LEAK DETECTION IN GAS PIPELINE BASED ON TIME-FREQUENCY ANALYSIS

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Thesis submitted in fulfilment of the requirements
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Dedicated to my father, Mr. Adnan bin Mohd. Soud, my beloved mother, Mrs. Rusnah bt. Mat Jusoh, my husband, Muhammad Firdaus bin Ab. Moin, my younger brothers Mohd. Farahim b. Adnan, Muhd Afiq Naqiuddin b. Adnan, Muhd. Haris Haiqal b. Adnan, my younger sisters Nurul Amenina bt. Adnan, Nurul Najihah bt. Adnan, and last but not list to all my fellow friends.

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ABSTRACT

Pipelines are very important part of any engineering infrastructure. Gas leak is a prominent problem associated with pipelines and it is inevitable in many systems. Prevention of leak is important since gas leak will lead to deficiency and also effects the environment. The safety is one of the main reasons why leak detection is popular in research and development sector. Subsequently, many researchers studied various available methods for leak detection in gas pipeline. One of them is acoustic method. Leak in gas pipelines can be detected and located precisely using certain sensor. However, high fast alarm rate is the main problem in detecting leak. Non-stationary signal is produced by gas flowing in the pipeline, making the analysis of signal becomes more difficult. The scope of this research is detecting and locating leak in straight pipeline and L-bend. The experiments were conducted by injecting the sinusoidal wave into the pipeline and the reflection of the signal is collected by using a microphone. The data is acquired by DASYlab and analysed using Matlab software. The important element in this study is the signal echoes produced by the disturbance of gas flow with leak (defect) or L-bend (feature). Analysing the signal echoes is very closely related to signal processing. In conjunction to that, Hilbert transform (HT) and Ensemble Empirical Mode Decomposition (EEMD) or simply called as Hilbert Huang Transform (HHT) is applied to produce robust results. EEMD is adopted to decompose the signal into IMFs and each IMF is analysed using HT to get instantaneous phase and instantaneous frequency. Besides, the study has shown that HT provides accurate leak location with application of instantaneous phase and instantaneous frequency. Hilbert spectrum (HS) has successfully displayed the energy-time-frequency distribution in proper presentation. The percentage error for all experiment is below 5 percent. In conclusion, HHT is a promising signal processing method that can be used to analyse the echoes acquired from experiments, producing accurate leak location with this method, it is possible to identify leaks and also features in a pipeline network with acceptable errors for both leak and L-bend.

