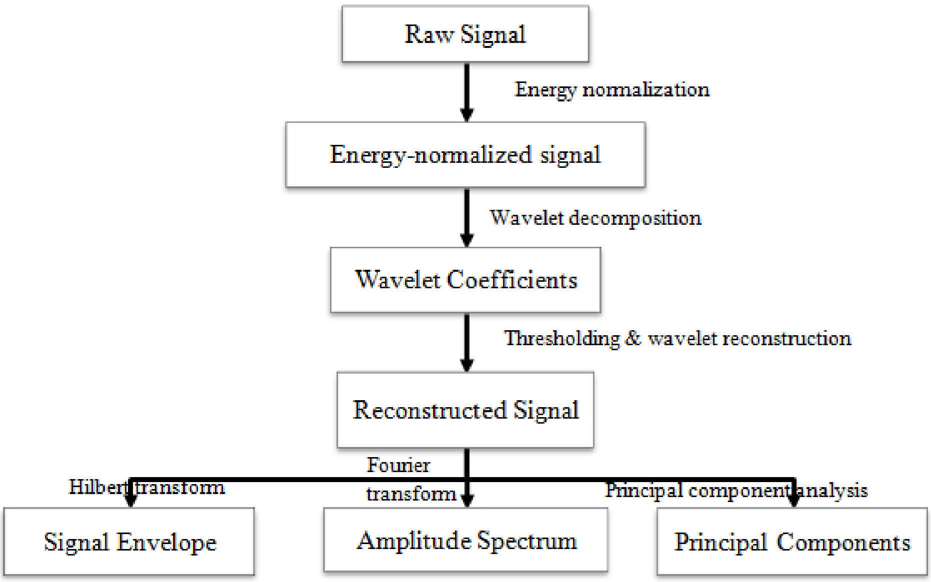


Figure 2.4: Flow Chart of Signal Processing for Feature Extraction (Ying et al., 2013)

From the figures above shown, the general steps involved in signal processing are filtering, windowing function, spectral analysis technique and cross correlation. Filtering performs to suppress noise while spectral analysis techniques like Fourier Transform (FT) and Wavelet Transform enable the signal to represent in frequency domain. Meanwhile, cross correlation is a technique to find the location of leakage occurs. The details of each technique will be introduced in subsequent sections.

## 2.3 Filtering Process

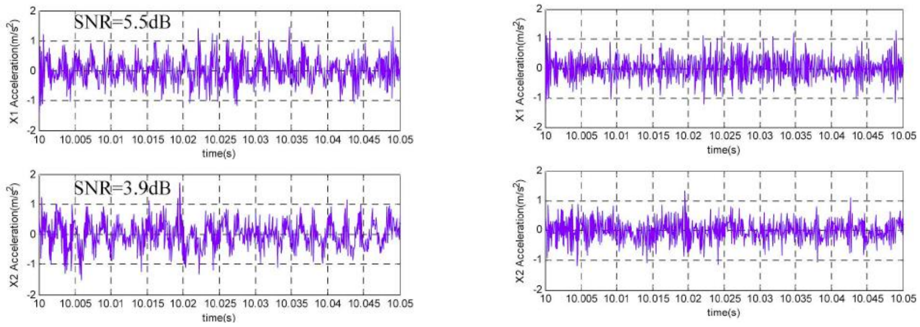
Referring to Section 2.2, recorded and sampled signal will first undergo noise cancellation technique.

Noise is like the signal which having time-varying characteristics but it does not carry useful information (Roberts, 2003). Noise is defined as those unwanted signal that distorted and affected desired signal information. Thus, noise presented in leak signal shall be cancelled off in order to enhance leak signal and reduce the occurrence of false alarm. General noise found in the pipeline signal can be considered as flow noise and background noise. The traditional ways used to eliminate acoustic noise are using enclosures, barriers and silencers (Chhikara and Singh, 2012). Following sections are discussing about some modern approaches used to remove noise in a signal such as digital filtering and adaptive filtering.

### 2.3.1 Digital Filtering

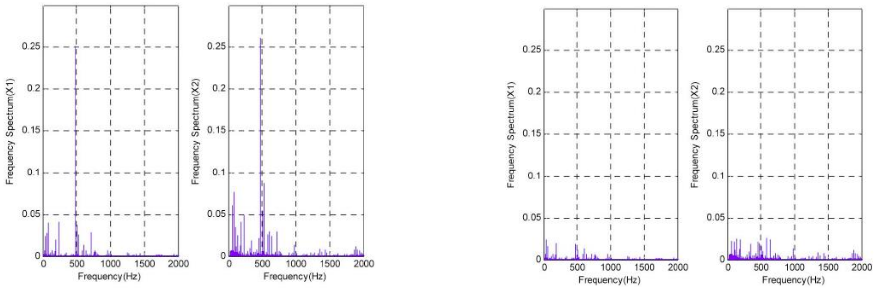
Filtering is used to suppress noise meanwhile the signal is unaffected. It performs by removing interfering noise outside the predominant frequency range of leak signal. There are two types of digital filters, which are fixed and adaptive (Roberts, 2003). In the experiment conducted by Hunaidi and Chu (1999), digital filtering had been used to band limit the signal.

From Figure 2.5, it can be seen that the signal is much clear with enhanced features after noise components had been removed. Actual time delay is easier to be identified through Figure 2.5(f) compared to Figure 2.5(e). Therefore, it is crucial to reject noise in order to obtain more precise and accurate signal information.



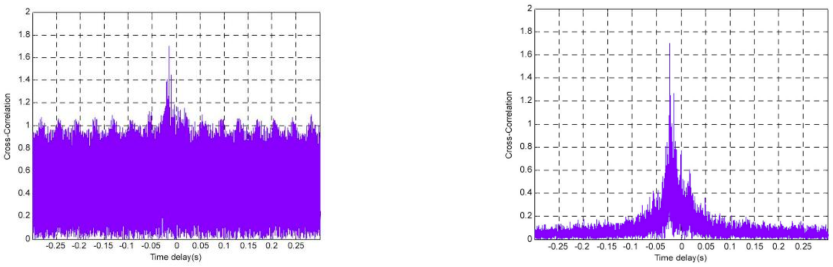
(a) Measured Signal

(b) Filtered Signal



(c) Frequency Spectrum before Noise Cancellation

(d) Frequency Spectrum after Noise Cancellation



(e) Cross Correlation before Noise Cancellation

(f) Cross Correlation after Noise Cancellation

Figure 2.5: Comparison before and after Noise Cancellation (Yoon, Park and Shin, 2012)

### 2.3.2 Fixed Filter

Fixed filter is designed based on prior knowledge of both signal and noise (Widrow et al., 1975). Examples of fixed filters are low-pass, high-pass, band pass, band stop and notch (Roberts, 2003). Widrow et al. (1975) identified that fixed filter is inapplicable in cancelling unknown inputs of signal and noise that are often varies with time. Fixed filter is only applicable when the desired signal and noise occupy different frequency bands so that noise beyond interested frequency bands can be removed. However, it can be applied with other noise suppressing method simultaneously. For example, low-pass filtering is used after the signal underwent wavelet de-noising to detect slow transients (Srirangarajan et al., 2012).

### 2.3.3 Adaptive Filtering

Design of adaptive filter requires little or no prior knowledge of signal and noise characteristics and it has ability to adjust its own parameters (Widrow et al., 1975). Adaptive filtering had been designed for background noise elimination whereas the main concern is that proper reference signal must be correlated with background noise instead of correlated with the leak signal (Yughay, Gribok and Volov, 1997).

Adjustment of parameters is made by adaptive algorithms. Common algorithms are Least Mean Square (LMS), Normalized Least Mean Square (NLMS), Recursive Least Square (RLS), Fast Affine Projection (AP) and Fast Euclidian Direction Search (FEDS). Choice of the adaptive algorithm is depending on computational complexity and convergence speed. The filter would be more effective if it has less computational complexity and fast adaption rate (Hadei and Iotfizad, 2010). Table 2.1 shows RLS offer the highest signal noise ratio (SNR) among these algorithms. Meanwhile, Figure 2.6 shows the original signal.

Table 2.1: SNR of Various Adaptive Algorithm (Hadei and Iotfizad, 2010)

| **Algorithm** | **SNR (dB)** |
|---|---|
| LMS | 13.5905 |
| NLMS | 16.8679 |
| AP | 20.0307 |
| FEDS | 22.2623 |
| FAP | 24.9078 |
| RLS | 29.7355 |

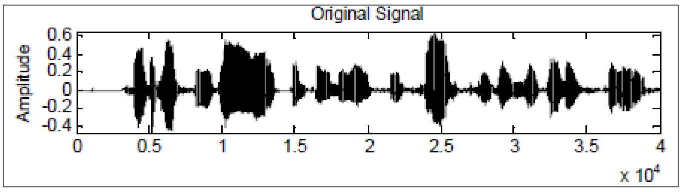
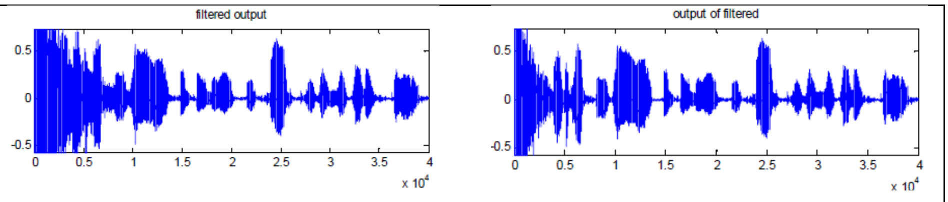
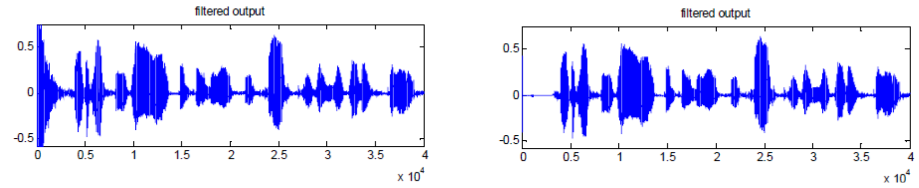


Figure 2.6: Original Signal (Hadei and Iotfizad, 2010)

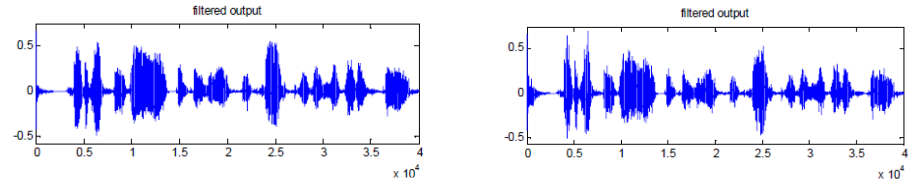
From Figure 2.7, it can be seen that filtered signal of RLS algorithm has the highest similarity with the original signal.



(a) LMS (b) NLMS



(c) AP (d) RLS



(e) FAP (f) FEDS

Figure 2.7: Filtered Output Signal of Six Algorithms (Hadei and Iotfizad, 2010)

## 2.4 De-noising Process

After filtering, de-noising method will be applied in order to enhance the signal features. Therefore, precision and accuracy of results can be increased by suppressing unwanted noise signal (Rashid et al., 2014).

### 2.4.1 Wavelet De-noising

Wavelet de-noising is a noise suppressing method by using wavelet analysis. It decomposes the signal through several levels and removed noise with little information loss. There are three procedures required to perform wavelet de-noising (Rashid et al., 2014). First, signal is decomposed using Discrete Wavelet Transform (DWT) to obtain noisy wavelet coefficient. According to Liu et al. (2017), wavelet coefficients of important signals are present in low amounts but high amplitudes. However, coefficients of noise scattered evenly and in large number but low amplitudes. The second step is to apply thresholding in order to diminish coefficients which have a low value because they are typically noise. Lastly, the signal can be reconstructed via inverse wavelet transform (Donoho and Johnstone, 1992; 1994).

Thresholding is a step applied to compare obtained coefficients with threshold. The coefficient which is smaller than threshold will be set to zero otherwise it is kept constant (Hedaoo and Godbole, 2011). There are four different ways to determine threshold value which are Universal Threshold, Minimax Threshold, Stein's Unbiased Estimated of Risk (SURE) and Spatial Adaptive Threshold. Among these four methods, Universal Threshold is simplest and fast (Bouchouareb and Benatia, 2014).

Wavelet de-noising is applied to suppress noise in the event of detect burst transients (Srirangarajan et al., 2012). In their study, threshold at each level is estimated from standard deviation of wavelet coefficients. Figure 2.8 and 2.9 depict that signal feature will be enhanced after wavelet de-noising and multi-scale wavelet analysis was carried out (Ying et al., 2013).

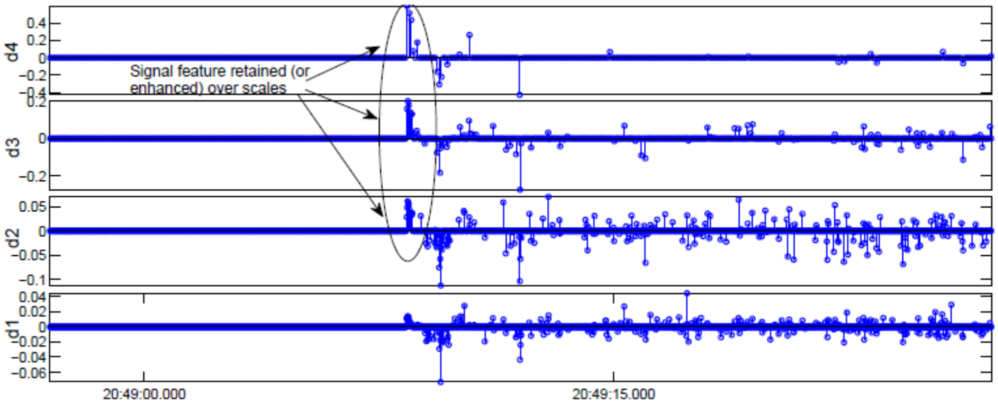


Figure 2.8: Multi-scale Wavelet Analysis (Ying et al., 2013)

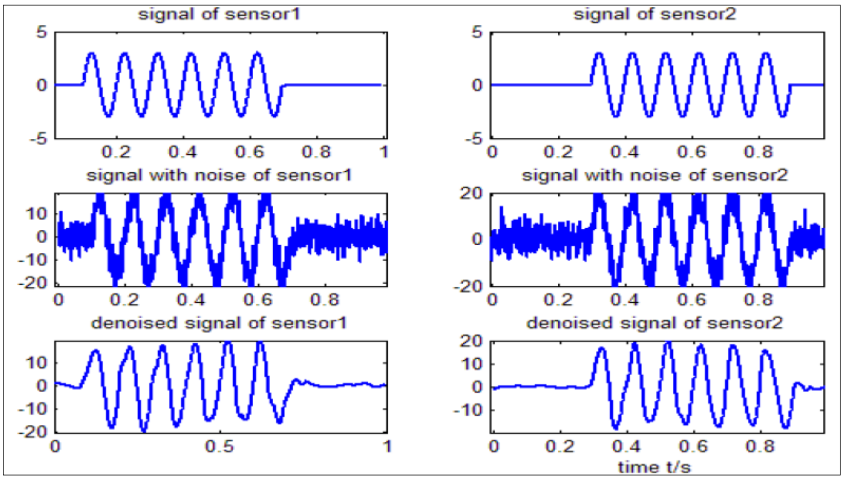


Figure 2.9: Simulated Signal and Wavelet De-noised Signal (Tang et al., 2009)

## 2.5 Windowing

Windowing function will be applied to the signal after the noise had been removed. Signal will be truncated to get rid of insignificant parts by multiplying the signal with windowing function in time domain (Silva, 2007). Windowing can overthrow spectral leakage and spectral bias (Yeong and Pearce, 1989). It reduces undesirable oscillations in the pass band and stop band. Windowing function can be applied to diminish signal discontinuities as shown in Figure 2.10 (Shreve, 1995). However, windowing has two side effects which are reduced frequency resolution of a spectrum and cause "frequency leakage" or truncation error due to sharp clipping of signal (Orfanidis, 2010).

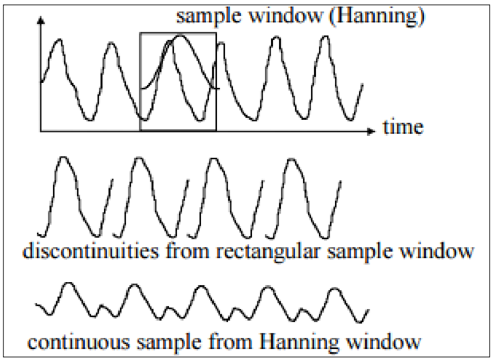


Figure 2.10: Signal Discontinuities can be reduced by Windowing (Shreve, 1995)

Windowing functions have main-lobe at the origin and side-lobes at both sides which are decaying with asymptotic attenuation (Yeong and Pearce, 1989). Orfanidis (2010) discussed about main-lobe width determines the frequency resolution of the signal while side-lobes determine the amount of frequency leakage. Frequency resolution is a measure to distinguish two closely spaced frequency components. It is difficult to identify exact frequency components exist in a signal but only can determine frequency bands exist when the frequency resolution is low. Meanwhile, frequency leakage related to loss of signal information.

Upon choosing type of window function, the frequency characteristics of window and signal had to be studied. Yeong and Pearce (1989) explained that large spectral leakage occurs through side-lobes when peak ripple value of first side-lobe is high but more attenuation can be done. Therefore, spectral leakage can be reduced by suppressing side-lobes (Silva, 2007). Smith (2011) discussed that narrowest main-lobe can produce maximum frequency resolution. Unfortunately, window energy spreads into side-lobes when main-lobe narrows and hence spectral leakage increases. Therefore, there is a trade off between spectral leakage suppression and frequency resolution. As introduced by Rakshit and Ullah (2014), longer window length can be utilized in order to compensate the drawback of broad main-lobe width and recover low frequency resolution. Table 2.2 describes main-lobe width, first side-lobe, advantages and disadvantages of few types of windowing function.

Table 2.2: Characteristics among Different Types of Windowing (Rakshit and Ullah, 2014; Smith, 2011)

| Type of Window | -3 dB Bandwidth | Peak of First Side-lobe | Advantages | Disadvantages |
|---|---|---|---|---|
| Blackman | 0.051 | -58 | | |
| Blackman-Harris | 0.059 | -92 | Highest peak and attenuation | Wide peak |
| Flat Top | 0.117 | -88 | More similar to actual amplitude | Broadest width |
| Hamming | 0.039 | -43 | Good frequency resolution, low roll off rate | Little signal discontinuity still exists |
| Hanning | 0.043 | -32 | Good frequency resolution with reduced spectral leakage | High roll off rate, decay faster |
| Rectangular | 0.027 | -13 | Narrowest main-lobe | Spectral leakage, signal discontinuities |

Hamming and Hanning Window are commonly being used because they have moderate bandwidth and peak side-lobe ripple (Silva, 2007). As a consequence, they are able to strike balance by gaining good frequency resolution with less spectral leakage. They can make energy concentrate at main-lobe (Qi and Que, 2013). Hanning is more suitable than Hamming as it touches zero exactly and eliminate entire discontinuities. Figure 2.11 shows Hamming does not reach zero exactly and slight discontinuities may still exist.

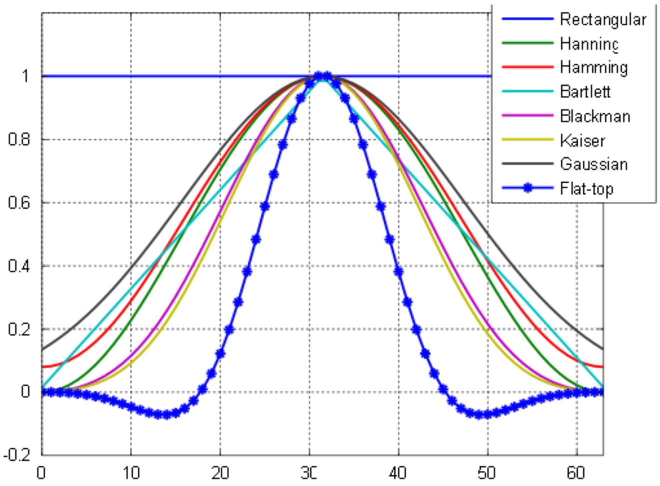


Figure 2.11: Shape of Generalized Window (Yeong and Pearce, 1989)

Hanning Window is applied in the experiment of Hunaidi and Chu (1999) and gave an accurate result of leak location. Their result showed leak located at 75.6 m from the first sensor whereas the actual locations of the leak can be shown in Figure 2.12. In their experiment, three leak points are placed within range of 75.1 m and 76 m.

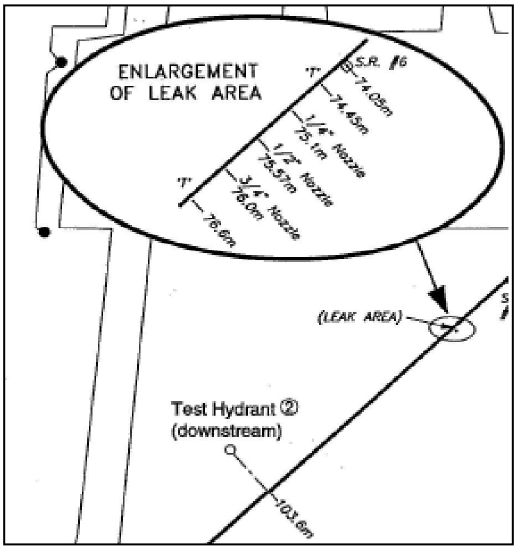
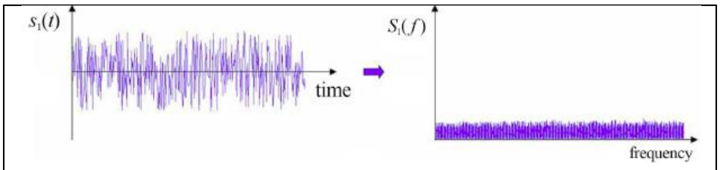


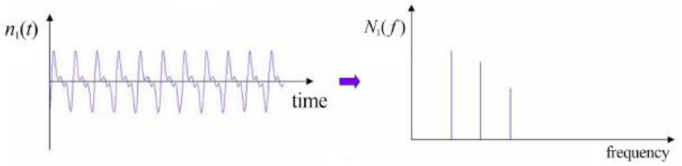
Figure 2.12: Leak Locations with respect to First Measuring Point (Hunaidi and Chu, 1999)

## 2.6 Spectral Analysis

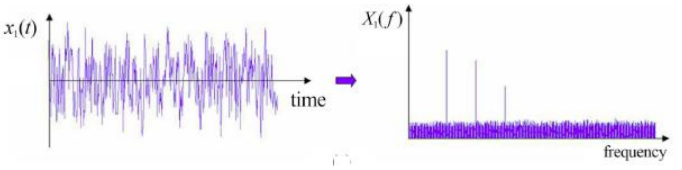
Spectrum indicates frequency content of a signal. Spectral analysis is an operation used to obtain the spectrum of a signal through mathematical basis (Proakis and Manolakis, 1996). Spectral analysis aimed to identify characteristics of frequency during a leakage event (Karkulali et al., 2016). Frequency domain features are considerable in AE source identification because signals in the frequency domain are less affected by threshold changes (Anastasopoulos, 2007). Yoon, Park and Shin (2012) considered that it is difficult to differentiate leak signal and vibrations of machines in time domain. However, leak signal has a flat broadband spectrum while vibrations of machines are denoted as harmonic peak component in the frequency domain. Hence, peak components can be eliminated by applying peak rejection criteria that removing peak components with amplitudes exceed threshold. Figures 2.13 shows leak signal and vibrations of machines have different frequency characteristics.



(a) Leakage Signal



(b) Noise



(c) Leak Signal and Noise

Figure 2.13: Frequency Characteristics of Signal (Yoon, Park and Shin, 2012)

Vibrations caused by leak signal are high and retain for a period. There will be a dominant region with frequency spikes whereas there is no dominant peak in no leak signal (Karkulali et al., 2016). There are few common methods can be used to transform the signal such as Hilbert Transform, Fast Fourier Transform, Short Time Fourier Transform and Wavelet Transform.

### 2.6.2 Fast Fourier Transform (FFT)

FFT transforms a signal into sine waves of different amplitudes and frequencies. In the paper proposed by Hunaidi and Chu (1999), FFT is used for spectral analysis. It is used to evaluate the dominant peak in the frequency domain (Karkulali et al., 2016). The basic concept of FFT is that the array of time-domain waveform samples is converted into the array of frequency-domain spectrum samples. FFT also utilized to determine the contribution of each frequency into total power of a signal (Yughay, Gribok and Volov, 1997). Besides, FFT is applied to study frequency components of each signal and compare the magnitude of each frequency. FFT can detect and quantify severity of leakage. For example, magnitude of FFT of the signal is lower for smaller leak size compared to larger leak size (Kadri, Yaacoub and Mushtaha, 2014).

The advantage of using FFT is that it is able to eliminate tedious calculation and analyse spectral properties of a signal. It tends to give rapid frequency domain analysis. Nevertheless, FFT may encounter signal information loss during transformation to the frequency domain. It is unable to represent a signal in the time-frequency domain (Salivahanan, 2015). Besides, it is difficult to deal with non-stationary or signal with abrupt changes. Stationary signal is a signal which its frequency components do not vary with time. Polikar (2006) remarked that FFT gives spectral information but it does not give information about when those spectral components appear.

### 2.6.3 Short Time Fourier Transform (STFT)

STFT is able to provide simultaneous time-frequency representation but it has limited precision due to its window size. STFT performs by multiplying each small segments of a signal with window function and applying FT over each segment. The drawback of STFT is it only provides constant resolution for whole signal hence resolution of frequency components cannot be differentiated (Wu et al., 2008). Nevertheless, overall time resolution and frequency resolution of STFT are good though the limitation of fix resolution exists. Another drawback of STFT is that there is a trade off between frequency resolution and time resolution. When window size is large, frequency resolution is high whereas the time resolution is high when window size is narrow (Wang, Ji and Xu, 2007).

Overlapping processing is applied when performing STFT in order to recoup the loss at the end of window length and phase out circular effect implicit (Hunaidi and Chu, 1999). Silva (2007) defined overlapping as a certain portion of samples at the end of computing block will be moved to the beginning of next processing block. In other words, overlapped samples will be processed more than one time. Overlapping is an effective technique of averaging spectral results.

STFT had been proposed as transient based leak localization approach by Zan et al. (2014) in their study. They applied STFT with the Blackman window. Meanwhile, STFT also applied to identify leakage of urban water distribution system and showed better uncertainty than FFT when leak is present and absent for a short time (Aime et al., 2009). Their results are presented in Table 2.3.

Table 2.3: Leak Detection Results (Aime et al., 2009)

| Points | Method | Uncertainty |
|---|---|---|
| 1 | FFT | ±3.90 m |
|  | STFT | ±3.20 m |
| 2 | FFT | ±1.94 m |
|  | STFT | ±1.80 m |

### 2.6.4 Wavelet Transform (WT)

WT is capable of representing signals in the time-frequency domain which delivering time and frequency information simultaneously. Thus, frequency bands exist at what time intervals can be identified. Its basic functions are formed by translating and dilating mother wavelet or can be stated as shifting and scaling the mother wavelet in time (Mallat, 1988). Mother wavelet is wavelet function that characterizes the basic wavelet shape. WT is effective to localize the location of leakage occurred by evaluating arrival times at the peak of waveform data on the time-frequency plane (Lee and Lee, 2006). WT used to analyse pipeline leak signals and filter noise out. WT is applied for noise reduction before cross correlation can help to localize leak location accurately (Tang et al., 2009).

WT analyses signal by decomposing signals into approximation and detail coefficients through high-pass and low-pass filtering. At each decomposition level, coefficients resulted from low-pass filter will be decomposed further while coefficients resulted from high-pass filter regard as noise and been eliminated (Polikar, 2006). High frequency components give detail coefficients while low frequency components resulted in approximate coefficients. Approximation coefficients will further decompose into second level approximation and detail (Tang et al., 2009). This process can be illustrated in Figure 2.14 where *x(n)* is an input signal that going to be decomposed, *g(n)* and *h(n)* refers to high-pass and low-pass filter, respectively.

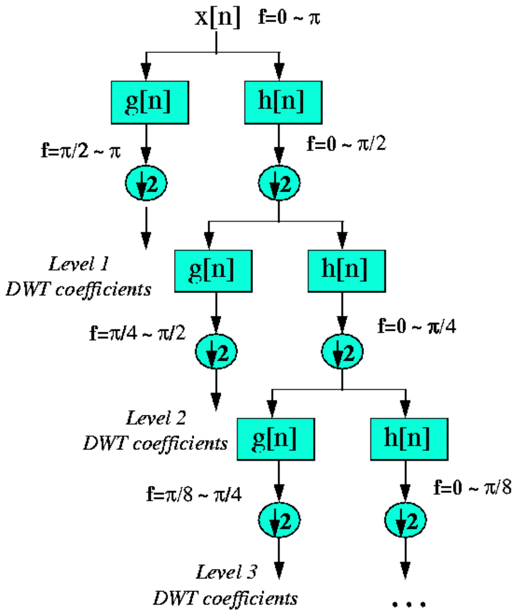


Figure 2.14: Decomposition Procedures in Wavelet Transform (Polikar, 2006)

Table 2.4 shows all burst events at three measurement points were detected by using multi-scale wavelet analysis.

Table 2.4: Burst Event Detection Results (Ying et al., 2013)

| **Measurement points** | **True detections** | **False detections** | **Missed events** |
|---|---|---|---|
| 1 | 9 | 1 | 0 |
| 2 | 9 | 0 | 0 |
| 3 | 9 | 0 | 0 |

Based on the experiment done by Srirangarajan et al. (2012), it is observed that noise decay extremely as the decomposition level increases. The feature can be classified as signal if its coefficient magnitudes are retained or enhanced when decomposition level increases. 4-level decomposition was found efficient and good fit in their experiment. However, 5-level decomposition is used in work of Tang et al. (2009). Choice of decomposition level depends on the signal to noise ratio. Therefore, appropriate decomposition level can be determined by comparing SNR after decomposed with different level. Increased level of decomposition can offer better performance especially for the signal with higher noise densities (Rashid et al., 2014). However, effective information will be eliminating if decomposition level exceeded an optimum level (Mostafapour and Davoodi, 2015). Typical decomposition number is 3-5. Wan et al. (2012) identified that maximum decomposition level, $n$ should satisfy expression below:

$$\frac{f_s}{2^{n+1}} \geq f_{\min} \tag{2.1}$$

where

$f_s$ = sampling frequency, Hz

$f_{min}$ = minimum interested frequency, Hz

The benefit of applying WT over FFT is that WT is adequate to analyse transient, non-stationary or time varying signal. Thus, it able to extract information whenever there is instantaneous change (Rashid et al., 2014). Salivahanan (2015) identified that WT analyse signals with abrupt transition better than FT. WT is more suitable to analyse complicated leak signals (Yalcinkaya and Ozevin, 2013).

WT has adaptable precision, better features extraction and detection compared to STFT because it has multi resolution capability. It has different resolution for different frequency components (Wu et al., 2008). For example, high frequency is better resolved in time but low frequency is better resolved in frequency. Disadvantage of WT is due to redundant computation (Rashid et al., 2014).