ABSTRAK

Saluran paip adalah bahagian yang sangat penting dalam mana-mana infrastruktur kejuruteraan. kebocoran gas adalah masalah utama yang dialami oleh saluran paip dan ia tidak dapat dielakkan dalam kebanyakan sistem. Pencegahan kebocoran adalah penting kerana ia akan membawa kepada pengurangan kecekapan dan juga memberi kesan kepada alam sekitar. Faktor keselamatan juga menjadi salah satu sebab utama mengapa pengesanan kebocoran adalah popular dalam sektor penyelidikan dan pembangunan. Oleh itu, ramai penyelidik mengkaji pelbagai kaedah sedia ada untuk mengesan kebocoran pada saluran paip gas, antaranya menggunakan kaedah akustik. Melalui kaedah ini, kebocoran saluran paip gas boleh dikesan dan ketepatan kedudukannya dapat ditentukan dengan tepat menggunakan alat pengesan tertentu. Walau bagaimanapun, kadar kesilapan penggera yang tinggi menjadi masalah utama dalam mengesan kebocoran. Isyarat bukan pegun yang dihasilkan oleh gas yang mengalir dalam saluran paip membuatkan proses menganalisis isyarat menjadi lebih sukar. Skop kajian ini adalah mengesan kebocoran dan kedudukannya dengan tepat dalam saluran paip yang lurus dan lengkuk L. Eksperimen dijalankan dengan menyuntik gelombang sinusoidal ke dalam saluran paip dan pantulan isyarat dikumpul oleh mikrofon. Data diperolehi menggunakan DASYlab dan dianalisis menggunakan perisian Matlab. Elemen penting dalam eksperimen ini ialah gema isyarat yang dihasilkan oleh gangguan aliran gas disebabkan kebocoran (kecacatan) atau lengkuk L (ciri-ciri). Menganalisa gema isyarat secara amnya adalah berkaitan dengan isyarat pemprosesan. Oleh itu, Hilbert transform (HT) dan Ensemble Empirical Mode Decomposition (EEMD) atau hanya dipanggil sebagai Hilbert Huang Transform (HHT) digunakan untuk mendapatkan hasil terbaik. EEMD diguna pakai untuk mengurai isyarat ke dalam bentuk IMFs dan setiap IMF dianalisis menggunakan HT untuk mendapatkan fasa serta-merta dan kekerapan serta-merta. Selain itu, kajian ini juga telah menunjukkan bahawa HT menyediakan lokasi kebocoran dengan tepat menggunakan fasa serta-merta dan kekerapan serta-merta. Hilbert spectrum (HS) telah menunjukkan pengagihan tenaga-masa-frekuensi dalam persembahan yang betul. Ralat peratusan bagi semua eksperimen adalah di bawah 5 peratus. Kesimpulannya, HHT menjanjikan kaedah pemprosesan isyarat untuk menganalisis gema diperolehi daripada eksperimen dan dapat menentukan kedudukan kebocoran dengan tepat. Kaedah ini mampu mengenal pasti kebocoran dan juga ciri-ciri sesuatu dalam rangkaian saluran paip dengan kesilapan yang boleh diterima pakai bagi kes kebocoran serta lengkuk L.

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LIST OF SYMBOLS

$\boldsymbol{c}$	Speed of sound (m/s)
f	Frequency
Hz	Hertz
k	Boltzmann constant
K_s	Coefficient of stiffness
L	Length (m)
m	Mass of a single molecule
M	Molar mass of the gas
p	Pressure
R	Molar gas constant (8.3145 J/(mol.K))
s	Distance (m)
t	Time (s)
T	Absolute temperature
v	Velocity (m/s)
x	Distance between leaking point and the front point
Δt	Time resolution
ρ	Density (Kg.m^{-3})
γ	Isentropic expansion factor or adiabatic index
ϑ	Temperature (^{o}C)
ω	Angular frequency
τ	Position in time of Gaussian window

LIST OF ABBREVIATIONS

CIA	Central Intelligence Agency
CWT	Continuous Wavelet Transform
DAQ	Data acquisition
DOSH	Department of Occupational Safety and Health
DSP	Digital signal processing
DWT	Discrete Wavelet Transform
EEMD	Ensemble Empirical Mode Decomposition
EMD	Empirical Mode Decomposition
FDTD	Finite Difference Time Domain
FT	Fourier transform
FFT	Fast Fourier transforms
GI	Galvanized Iron
GLR	Generalized Likehood Ratio
HS	Hilbert Spectrum
HSA	Hilbert spectral analysis
HT	Hilbert transform
HHT	Hilbert Huang transform
IMF	Intrinsic mode function
LPG	Liquefied petroleum gas
MDPE	Medium Density Polyethylene
NI	National Instruments
NPW	Negative pressure wave
PGU	Peninsular Gas Utilisation
PHMSA	Pipeline and Hazardous Material Safety Administration

PPA	Pressure point analysis
PSD	Power spectral density
PVC	Polyvinyl Chloride
RTTM	Real time transient modelling
STFT	Short Time Fourier transform
WT	Wavelet transform

CHAPTER 1

INTRODUCTION

1.1 Project Background

In most application of engineering structure, pipelines are the most important aspect in completing media transport. Pipelines can be used to transfer air, water, oil and other fluids because of their cost-effectiveness and safety. Pipelines must be reliable, safe and cheap for delivering large volumes of a wide range of refined products from refineries to distant depots (Cerda, 2011). Yet, poor maintenance of the pipelines will result to poor safety conditions and leads to leakages.