Furthermore, the most important challenge of using WT is the selection of optimum mother wavelet since transformed signal of WT is basically translated and dilated version of mother wavelet (Mostafapour and Davoodi, 2015). Ngui et al. (2013) discussed that selection of mother wavelet is depending on the properties of mother wavelet and similarity between analysed signal and mother wavelet. Results are different if different mother wavelet is used. The results will obviously show two transient events if chosen mother wavelet function is similar to transient event but WT will not show the desired result if mother wavelet has little or no similarity to transient event (Ahadi and Bakhtiar, 2010).

Daubechies, Morlet and Harr wavelet are popular wavelet functions (Lee et al., 2012). Rashid et al. (2014) commented that Daubechies wavelet offers high accuracy in leakage detection due to its excellent decomposition and de-noising properties. Daubechies wavelet also being used in the study of Wan et al. (2012). They claimed that Daubechies has advantages of being sensitive to leak signals, can reduce distortion of signal and reconstruct the signal well.

## 2.7 Localization of Leak Source

Cross correlation is a method used to measure similarity of two waveforms (Hafezi and Mirhosseini, 2015). It is developed to locate the source of the leak occurred by estimating the time delay between two received signals (Yoon, Park and Shin, 2012). It can be deployed to indicate the presence of boundaries and wall thickness change in the pipe network (Hafezi and Mirhosseini, 2015).

As long as the leak is located asymmetrically between two measurement points, there would be a difference in arrival time between leak signals (Hunaidi, 2000). On the other hand, Hunaidi et al. (2004) investigated that if the leak location is situated symmetrically between two measurement points, then leaks signals would arrive simultaneously so there is no time delay. Yet, if the leak location is exactly at one of the measurement points or not locate between two points, time delay will be equal to the total distance between two points divided by propagation velocity of the signal.

Yoon, Park and Shin (2012) noted that the effectiveness of cross correlation technique is highly depended on background noise. It may fail to estimate leakage point in a noisy environment. Cross correlation may render false results in the presence of material or geometric discontinuities such as joints and sharp bends. This is caused by leak signals are partially or fully reflected at the discontinuities (Hunaidi et al., 2004).

An equation called linear source location method can be utilized to find the leak location. Figure 2.15 shows how this equation can be utilized to detect location of leak source.

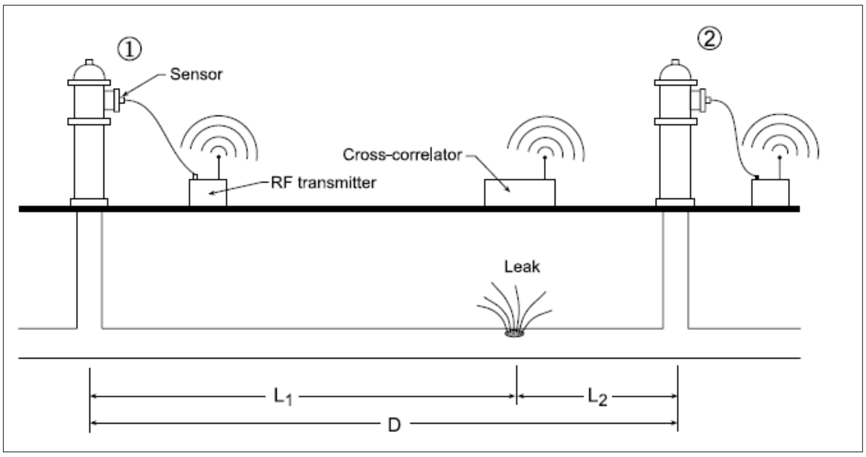


Figure 2.15: Cross Correlation Used in Leak Source Localization (Hunaidi, 2000)

$$L_1 = 0.5(D + vt) \tag{2.2}$$

where

$L_1$ = leak location relative to first measuring point, m

$D$ = total distance between two measuring points, m

$v$ = wave propagation velocity, m/s

$t$ = time delay, s

This equation is effective to locate the location of leakage precisely and it is used in many papers (Beck et al., 2005; Hafezi and Mirhosseini, 2015; Hunaidi and Chu, 1999; Hunaidi, 2000; Ionel et al., 2015; Lee and Lee, 2006; Qi and Que, 2013). However, this equation is valid only if the source path is straight (Yalcinkaya and Ozevin, 2013).

Effectiveness and accuracy of cross correlation method can be evaluated from Figure 2.16 and 2.17. Leak was located 4.8 m from Sensor A in the actual experiment conducted by Hafezi and Mirhosseini (2015). Cross correlation function gave a result that peak occurred at about 4.9 m. This value represented the distance of leak location from Sensor A. A percentage error of 2.08 % was obtained and showed that cross correlation function is capable to determine leak point accurately.

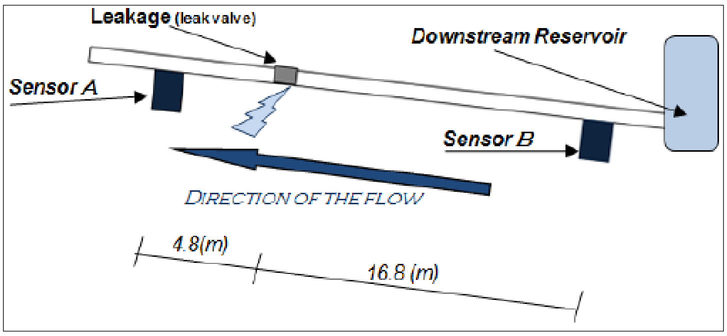


Figure 2.16: Layout of Laboratory Experiment (Hafezi and Mirhosseini, 2015)

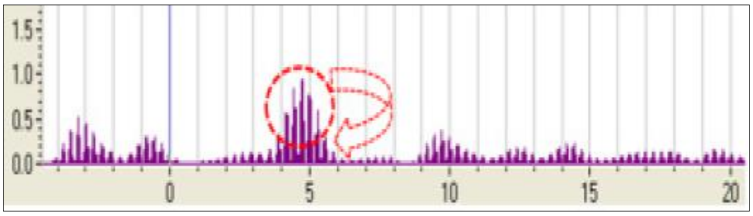


Figure 2.17: Cross Correlation of Acoustic Signals (Hafezi and Mirhosseini, 2015)

### 2.7.1 Wave Propagation Velocity

Previous section showed that localization of the leak source is remarkably depending on two variables, which are time delay and propagation velocity of the wave. Time delay is determined through cross correlation between two signals collected.

In practice, propagation velocity, $v$ is depending on properties of the pipe such as material, thickness and pressure (Hunaidi and Chu, 1999). Besides, it is varying with frequency due to dispersion phenomenon (Lee and Lee, 2006; Li et al., 2014). Shen et al. (2012) noted that dispersion is a phenomenon whereby amplitude and energy of wave are decreasing along travelling distance.

Guided waves in pipes are classified into axially symmetric longitudinal $L(0,m)$, axially symmetric torsional $T(0,m)$ and non-axially symmetric bending mode $F(n,m)$, where $n$ refers to circumferential order number while $m$ relates to vibration shape of modal (Shen et al., 2012). Figure 2.18 shows peripheral vibration diagrams of three modes. Shen et al. (2012) commented that pipeline leakage acoustic wave mainly consists of $F(1,m)$ modes.

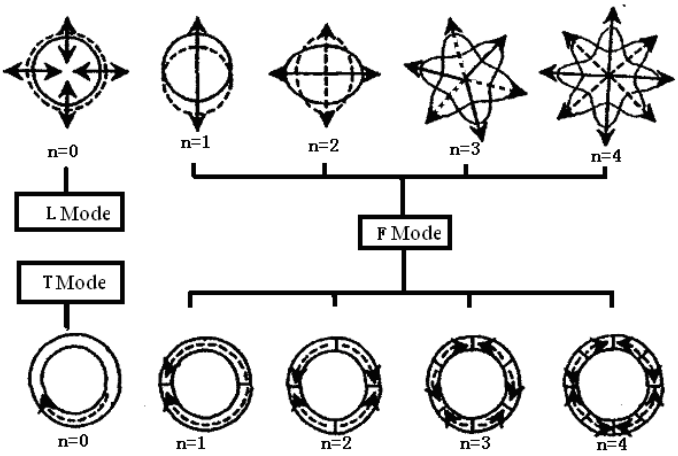


Figure 2.18: Peripheral Vibration Diagram (Shen et al., 2012)

Relationship between frequency and wave propagation velocity can be plotted as dispersion curves. From dispersion curve, velocity of the wave can be known and used to detect the location of leak effectively by substituting it into Equation 2.2 together with the time delay determined by cross correlation (Gopalakrishnan and Narendar, 2013). Group velocity is the velocity of a group of waves propagates at similar frequency while phase velocity is velocity at fixed phase of any one frequency components propagates (Shen et al., 2012). The speed at which information and energy a guide wave propagates is group velocity. However, this only occurs under the condition of normal dispersion which group velocity is less than phase velocity. In other circumstances, group velocity not necessarily represents the actual propagation speed of waves (Gopalakrishnan and Narendar, 2013).

# CHAPTER 3

# METHODOLOGY AND WORK PLAN

## 3.1 Introduction

Conventionally, detection of pipeline leakage was based on basic sensing and visual observation by skilful personnel. Referring to Fiedler (2014), leak detection systems can be grouped as Figure 3.1.

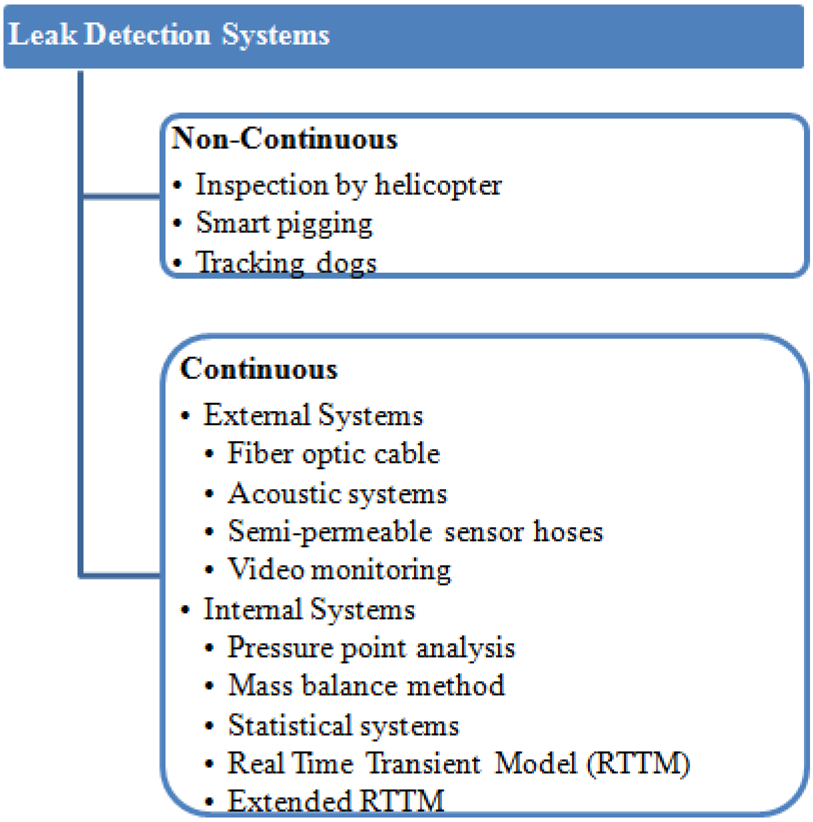


Figure 3.1: Leak Detection Methods (Fiedler, 2014)

In this research study, acoustic system is employed to detect water leakage. The basic idea of how it works can be described as Figure 3.2. Two sensors mount on a constructed test rig to measure the signal. The measured signals will be transmitted to the data acquisition system. The signals are pre-filtered, sampled and pre-amplify. Next, signals are transmitted to a computer in order to perform signal processing on them.

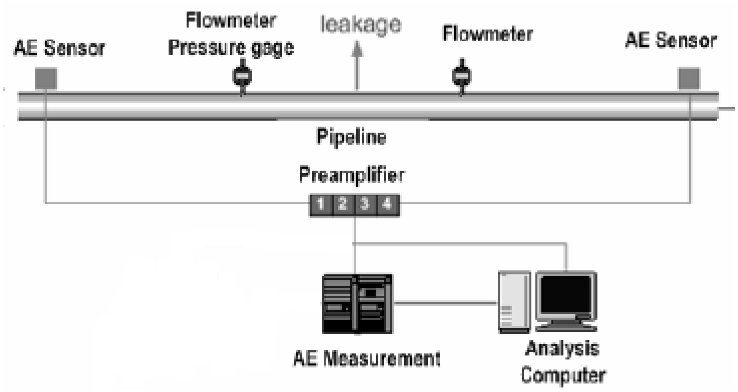


Figure 3.2: Experimental Set-Up

Figure 3.3 shows the test rig constructed and being used throughout this study. It is constructed by 3.5 m long galvanized iron (GI) pipe with inner diameter of 1.5 inches and 3.14 mm wall thickness. Leak hole is introduced by threading at the centre point of the test rig. During the data collection process, two sensors are placed 1.3 m and 1.1 m from leaking hole, respectively.

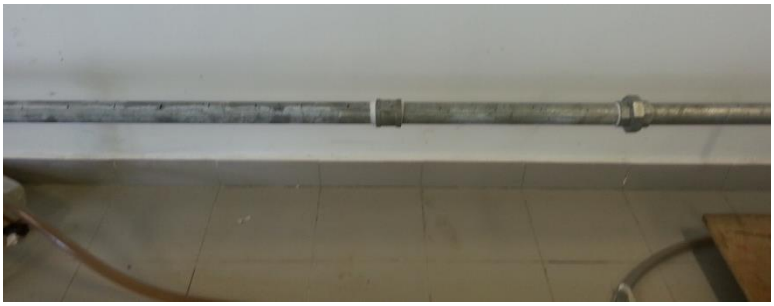


Figure 3.3: Constructed Test Rig

## 3.2 Signal Processing Steps

By referring to Section 2.2 as guideline, signal processing steps involved in this study are illustrated in Figure 3.4.

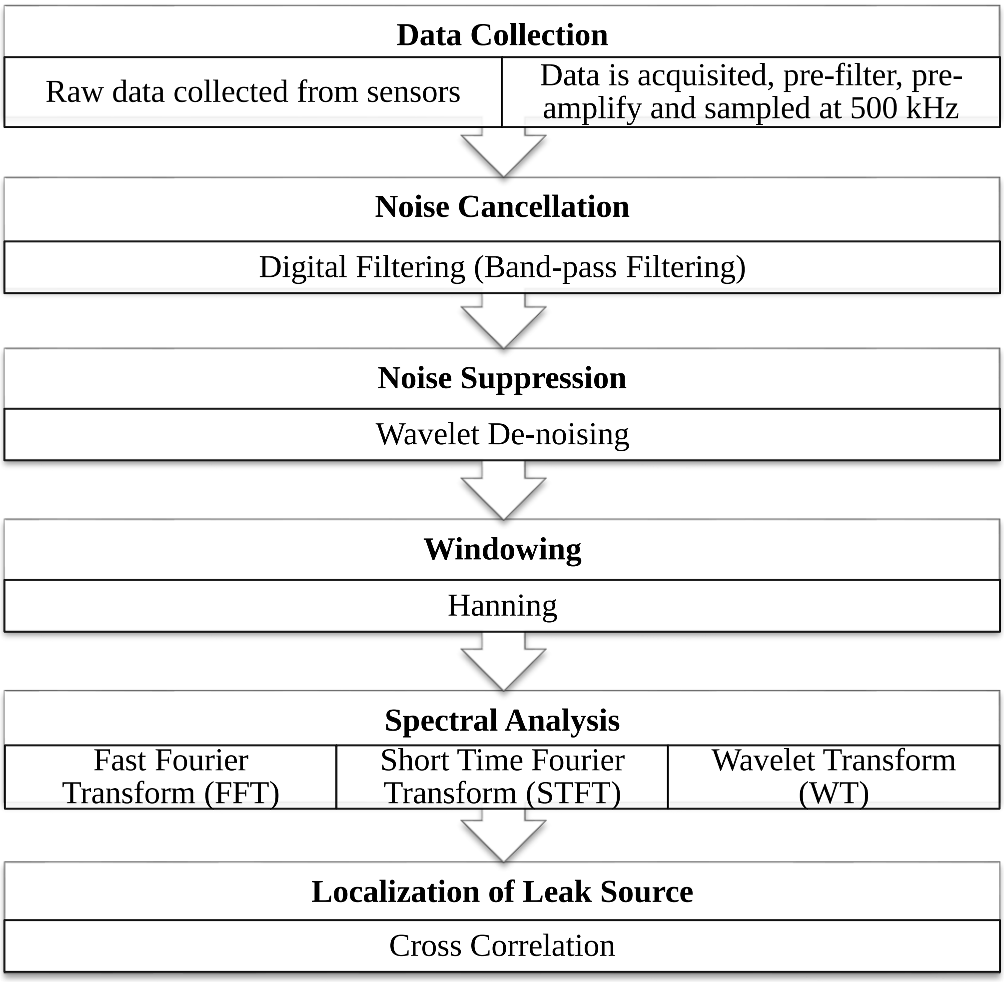


Figure 3.4: Signal Processing Steps

Collected signals will be first pre-amplify and pre-filter by using amplifier and data acquisition system. In order to avoid loss of important signal feature, the sampling frequency is set at 500 kHz hence the cut-off frequency is 250 kHz as referring to Nyquist sampling theorem.

After that, signal will be processed by using Matlab software. First, noise elimination technique through digital filtering and wavelet de-noising will be utilized. De-noised signals will be applying with windowing function like Hanning Window to reduce spectral leakage and signal discontinuities. Next, signal in the time domain will be transformed to the frequency domain via FFT or time-frequency domain via STFT and WT. Spectral features like peak frequency can be evaluated. Results obtained will be compared to determine which method is more effective and applicable. Cross correlation is applied to find the difference between arrival times of the signals from two sensors. Finally, location of the leak can be calculated by input the time delay in Equation 2.2.

### 3.2.1 Determining Wave Propagation Velocity

To identify velocity of wave propagate at particular frequency, dispersion curve of velocity for test pipeline had to be plotted. GUIGUW software had been utilized to generate dispersion curve (Bocchini, Marzani and Viola, 2011). The parameters required are shown in Table 3.1.

Table 3.1: Parameters Input in GUIGUW Software

| **Parameters** | **Value** |
|---|---|
| Material | Iron |
| Density | 7850 kg/m$^3$ |
| Internal Radius | 19.05 mm |
| Thickness | 3.14 mm |
| Longitudinal Speed | 5900 m/s |
| Shear Speed | 3200 m/s |

Figure 3.5, 3.6 and 3.7 show dispersion curves in terms of wavenumber, phase velocity and group velocity.

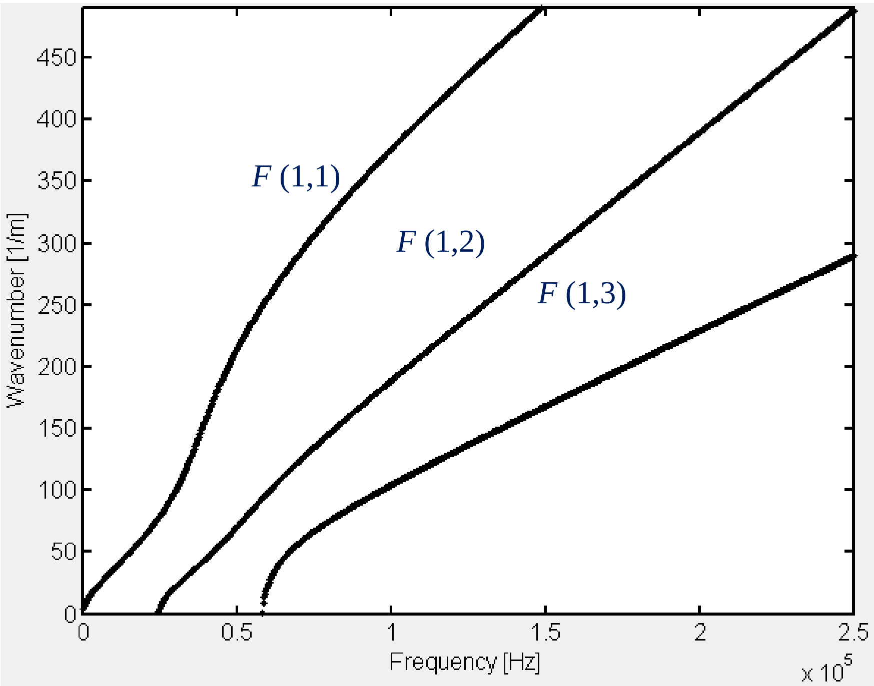


Figure 3.5: Wavenumber versus Frequency

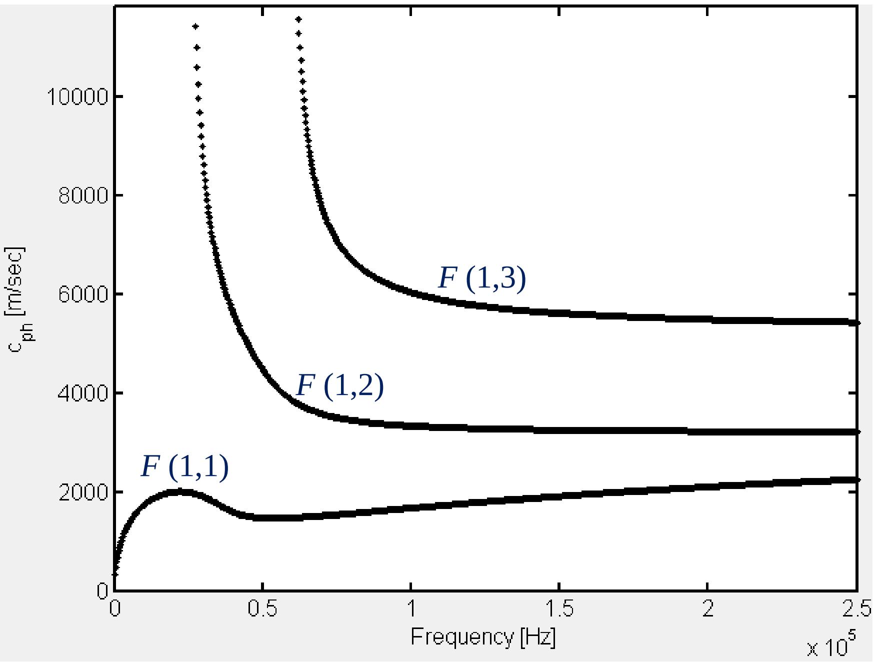


Figure 3.6: Phase Velocity versus Frequency

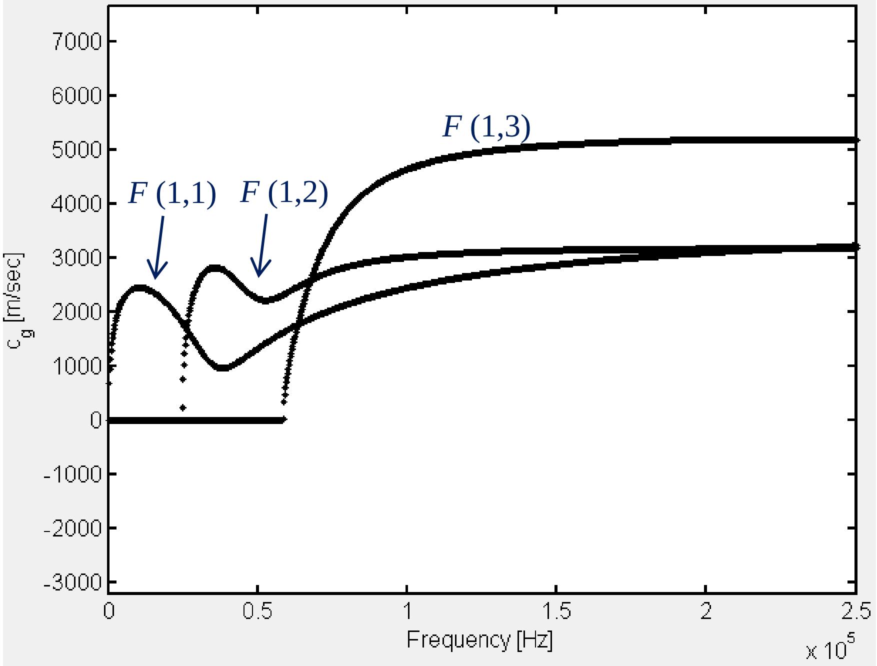


Figure 3.7: Group Velocity versus Frequency

# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1 Time and Frequency Signal

Signals in time domain do not reveal important information because they do not show particular pattern or give significant peak. Hence, it is difficult to identify a water leakage event if the signal is merely represented in a time domain. Based on Figure 4.1 and 4.2, there is no obvious difference between signals with and without water leakage occurred.

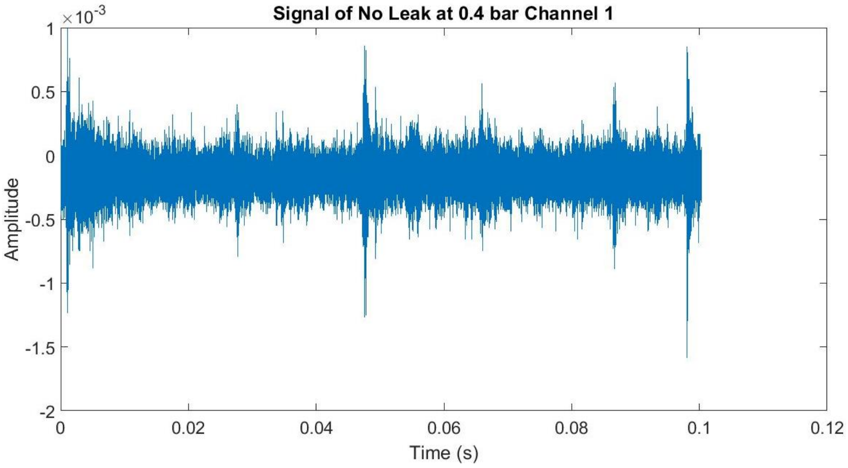


Figure 4.1: Signal Collected when Pipe Running without Leakage

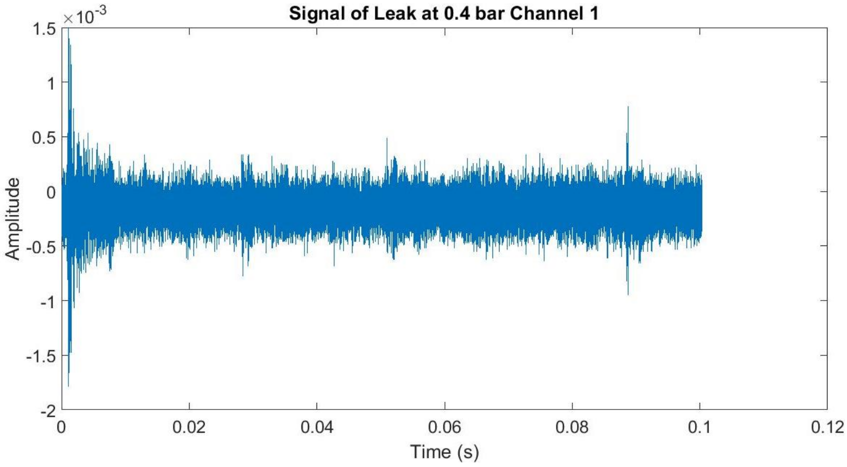


Figure 4.2: Signal Collected when Pipe Running with Leakage

Therefore, frequency signals are essential to deliver information that cannot be readily seen in the time domain signal especially to evaluate frequency band at where water leakage occurred. Figure 4.3 shows signal with and without leakage in the frequency domain. The behaviour of signal is easier to be identified in the frequency domain compared to the time domain. As Figure 4.3 shown, there is excitation of frequency during leakage event.

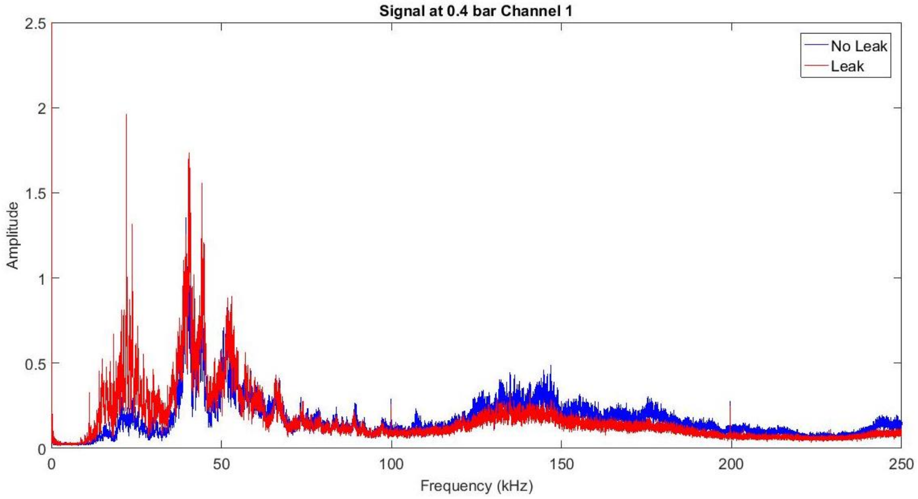


Figure 4.3: Signal with Leak and without Leak in Frequency Domain

## 4.2 Results of Spectral Analysis

As discussed in Chapter 2, there are few methods can be used to transform the signal from the time domain into the frequency or time-frequency domain. Fast Fourier Transform (FFT), Short Time Fourier Transform (STFT) and Wavelet Transform (WT) had been used in the current study. Figure 4.4, 4.5 and 4.6 show results from FFT, STFT and WT respectively. The results are analysed from a similar set of signal which is collected under the same condition, which is illustrated in Table 4.1.