Usually, leakages that occurred are caused by damage from nearby excavation equipment, accident, terrorism, earth movement and sabotage. Therefore, leak condition and location of leaks need to be detected as early as possible. Monitoring leak is important in order to prevent any loss of fluid, that has proven to be costly. In addition, it can prevent any hazardous situation from happening. Recently, researchers have shown an increased interest in detection of gas leak after the effects of harmful gases on human health were discovered. There has been dramatic improvement of awareness in the industry on the need to prevent this kind of loss and most importantly assessing the reliability of this industry and safety of the public, employees, environment and to reduce economic losses. In order to accomplish this, the pipeline industry needs to follow the regulations set by governments and strive to find more reliable pipeline inspection systems and that is also cost-effective (Webb, 2015).

Thus, the challenge is to find a leak detection method that is capable of accurately detecting leaks and their location in a timely fashion. As will be presented in the review of the literature in the next chapter, great efforts have been made in order to develop methodologies or devices for determination of leaks, with some limited success.

1.1.1 Pipeline System

According to the latest Central Intelligence Agency (CIA) report, there is a total of slightly less than 3.5 million km of pipelines in 120 countries. From that figure, the United States had 65% of them, Russia 8%, and Canada 3%, meaning that 75% of world's pipeline is in these three countries. Our country Malaysia has one of the most extensive natural gas pipeline networks in Asia (Rahim and Liwan, 2012).

Based on Gas Malaysia Berhad (2015), the Peninsular Gas Utilisation (PGU) project which commenced in 1984 is the longest pipeline project in Malaysia spanning more than 2,500 km. The distribution of the pipeline is described as shown in Figure 1.1. The delivery of natural gas is divided into three categories which are industrial, residential and commercial users. The district stations, service stations, area stations and regulating stations is the place to reduce the volume and pressure to the suitable level before being delivered to the customer.