Table 4.1: Conditions for Data Collection

| Parameter | Value |
|---|---|
| Pressure | 0.8 bar |
| Sampling frequency | 500 kHz |
| Distance between sensor and water leak source | 1.3 m |
| Time when leaking condition is introduced | 100 ms |

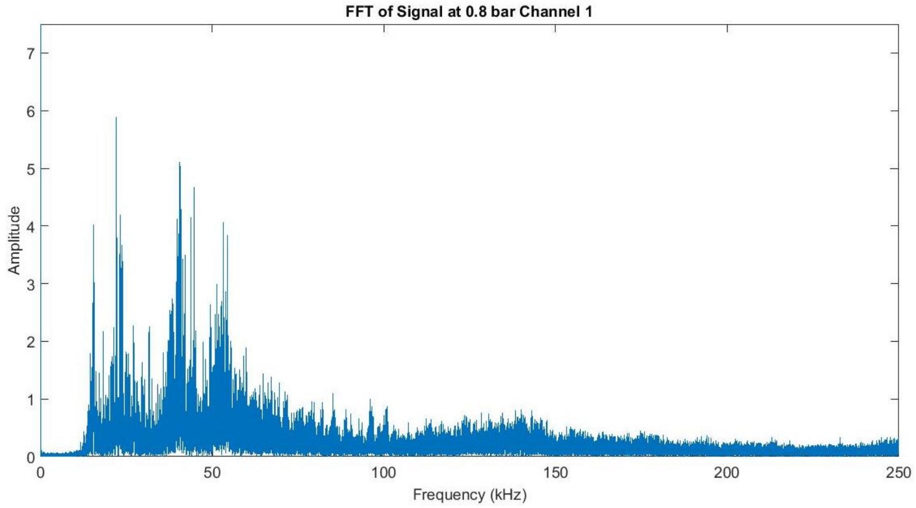
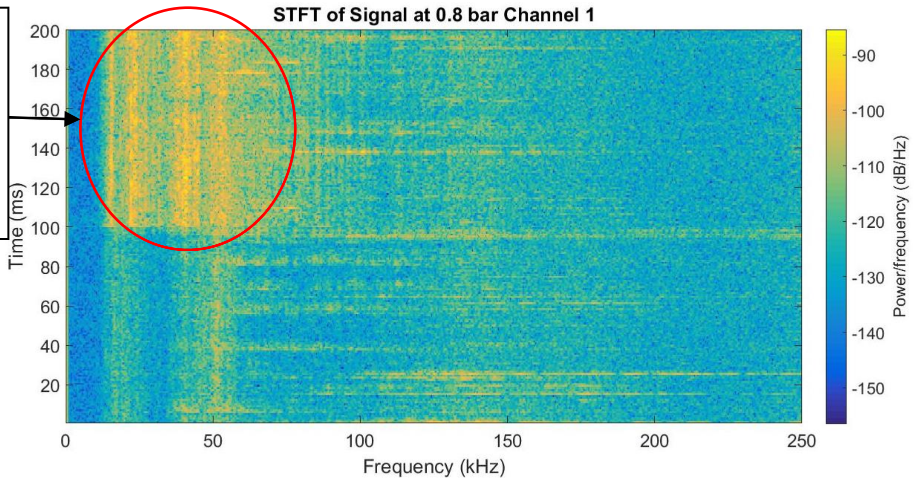
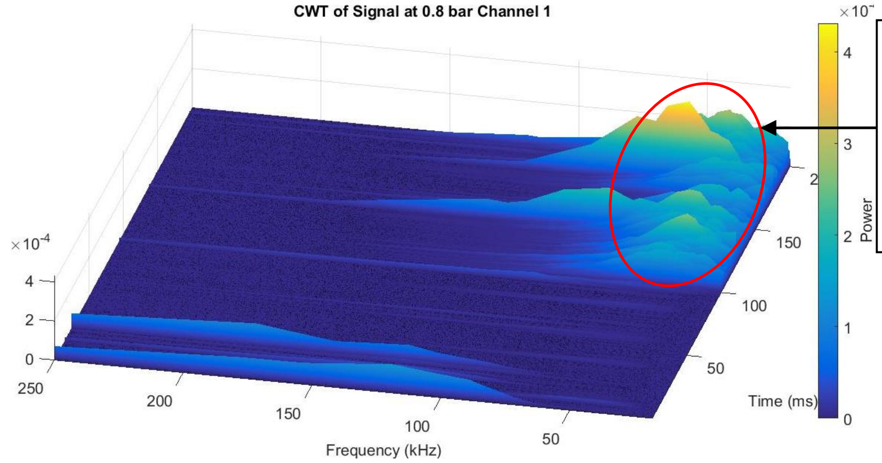


Figure 4.4: Signal in Frequency Domain Resulted from FFT



Excitation of frequency due to water leakage event

Figure 4.5: Signal in Time-Frequency Domain Resulted from STFT



Excitation of frequency due to water leakage event

Figure 4.6: Signal in Time-Frequency Domain Resulted from WT

As mentioned by Polikar (2006), FFT only gives spectral information but not time information. In Figure 4.4, FFT result showed what frequency band exists in the signal but did not indicate when those frequencies occurred. Besides, FFT is unable to identify that particular signal is stationary or non-stationary which refers to frequency components of the signal are changing in time or not. Thus, FFT is not suitable to be used for analyzing non-stationary signal for example a sudden leak event.

Both STFT and WT are capable to deliver time and frequency information of the signal simultaneously. As showed in Figure 4.5 and 4.6, at 100 milliseconds, there is excitation of frequency at range 15 kHz to 44 kHz. Hence, there is a water leakage event at about 100 ms and dominant frequency band of water leakage is at 15 kHz to 44 kHz. The results are correlated with the actual condition because water leak is introduced at 100 milliseconds during the data collection process.

Based on Figure 4.5 and Figure 4.6, WT shows a better result than STFT because the excitation of frequency is more noticeable in WT hence water leak can be easily and accurately identified. The details of STFT and WT are shown in the following sections.

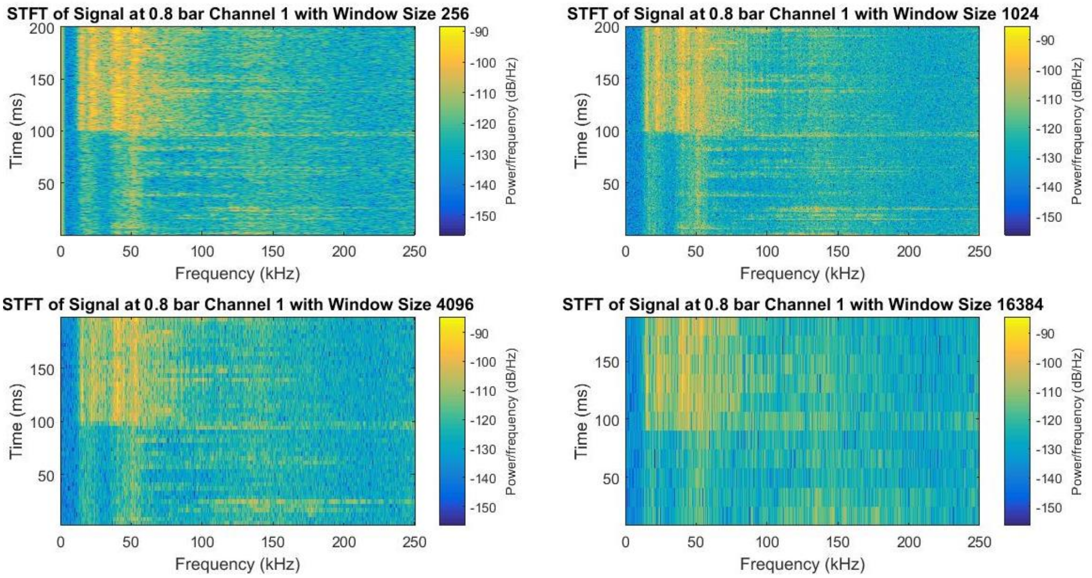
### 4.2.1 Short Time Fourier Transform (STFT)

The result displayed in Figure 4.5 is in agreement with Wu et al. (2008) who commented that STFT gives constant resolution for whole signal. As seen in Figure 4.5, frequency resolution is consistent along time-frequency plane. Figure 4.7 shows the results obtained by performing STFT with different window sizes, which are 256, 1024, 4096 and 16384. The results are analysed based on a similar signal which is collected under the same condition as demonstrated in Table 4.2.

Table 4.2: Conditions during Data Collection

| **Parameter** | **Value** |
|---|---|
| Pressure | 0.8 bar |
| Sampling frequency | 500 kHz |
| Distance between sensor and water leak source | 1.3 m |

There is reduced of frequency resolution but increased of time resolution when window size is small and vice versa (Wang, Ji and Xu, 2007) and this is agreed with the results presented in Figure 4.7. Signal information is much distorted when window size is larger like 4096 and 16384. Meanwhile, it is easier to identify the frequency band from results with window size 1024 compared to 256 because two closely-spaced frequency components can be accurately distinguish and the exact value of frequency can be determined. In addition, as mentioned by Shreve (1995) and CRCnetBase (1999), typical window length is 1024 so the window length used to perform STFT in current study is 1024.


STFT of Signal at 0.8 bar Channel 1 with Window Size 256

STFT of Signal at 0.8 bar Channel 1 with Window Size 1024

STFT of Signal at 0.8 bar Channel 1 with Window Size 4096

STFT of Signal at 0.8 bar Channel 1 with Window Size 16384

Figure 4.7: Results of performing STFT with Varied Window Sizes

### 4.2.2 Wavelet Transform (WT)

As Figure 4.6 shown, WT performs better than STFT because WT has multi-resolution capability in which those high frequency components are poorer resolved in frequency while low frequency is better resolved in time (Salivahanan, 2015). Therefore, signal feature is clearer in the low frequency region.

Selection of mother wavelet is an utmost procedure when performing WT because its result is greatly depends on the shape of mother wavelet and similarity between analysed signal and mother wavelet (Ngui et al., 2013). Figure 4.8 illustrates the pattern of the signal when leakage is occurred. Meanwhile, Figure 4.9 shows few popular types of wavelet function. WT results obtained by using different types of mother wavelet can be seen in Figure 4.10. The results are in agreement with Ahadi and Bakhtiar (2010) who claimed that two transient events will be clearly shown if shape of mother wavelet is similar to transient event but WT will not show desired result if mother wavelet has little or no similarity with transient event.

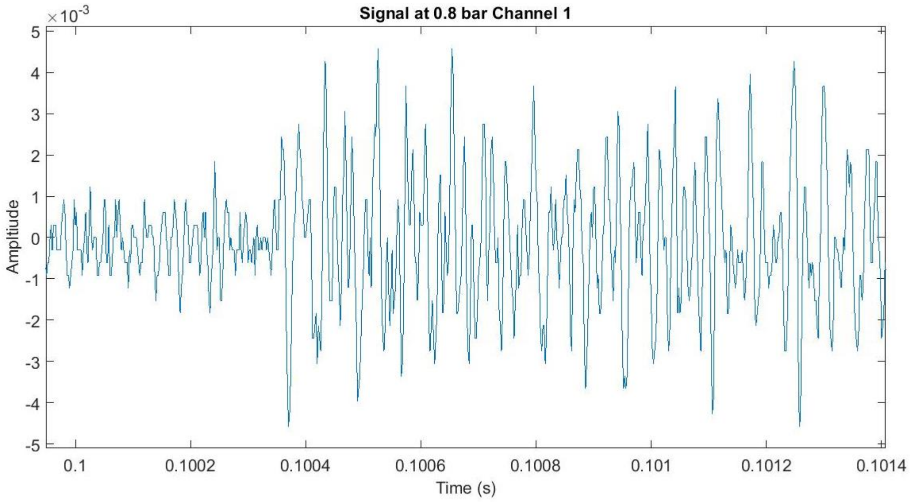


Figure 4.8: Pattern of Leakage Signal

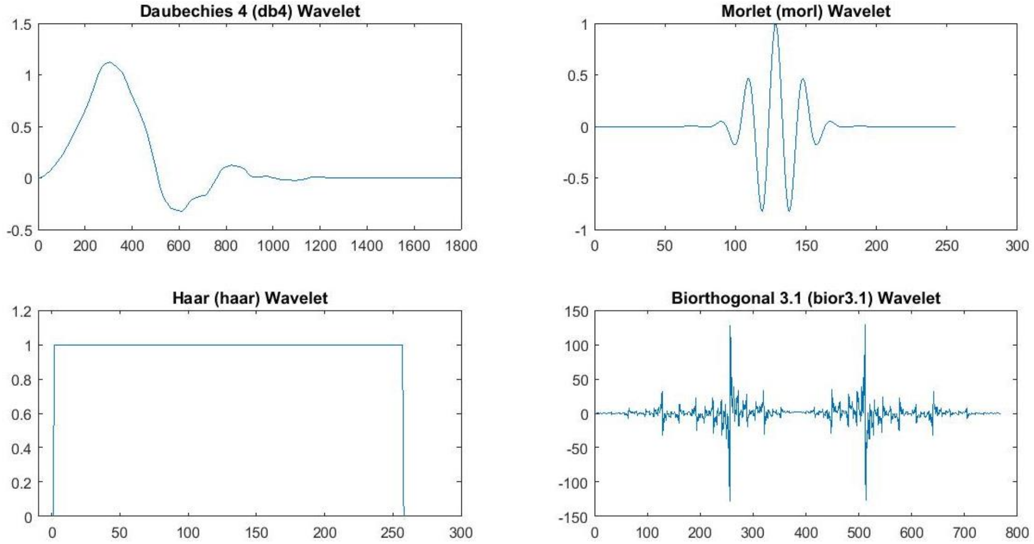


Figure 4.9: Mother Wavelet Functions

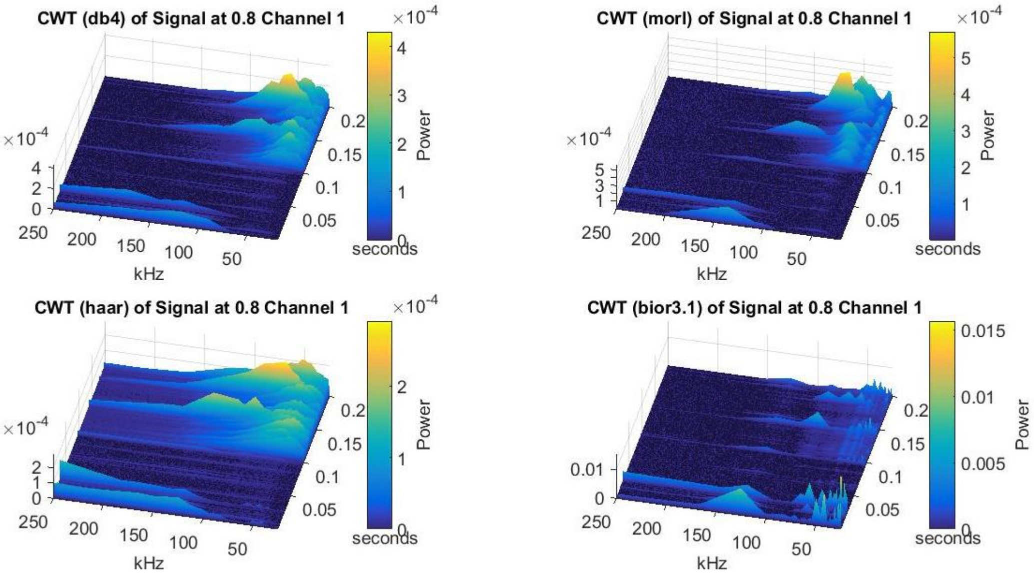


Figure 4.10: WT Results by using Different Mother Wavelets

By referring to Figure 4.9, Daubechies 4 and Morlet tend to be similar with leakage signal pattern which illustrated in Figure 4.8 while Haar and Biorthogonal 3.1 have no or little similarity. As a result, both Daubechies 4 and Morlet performed better and gave the desired results by showing a transient event happened at 0.1 second but Haar and Biorthogonal 3.1 show poor results. Therefore, Daubechies 4 is chosen to be used in this project as it also had been used in other leakage detection works (Mostafapour and Davoodi, 2015; Rashid et al., 2014; Tang et al., 2009; Wan et al., 2012). Figure 4.11 and Table 4.3 show the result obtained by Daubechies mother wavelet offers higher accuracy for detection of the leak location.

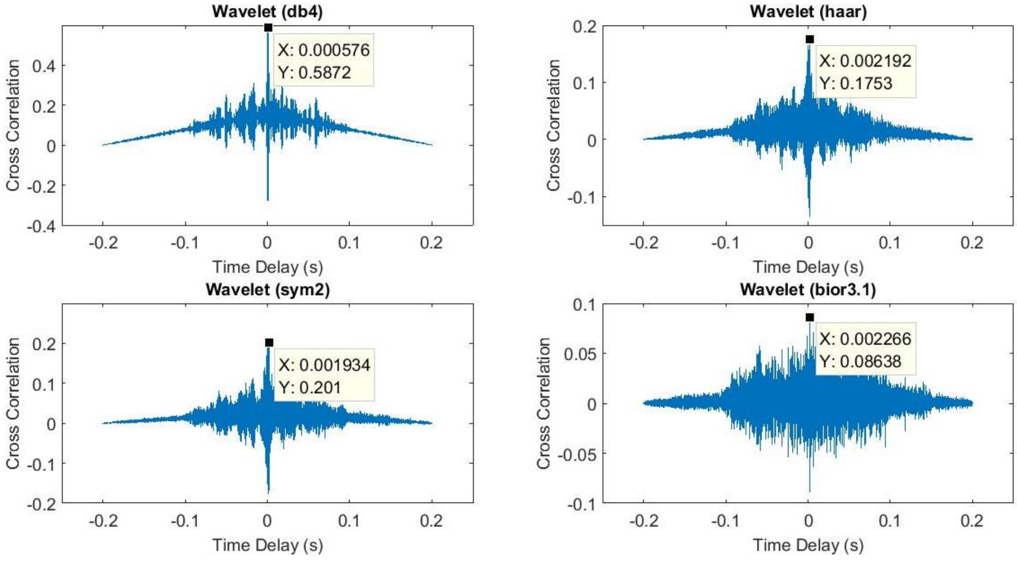


Figure 4.11: Results of Cross Correlation after Different Wavelet Type Analysis

Table 4.3: Accuracy of Results by using Different Wavelet Type Analysis

| **Wavelet Functions** | **Detected Location of Leak (m)** | **Percentage Error (%)** |
|---|---|---|
| Without wavelet analysis | 1.80 | 38.46 |
| Daubechies 4 | 1.40 | 7.69 |
| Haar | 1.96 | 50.77 |
| Symlet 2 | 1.87 | 43.85 |
| Biorthogonal 3.1 | 1.98 | 52.31 |

## 4.3 Effect of Filtering

Digital filtering works to remove uninterested range of frequency. Band-pass filtering is used in this study. As presented in Figure 4.5 and Figure 4.6, dominant frequency of leakage occurs at range 15 kHz to 44 kHz. Figures 4.12, 4.13 and 4.14 are the results obtained after performing band-pass filtering at frequency range of 10 kHz to 100 kHz. Leakage signals are clearer and less noisy after band-pass filtering applied. Frequencies beyond band-pass filtering range are eliminated.

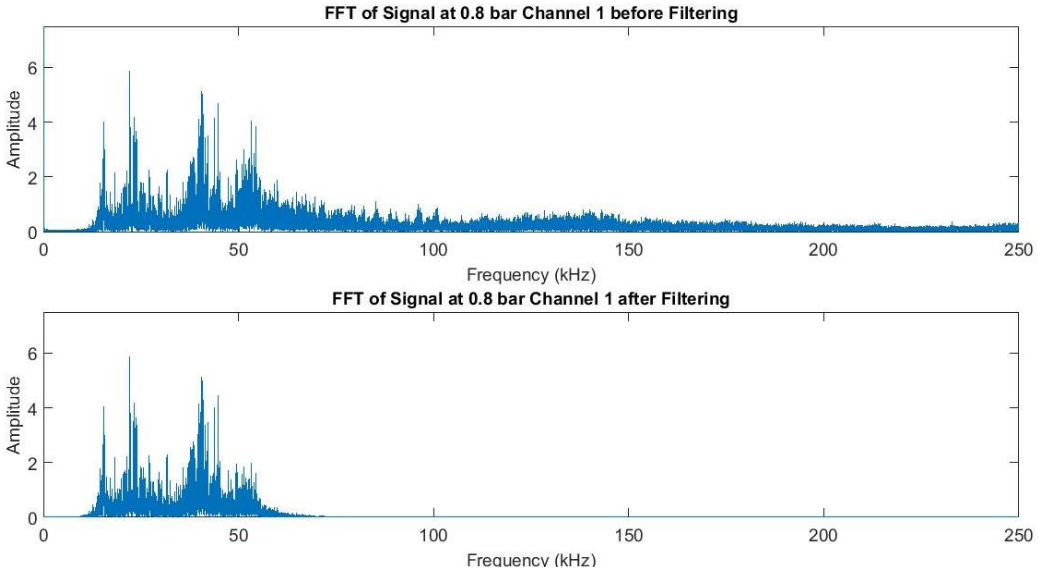


Figure 4.12: FFT Results Before and After Band-pass Filtering

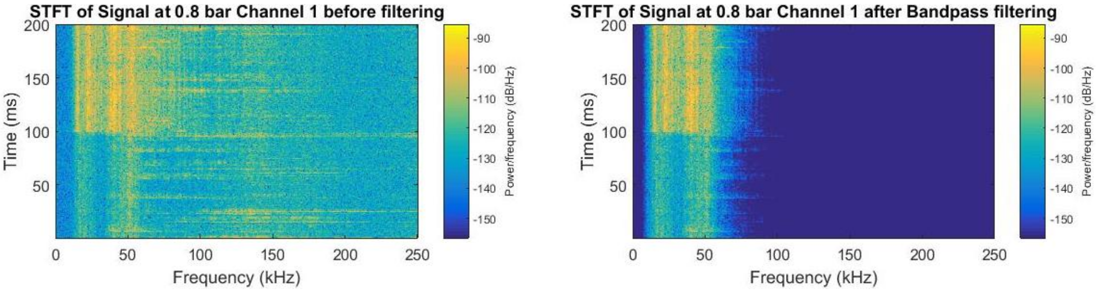


Figure 4.13: STFT Results Before and After Band-pass Filtering

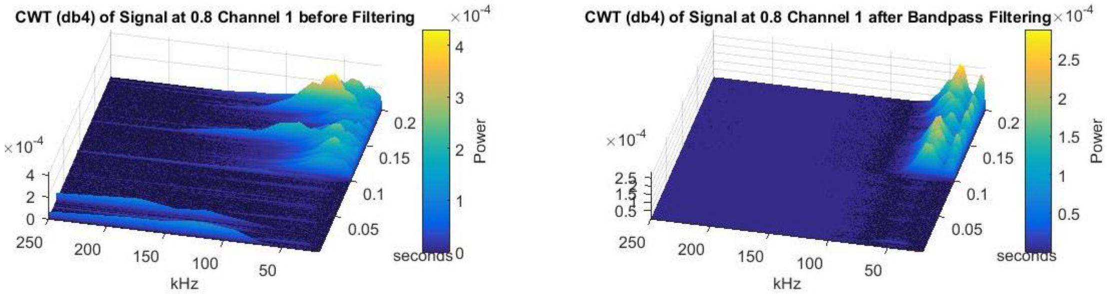


Figure 4.14: WT Results Before and After Band-pass Filtering

## 4.4 Effect of Wavelet De-noising

As the figures showed previously, the signals obtained are very noisy due to presence of noise such as background noise and flow noise. It may be due to vibration of pipeline and pump. Wavelet de-noising is used in this study to suppress noise and the subsequent figures show results obtained after wavelet de-noising. Based on Figure 4.15, 4.16 and 4.17, wavelet de-noising is effective to suppress noise with little information loss.

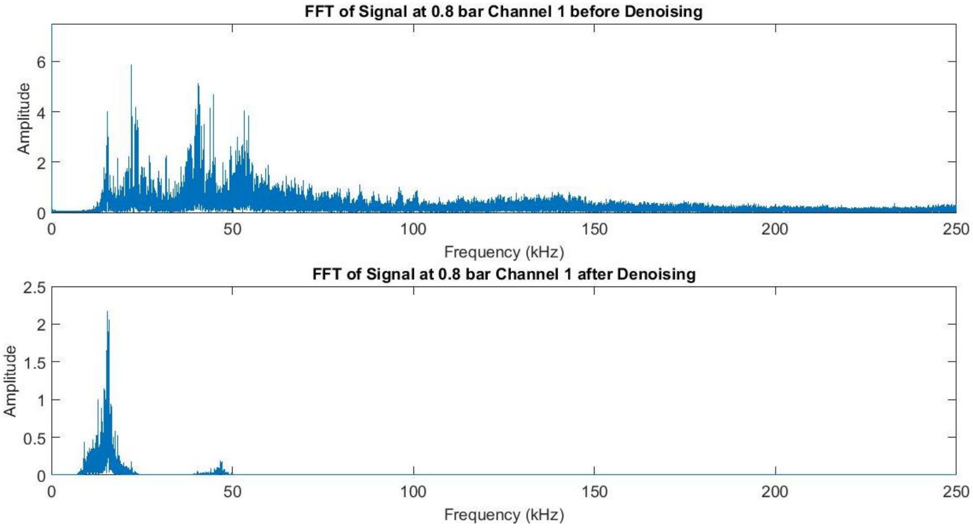


Figure 4.15: FFT Results Before and After Wavelet De-noising

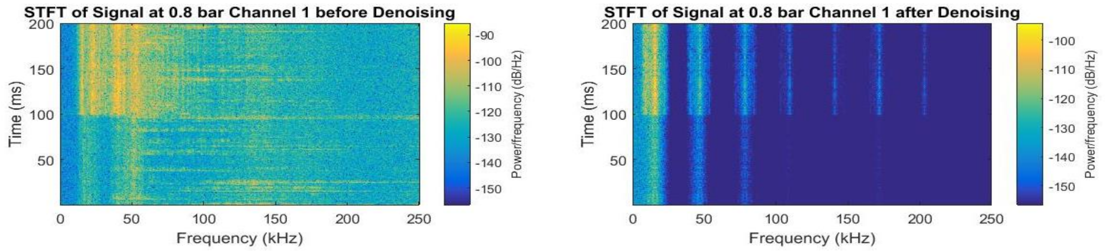


Figure 4.16: STFT Results Before and After Wavelet De-noising

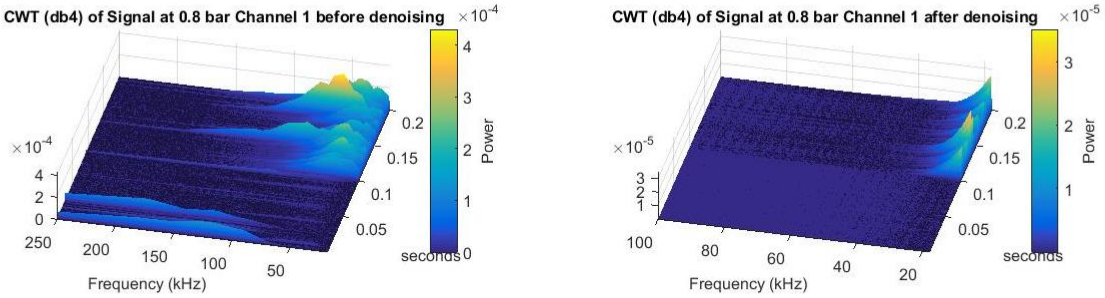


Figure 4.17: WT Results Before and After Wavelet De-noising

According to Donoho and Johnstone (1992; 1994), there are three steps involving in wavelet de-noising. Therefore, wavelet function and number of decomposition level are chosen first. In this project, mother wavelet and decomposition level are same for both WT and wavelet de-noising. Figure 4.18 shows the results obtained after applying wavelet de-noising with different types of mother wavelets. It can be seen that Daubechies 4 performed better than other wavelet types because its result has better SNR performance. This is agreed with Zhao, Sun and Wang (2011) who explained that Daubechies 4 can offer higher time resolution when adopting in wavelet de-noising.

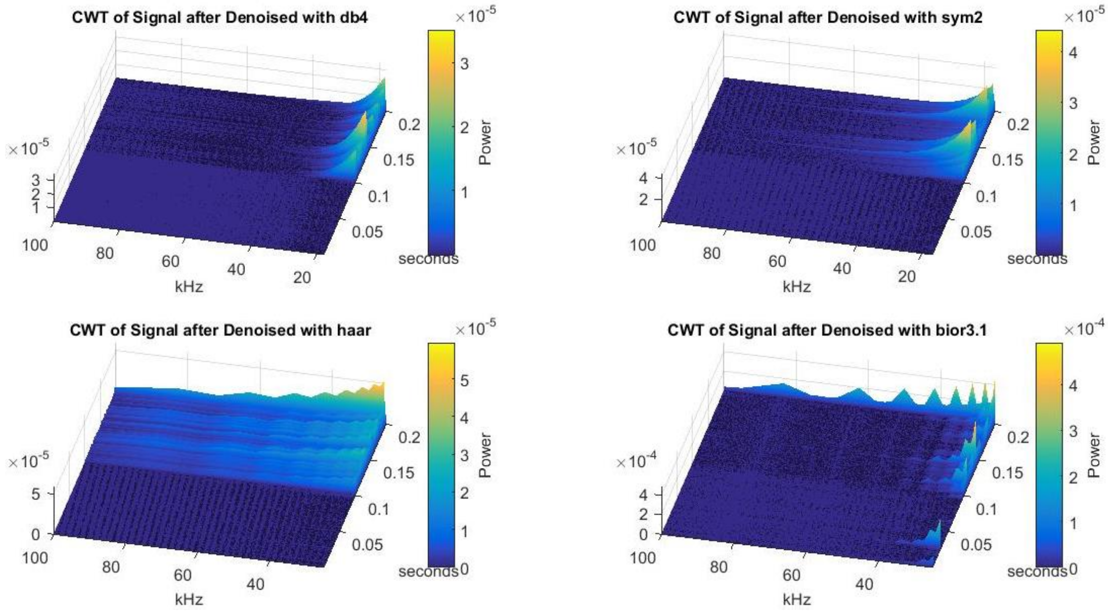


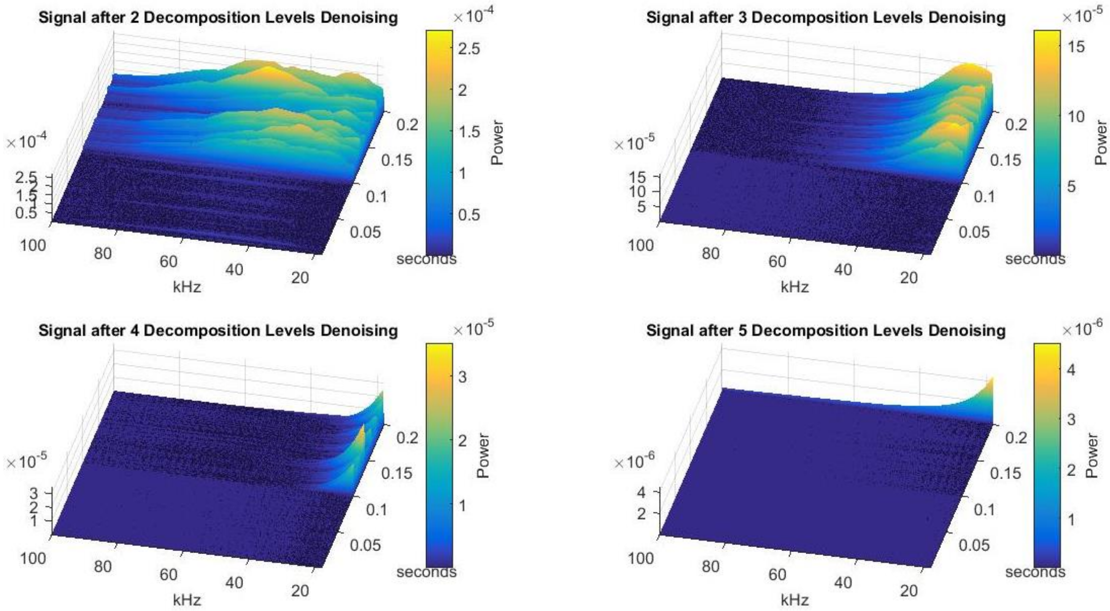
Figure 4.18: WT Results after De-noised by using Different Wavelet Functions

Another important step is to choose decomposition level of DWT. Based on Equation 2.1 which was determined by Wan et al. (2012).

$$\frac{f_s}{2^{n+1}} \geq f_{\min} \tag{4.1}$$

Optimum decomposition level, $n$ is 4 since $f_s$ is 500 kHz and $f_{min}$ is 10 kHz.