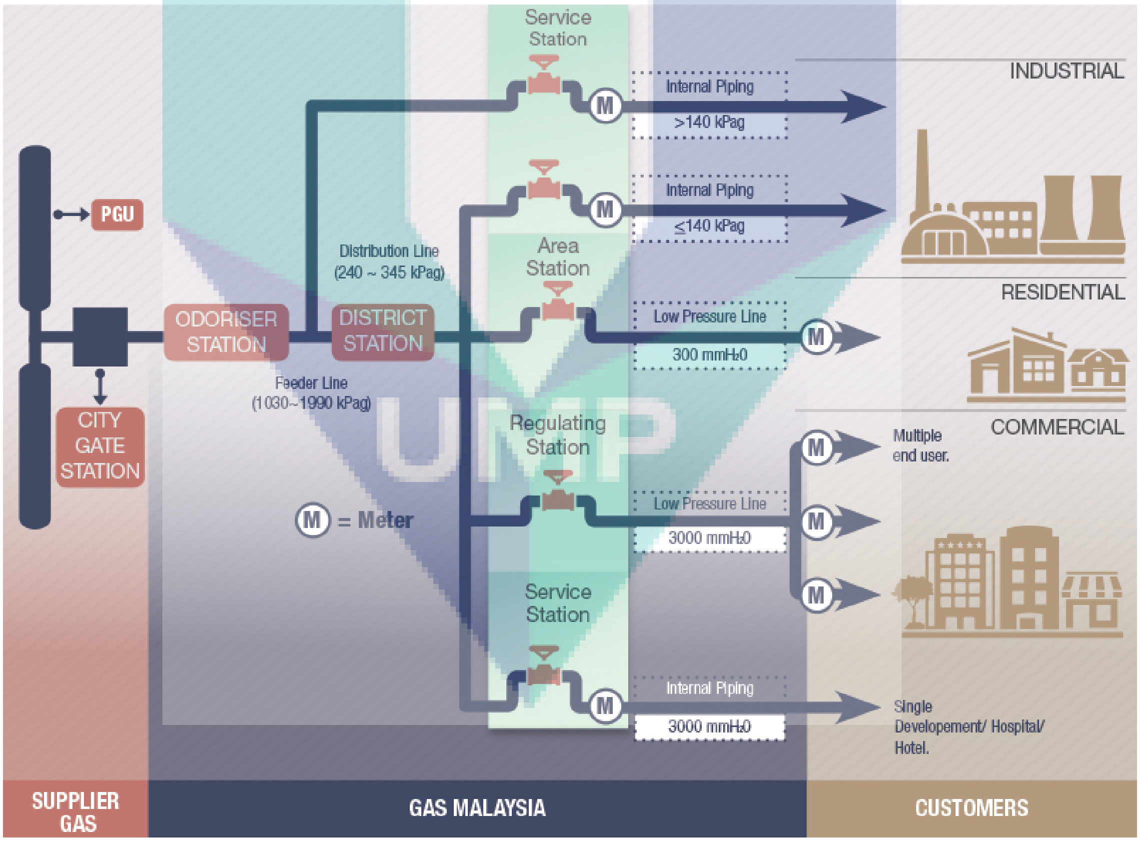


Figure 1.1: Operation process flow

Source: Gas Malaysia Berhad, (2015)

1.1.2 Types of Leak

There are many types of leak that can occur in pipelines and piping systems with different types of leak detection methods suitable for each of them. A leak means an unintended crack, hole or porosity in an enveloping wall or joint which must contain or exclude different fluids and gases allowing the escape of closed medium. Rupture is the least common but most dangerous leak. A challenge to the leak detection system and fairly dangerous leak is 'small' hard-to-detect leak. This kind of leak may result from corrosion, erosion, weld or joint failure and fatigue.

Figure 1.2: Example of a pipeline rupture.

Source: Upton, (2014)

1.1.3 Effect of Gas Leaking

Leaks are most likely to occur to older pipelines. The risk of a pipeline accident is fairly small relative to the volume of gas transported. Each year, several trillion cubic feet of gas is transported via approximately 2.5 million miles of pipeline. Large, high capacity pipelines (known as transmission pipelines) are used to move gas from field production and processing areas to local utilities, which then use smaller lines (known as distribution pipelines) to deliver the gas to consumers. Most of the time, the gas is delivered without incident. Occasionally however, gas may leak from the pipeline, endangering public safety.

According to Pipeline and Hazardous Material Safety Administration (PHMSA) in the United State, there were 818 accidents that were caused by leaked pipelines resulting to death and personal injury between 1995 to 2014 (Webb, 2015). Recently, an accident occurred in the East Village, near to Manhattan, New York City. It is caused by illegal tap made to the gas main (McGeehan and Ham, 2015).

Other than that, on December 2009, the liquefied petroleum gas (LPG) explosion occurred in a supermarket in Malaysia as reported by Department of Occupational Safety and Health (DOSH). During the accident, workers were making final preparations for the official opening of the complex. The LPG was channelled from the bulk storage tanks through a gas piping network and controlled by a shut-off valve at each of the shop-lot- which is used as food and beverages outlet. Forensic engineering investigation found out that the explosion occurred when a shut-off valve in one of the shop-lots was inadvertently left opened (DOSH, 2011).

Apart from endangering public safety, these accidents are also resulting in financial loss. The loss of the fluid itself can lead to waste. Furthermore, the additional number of cases of death and injuries, gas leakage is truly causing huge loss in term of money, time, and energy. Based on PHMSA report, there have been 10844 accidents reported in the United States as shown in Table 1.1. From 1995 to 2014, the trend has been increasing. It is also causing the rise of injuries and fatalities where 96 people were injured and 19 people were died as reported. The pipeline incidents also contribute to the increasing of property damage. The losses are affecting the company and family as well.