Figure 4.19 shows noise decay abundantly by increasing the decomposition levels. It can be seen that excessive of effective signal information had been eliminated when signal underwent five decomposition levels so four levels of decomposition is preferable. Furthermore, Figure 4.20 and Table 4.4 show that de-noised signal after four decomposition levels gives the highest accuracy for detection of the location of the leak source.



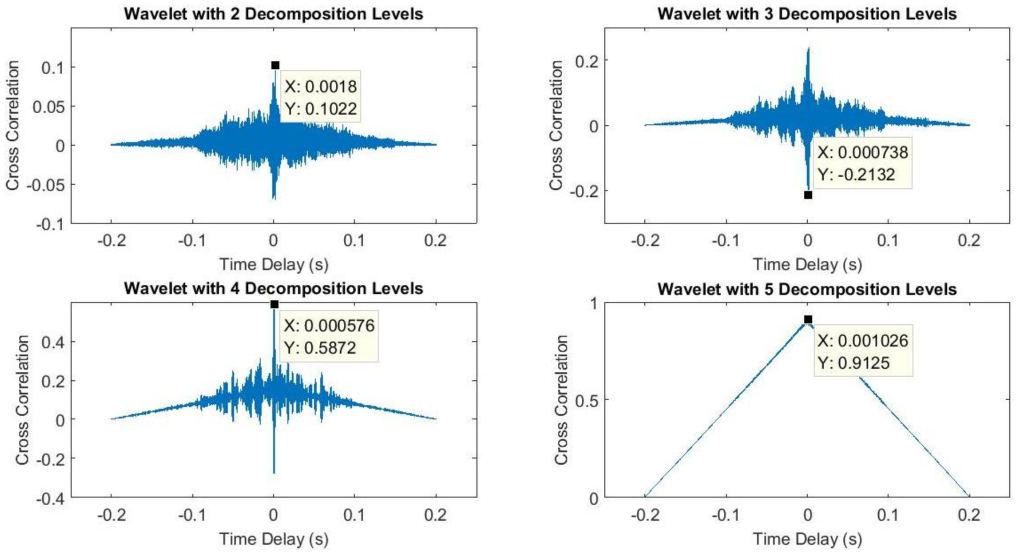
Signal after 2 Decomposition Levels Denoising

Signal after 3 Decomposition Levels Denoising

Signal after 4 Decomposition Levels Denoising

Signal after 5 Decomposition Levels Denoising

Figure 4.19: WT Results after De-noised with Different Decomposition Levels



Wavelet with 2 Decomposition Levels

Wavelet with 3 Decomposition Levels

Wavelet with 4 Decomposition Levels

Wavelet with 5 Decomposition Levels

Figure 4.20: Results of Cross Correlation after Varied Decomposition Levels

Table 4.4: Accuracy of Results by using Varied Decomposition Levels

| **Decomposition Level** | **Detected Location of Leak (m)** | **Percentage Error (%)** |
|---|---|---|
| Without wavelet analysis | 1.80 | 38.46 |
| 2 | 1.82 | 40.00 |
| 3 | 1.46 | 12.31 |
| 4 | 1.40 | 7.69 |
| 5 | 1.56 | 20.00 |

## 4.5 Results of Cross Correlation

Cross correlation performed to determine the time delay between two signals. By obtaining time delay, locations of water leakage occur can be detected. Figure below show the result of cross correlation between the signals from both sensors. Peak of cross correlation indicates that both signals have the highest similarity at the particular moment. Figure 4.21 depicts the signals from sensor 1 and 2 have similarity of 5.428 % at time delay of 0.001746 second. In this case, signal from sensor 1 is 0.001746 second lag relative to signal from sensor 2 which means sensor 1 might be located further from the leak source compared to sensor 2 because it took longer time for leak sound to be transmitted to sensor 1. Next, time delay value can be substitute into Equation 2.2 to evaluate the location of leak from sensor 1.

$$L_1 = 0.5(D + vt) \tag{4.2}$$

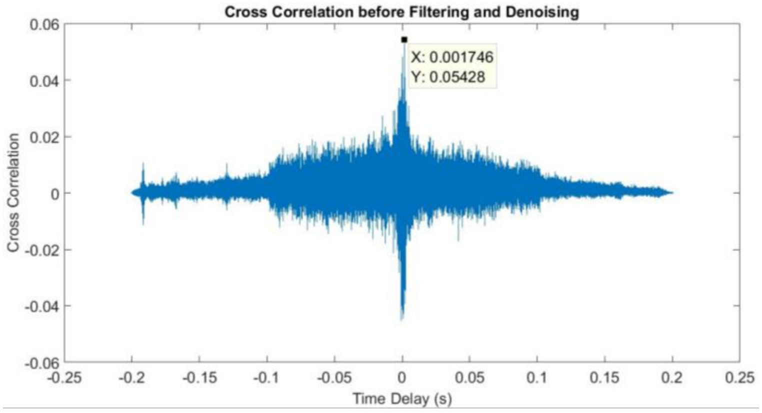


Figure 4.21: Cross Correlation Result

Prior to calculation of location of the leak source by using Equation 2.2, wave propagation velocity had to be analysed first. From the results of STFT and WT, frequency range due to leak occurrence is 15 kHz to 44 kHz. Dominant frequency peak at 16 kHz after underwent wavelet de-noising. Subsequently, wave propagation velocity that had to be used in Equation 2.2 can be identified from the dispersion curve plotted. Figure 4.22 shows the phase velocity is 692.1 m/s when frequency is 16 kHz.

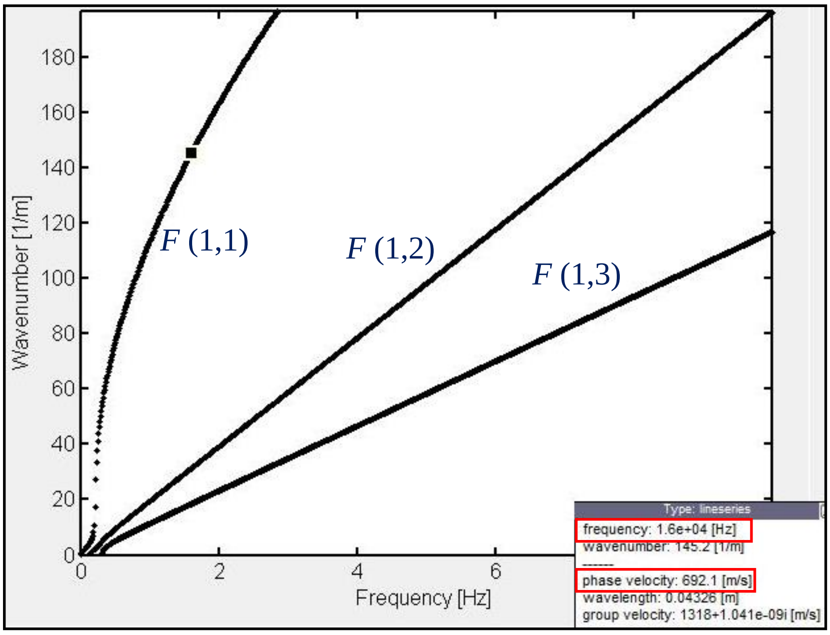


Figure 4.22: Wavenumber Frequency Plot of 1.5 inches GI Pipe

By using results from Figure 4.21, calculated distance of leak location from sensor 1 is 1.80 m with 38.46 % percentage error. High percentage error may be due to noise presented in signal thus cross correlation may not correlate between leak signals. Therefore, filtering and de-noising process are necessary before performing cross correlation in order to improve accuracy of the results. Figure 4.23 and Table 4.5 show the results of cross correlation after the signal underwent wavelet de-noising, band-pass filtering and both of them. The similarity between two signals increased after wavelet de-noising and band-pass filtering thus the results are more precise. By applying both filtering and de-noising method together may help to properly pinpoint the leak source because the percentage error had reduced to 2.31 %. The signal will give most accurate result by applying band-pass filtering before wavelet de-noising.

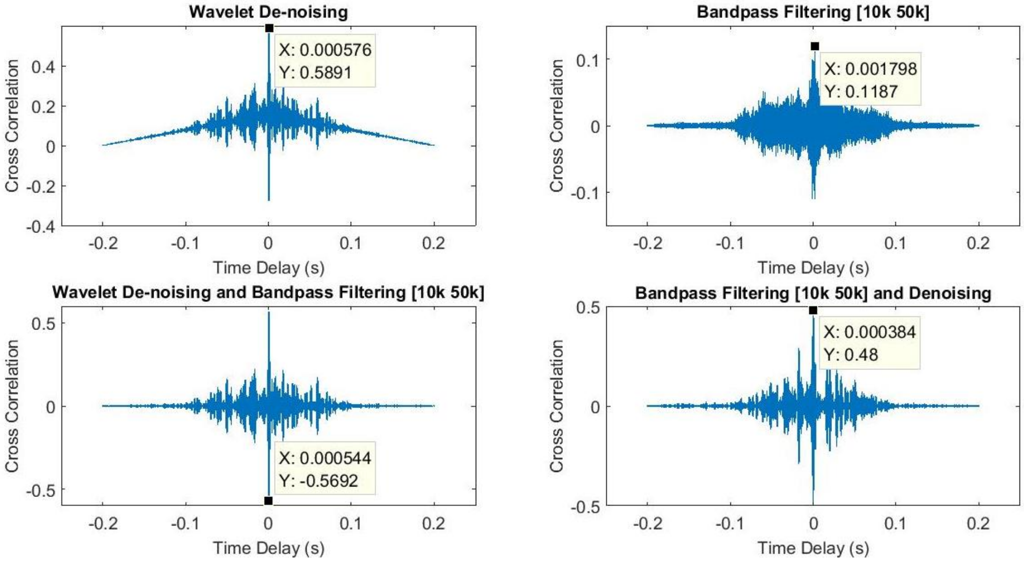


Figure 4.23: Results of Cross Correlation after Signal Band-pass at 10 - 50 kHz

Table 4.5: Cross Correlation Results at 0.8 bar

| Condition | Time Delay, *t* (s) | $L_1$ (m) | Percentage Error (%) |
|---|---|---|---|
| Original signal | 0.001746 | 1.80 | 38.46 |
| Wavelet de-noised | 0.000576 | 1.40 | 7.69 |
| Band-pass at 10 – 50 kHz | 0.001798 | 1.82 | 40.00 |
| Wavelet de-noised & Band-pass at 10 – 50 kHz | 0.000544 | 1.39 | 6.92 |
| Band-pass at 10 - 50 kHz then Wavelet de-noised | 0.000384 | 1.33 | 2.31 |

### 4.6 Results under Different Pressures

According to Hunaidi (2000), Lee and Lee (2006) and Yalcinkaya and Ozevin (2013), amplitude of leak signal increased when water pressure is increasing due to increased of turbulence at leak location. Results showed in Figure 4.24 and 4.25 are in agreement with this comment. Figure 4.24 and 4.25 show signals in time domain and frequency domain, respectively at pressures 0.4 bar, 0.8 bar, 1.2 bar and 1.6 bar. As seen in both Figure 4.23 and 4.24, the amplitude of the leak signal increased when pressure increased.

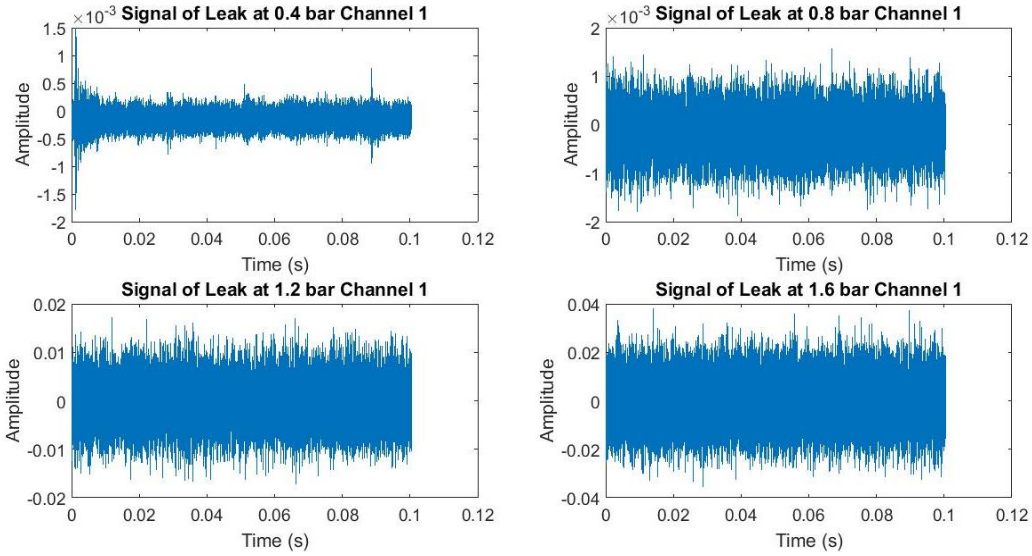


Figure 4.24: Time Domain Signals at Varied Pressures

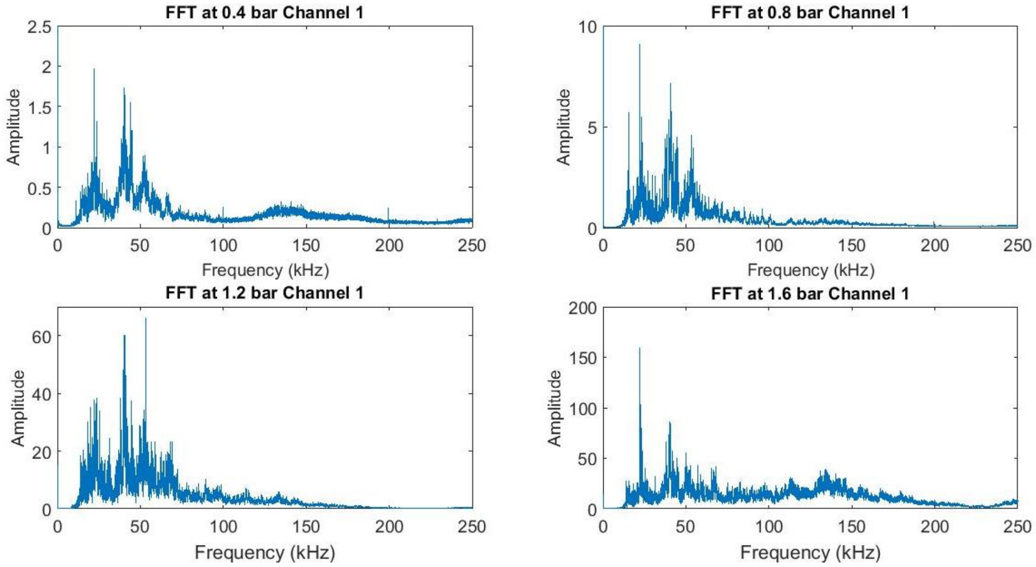


Figure 4.25: Frequency Domain Signals at Varied Pressures

Calculated distances of leaks from sensor 1 through results of cross correlation at pressures 0.4 bar and 1.2 bar are presented in Table 4.6 and 4.7, respectively. Both tables show that cross correlation is able to determine the locations of leaks at different pressures. In addition, the percentage errors of calculated distances are reduced after band-pass filtering and wavelet de-noising applied.

Table 4.6: Cross Correlation Results at 0.4 bar

| **Condition** | **Time Delay, *t* (s)** | **$L_1$ (m)** | **Percentage Error (%)** |
|---|---|---|---|
| Original signal | -0.002646 | -0.29 | 122.31 |
| Wavelet de-noised | -0.001152 | 0.55 | 57.69 |
| Band-pass | -0.002448 | -0.18 | 113.85 |
| Wavelet de-noised then Band-pass | 0.000286 | 1.36 | 4.62 |
| Band-pass then Wavelet de-noised | 0.000292 | 1.36 | 4.62 |

Table 4.7: Cross Correlation Results at 1.2 bar

| **Condition** | **Time Delay, *t* (s)** | **$L_1$ (m)** | **Percentage Error (%)** |
|---|---|---|---|
| Original signal | 0.001626 | 2.12 | 63.08 |
| Wavelet de-noised | 0.00272 | 2.73 | 110 |
| Band-pass | 0.002838 | 2.80 | 115.38 |
| Wavelet de-noised then Band-pass | 0.00072 | 1.61 | 23.85 |
| Band-pass then Wavelet de-noised | 0.000674 | 1.58 | 21.54 |

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

In this project, water leakage event and its location was successfully detected. Leakage signal was enhanced through band-pass filtering and wavelet de-nosing. Hence, band-pass filtering and wavelet de-noising methods are efficiently to suppress and remove pipeline background noise. In consequence, filtered and de-noised signal can render a better result with enhanced accuracy. Improvement of accuracy can be proven by reduction of percentage error before and after band-pass filtering and wavelet de-noising, which are from 38.46 % to 2.31 %.

Characteristics of different types of signal processing methods had been studied. For instance, FFT has less computation time but it is poorly in analyzing non-stationary signal. It is unable to represent the signal in the time-frequency domain. STFT and WT are able to give time and spectral information simultaneously but WT tends to give a better result because it has multi-resolution capability so obtained signal is clearer with enhanced signal to noise ratio. Thus, WT can show a discernible transient event when water leakage is happening.

Furthermore, relationship between leak signals with pressure level had been investigated. When water pressure increases, amplitudes of signals collected increase as well.

In conclusion, acoustic-leak detection technique is adequately and effectively to detect and locate the location of the leak by performing signal processing method on the signal collected.

## 5.2 Recommendations for future work

For future works, a longer test rig can be constructed to investigate the accuracy of results when distance between sensor and leak source is highly increased. It is susceptible that the wave has a maximum propagation distance and it will attenuate greatly when the travelling distance increases. Wave may experience reduced of wave energy and amplitude when it is travelled further. Therefore, different results might be obtained.

Besides, different pipe diameters can be used to study effects of pipe diameters on leak signals and accuracy of the results. Generally, the larger the diameter of the pipe, the attenuation of signal will increase. This may cause difficulty to detect water leakage precisely.

In addition, the project can be conducted with different leak sizes because strength of the leak signal may be varied with the leak sizes. Leak signal tends to be stronger if the leak size is larger.

## REFERENCES

Aastroem, T., From Fifteen to Two Hundred NDT- Methods in Fifty Year. 17th World Conference on Non-Destructive Testing WCNDT, 2008 Shanghai, China. Pohjola Non-Life Insurance Company.

Ahadi, M. and Bakhtiar, M.S., 2010. Leak Detection in Water-filled Plastic Pipes through the Application of Tuned Wavelet Transforms to Acoustic Emission Signals. *Applied Acoustics,* 71**,** pp. 634-639.

Aime, L., Giuseppe, V., Amerigo, T. and Philippe, V., 2009. STFT-Based Spectral Analysis of Urban Waterworks Leakage Detection. XIX IMEKO World Congress Fundamental and Applied Metrology, 2009 Lisbon, Portugal. pp. 2172-2176.

Anastasopoulos, A.A., 2007. Signal Processing and Pattern Recognition of AE Signatures. pp. 929-930.

Beck, S.B., Curren, M.D., Sims, N.D. and Stanway, R., 2005. Pipeline Network Features and Leak Detection by Cross-Correlation Analysis of Reflected Waves. *Journal of Hydraulic Engineering,* 131**,** pp. 715-723.

Bocchini, P., Marzani, A. and Viola, E., 2011. Graphical User Interface for Guided Acoustic Waves. *Journal of Computing in Civil Engineering,* 25**,** pp. 202-210.

Bouchouareb, R. and Benatia, D., 2014. Comparative Study between Wavelet Thresholding Techniques (Hard, Soft and Invariant-translation) in Ultrasound Images. *International Journal of Bio-Science and Bio-Technology,* 6**,** pp. 29-38.

Chhikara, J. and Singh, J., 2012. Noise Cancellation using Adaptive Algorithms. *International Journal of Modern Engineering Research (IJMER),* 2**,** pp. 792-795.

CRCnetBase, 1999. *Digital Signal Processing Handbook*, CRC Press LLC.

Donoho, D.L. and Johnstone, I.M., 1992. Ideal Spatial Adaptation by Wavelet Shrinkage. Stanford University, Stanford, CA, USA.

Donoho, D.L. and Johnstone, I.M., 1994. Adapting to Unknown Smoothness via Wavelet Shrinkage. Stanford University.

Fiedler, J. 2014. An Overview of Pipeline Leak Detection Technologies. Peabody: American School of Gas Measurement Technology.

Gopalakrishnan, S. and Narendar, S., 2013. Introductory Concepts of Wave Propagation Analysis in Structures. *Wave Propagation in Nanostructures.* Springer, Cham.

Hadei, S.A. and Iotfizad, M., 2010. A Family of Adaptive Filter Algorithms in Noise Cancellation for Speech Enhancement. *International Journal of Computer and Electrical Engineering,* 2**,** pp. 307-315.

Hafezi, M.M. and Mirhosseini, M., 2015. Application of Cross-Correlation in Pipe Condition Assessment and Leak Detection; Using Transient Pressure and Acoustic Waves. *Resources and Environment,* 5**,** pp. 159-166.

Hedaoo, P. and Godbole, S.S., 2011. Wavelet Thresholding Approach For Image Denoising. *International Journal of Network Security & Its Applications,* 3**,** pp. 16-21.

Hunaidi, O., 2000. Detection Leaks in Water Distribution Pipes. *Construction Technology Update No. 40*.

Hunaidi, O. and Chu, W.T., 1999. Acoustical Characteristics of Leak Signals in Plastic Water Distribution Pipes. *Applied Acoustics,* 58**,** pp. 235-254.

Hunaidi, O., Wang, A., Bracken, M., Gambino, T. and Fricke, C., 2004. Acoustic Methods for Locating Leaks in Municipal Water Pipe. International Water Demand Management Conference, 2004 Dead Sea, Jordan. National Research Council Canada (NRC), pp. 1-14.

Ionel, R., Ionel, S., Bauer, P. and Quint, F., 2015. Water Leakage Monitoring Education Cross Correlation Study via Spectral Whitening. *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society.* Dallas, TX, USA: Institute of Electrical and Electronics Engineers (IEEE).

Juliano, T.M., Meegoda, J.N. and Watts, D.J., 2013. Acoustic Emission Leak Detection on a Metal Pipeline Buried in Sandy Soil. *Journal of Pipeline Systems Engineering and Practice,* 4**,** pp. 149-155.

Kadri, A., Yaacoub, E. and Mushtaha, M., 2014. Empirical Evaluation of Acoustical Signals for Leakage Detection in Underground Plastic Pipe. *17th IEEE Mediterranean Electrotechnical Conference.* Belrut, Lebanon: Institute of Electrical and Electronics Engineers (IEEE).

Kaphle, M. and Tan, A.C.C., 2015. Differentiating Signals from Different Sources of Acoustic Emission for Structural Health Monitoring Purposes. *Advances in Acoustic Emission Technology.* Springer Proceedings in Physics.

Karkulali, P., Mishra, H., Ukil, A. and Dauwels, J., 2016. Leak Detection in Gas Distribution Pipelines using acoustic impact monitoring. *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society.* Florence, Italy: Institute of Electrical and Electronics Engineers (IEEE).

Khulief, Y.A., Khalifa, A., Mansour, R.B. and Habib, M.A., 2012. Acoustic Detection of Leaks in Water Pipelines Using Measurement inside Pipes. *Journal of Pipeline Systems Engineering and Practice,* 3**,** pp. 47-54.

Kingdom, B.L., R.; Marin, P., 2006. The Challenge of Reducing Non-Revenue Water (NRW) in Developing Countries.

Lee, M.R. and Lee, J.H., 2006. A Study on Characteristics of Leak Signals of Pipeline Using Acoustic Emission Technique. *Solid State Phenomena,* 110**,** pp. 79-88.

Lee, P., 2014. *4.27 Billion litres Water Waste via Leaky Pipes*.

Lee, S.J., Choi, G.B., Seo, J.C., Lee, J.M. and Lee, G., 2012. Fault Detection of Pipeline in Water Distribution Network System. *International Journal of Mathematical, Computational, Physical, Electrical and Computer Engineering,* 6**,** pp. 490-495.

Li, S., Wen, Y., Li, P., Yang, J., Dong, X. and Mu, Y., 2014. Leak Location in Gas Pipelines Using Cross-time-frequency Spectrum of Leakage-induced Acoustic Vibrations. *Journal of Sound and Vibration,* 333**,** pp. 3889-3903.

Lin, T.R., Wu, W. and Tan, A., 2015. A Signal Processing Approach to Overcome the Non-linearity Problem of Acoustic Emission Sensors. *In:* Amadi-Echendu J., H. C., Mathew J. (ed.) *9th WCEAM Research Papers.* Springer.

Liu, H., Wang, W., Xiang, C., Han, L. and Nie, H., 2017. A De-noising Method using the Improved Wavelet Threshold Function Based on Noise Variance Estimation. *Mechanical Systems and Signal Processing,* 99**,** pp. 30-46.

Mallat, S., 1988. A Wavelet Tour of Signal Processing. 2nd ed.: Academic Press, New York.

Mostafapour, A. and Davoodi, S., 2015. Continuous Leakage Location in Noisy Environment using Modal and Wavelet Analysis with one AE Sensor. *Ultrasonics,* 62**,** pp. 305-311.

Ngui, W.K., Leong, M.S., Lim, M.H. and Abdelrhman, A.M., 2013. Wavelet Analysis: Mother Wavelet Selection Methods. *Applied Mechanics and Materials,* 393**,** pp. 953-958.

Orfanidis, S.J., 2010. *Introduction to Signal Processing,* Pearson Education, Inc.

Polikar, R., 2006. Wavelet Tutorial. *Tutorials to Wavelet Transform.* 2nd ed.: Rowan University, Glassboro, NJ, USA.

Proakis, J.G. and Manolakis, D.G., 1996. *Digital Signal Processing,* Upper Saddle River, New Jersey, Prentice-Hall International, INC.

Qi, C. and Que, D., 2013. Design of Pipeline Leakage Point Location System and Simulation of Related Algorithm. *International Conference on Information and Automation (ICIA).* Yinchuan, China: Institute of Electrical and Electronics Engineers (IEEE).

Rakshit, H. and Ullah, M.A., 2014. A Comparative Study on Window Functions for Designing Efficient FIR Filter. *2014 9th International Forum on Strategic Technology (IFOST).* Cox's Bazar, Bangladesh: Institute of Electrical and Electronics Engineers (IEEE).

Rashid, S., Qaisar, S., Saeed, H. and Felemban, E., 2014. A Method for Distributed Pipeline Burst and Leakage Detection in Wireless Sensor Networks Using Transform Analysis. *International Journal of Distributed Sensor Networks,* 10**,** pp. 1-14.

Roberts, M.J., 2003. *Signals and Systems,* America, Mc Graw Hill.

Salivahanan, S., 2015. *Digital Signal Processing,* Green Park Extension, New Delhi, India, McGraw Hill Education (India) Private Limited.

Shen, G., Qin, X., He, R. and Xiu, C., Theoretical Analysis and Experimental Study of Gas Pipeline Leak Acoustic Emission Signal Transmit Speed. 30th European Conference on Acoustic Emission Testing & 7th International Conference on Acoustic Emission, 12-15 Sept 2012 University of Granada.

Shreve, D.H., 1995. Signal Processing for Effective Vibration Aanalysis. Columbus, Ohio.

Silva, C.W., 2007. *Vibration,* Boca Raton, FL, CRC Press Taylor & Francis Group.

Smith, J.O., 2011. *Spectral Audio Signal Processing,* W3K Publishing.

Srirangarajan, S., Allen, M., Preis, A., Iqbal, M., Lim, H.B. and Whittle, A.J., 2012. Wavelet-based Burst Event Detection and Localization in Water Distribution Systems. *Journal of Signal Processing Systems,* 72**,** pp. 1-16.

Tai, Y., 2004. China Faces Serious Water Shortages. March 22.

Tang, X., Liu, Y., Zheng, L., Ma, C. and Wang, H., 2009. Leak Detection of Water Pipeline Using Wavelet Transform Method. pp. 217-220.

Wan, J., Yu, Y., Wu, Y., Feng, R. and Yu, N., 2012. Hierarchical Leak Detection and Localization Method in Natural Gas Pipeline Monitoring Sensor Networks. *Sensors 2012,* 12**,** pp. 189-214.

Wang, Y., Ji, S. and Xu, H., 2007. Non-stationary Signals Processing Based on STFT. *8th International Conference on Electronic Measurement and Instruments.* Xi'an, China: Institute of Electrical and Electronics Engineers (IEEE).

Widrow, B., Glover, J.R., McCool, J.M., Kaunitz, J., Williams, C.S., Hearn, R.H., Zeidler, J.R., Dong, E. and Goodlin, R.C., 1975. Adaptive Noise Cancelling-Principles and Applications. *Proceedings of the IEEE,* 63**,** pp. 1692-1716.

Wu, R., Liao, Z., Zhao, L. and Kong, X., 2008. Wavelets Application on Acoustic Emission Signal Detection in Pipeline. *Canadian Conference on Electrical and Computer Engineering.* Niagara Falls, ON, Canada: Institute of Electrical and Electronics Engineers (IEEE).

Yalcinkaya, H. and Ozevin, D., 2013. Reliable Monitoring of Leak in Gas Pipelines Using Acoustic Emission Method. Chicago IL US: University of Illinois at Chicago.

Yeong, H.H. and Pearce, J.A., 1989. A New Window and Comparison to Standard Windows. *Transactions on Acoustics, Speech, and Signal Processing,* 37**,** pp. 298-301.

Ying, Y., Garrett, J.H., Harley, J., Oppenheim, I.J., Shi, J. and Soibelman, L., 2013. Damage Detection in Pipes under Changing Environmental Conditions Using Embedded Piezoelectric Transducers and Pattern Recognition Techniques. *Journal of Pipeline Systems Engineering and Practice,* 4**,** pp. 17-23.

Yoon, D.B., Park, J.H. and Shin, S.H., 2012. Improvement of Cross-Correlation Technique for Leak Detection of a Buried Pipe in a Tonal Noisy Environment. *Nuclear Engineering and Technology,* 44**,** pp. 977-984.

Yughay, V.S., Gribok, A.V. and Volov, A.N., 1997. Advanced Signal Processing Technique for Acoustic Detection of Sodium- Water Reaction. Vienna (Austria): Institute of Physics and Power Engineering.

Zan, T.T.T., Wong, K.J., Lim, H.B., Whittle, A.J. and Lee, B.S., 2014. Leak Detection and Localization in Water Distribution System using Time Frequency Analysis. *2014 22nd European Signal Processing Conference (EUSIPCO).* Lisbon, Portugal: Institute of Electrical and Electronics Engineers (IEEE).

Zhao, J., Sun, F. and Wang, H., 2011. Pipeline Leak Fault Feature Extraction based on Wavelet Packet Analysis and Application. *2011 International Conference on Electrical and Control Engineering.* Yichang, China: Institute of Electrical and Electronics Engineers (IEEE).