Table 1.1
PHMSA Pipeline Incidents: (1995-2014)

Calendar Year	Number	Fatalities	Injuries	Property Damage as Reported ($)
1995	349	21	64	53,427,112
1996	381	53	127	114,467,631
1997	346	10	77	79,757,922
1998	389	21	81	126,851,351
1999	339	22	108	130,110,339
2000	380	38	81	191,822,840
2001	341	7	61	63,092,462
2002	642	12	49	102,167,588
2003	672	12	71	139,057,814
2004	671	23	60	267,836,502
2005	719	17	47	1,245,463,189
2006	639	21	36	151,983,767
2007	613	16	49	154,533,794
2008	659	8	56	565,519,340
2009	628	13	64	179,070,183
2010	588	22	108	1,509,635,198
2011	594	14	56	426,819,470
2012	572	12	57	228,447,641
2013	620	10	47	347,806,517
2014	702	19	96	310,272,540
Grand Total	10844	371	1395	6,388,143,200

1.1.4 Leakage Detection Method

Gas leak is difficult to be detected using plain sight compared to water leakage because of the gas property itself which is colourless and odourless. Figure 1.3 shows the three types of warning sign of gas leak. For long pipelines, it is much more difficult to detect the leak in a short period of time.

The topic of leak detection method is one of the most active areas in gas pipeline research today. As discussed above, there are many methods used in order to detect the leaks effectively. Different methods of leak detection in gas pipeline with different applicability and limitation have been proposed by researchers around the world to ensure safety and efficiency of pipelines (Muhlbauer, 2004). Conventional method such as soap bubble screening and trained dog method is not very effective and have several limitations even though maintenance cost is very low. These methods usually utilize human's or animal's sense. In 2012, many leak detection techniques have been implemented. Murvay and Silea (2012) had differentiated the gas pipeline technique into non-technical method, software based method and hardware based method while Folga (2007) divided into direct or indirect method. With fundamental of leak detection, the leak detection method is

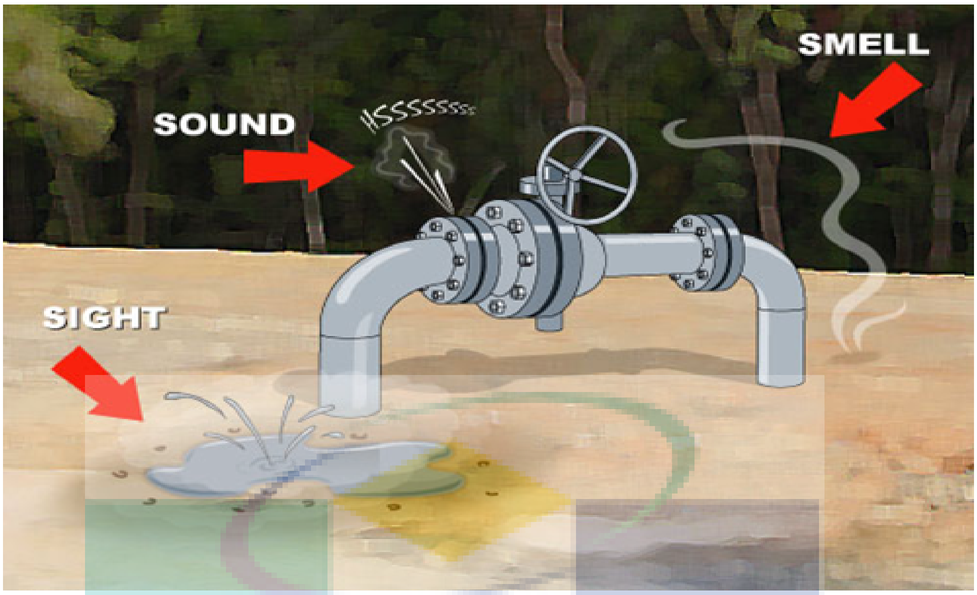


Figure 1.3: Warning signs of gas leaks

improved by the time. The most important detection method is the dynamic signal which is the main theory behind the detection of leaks.

Therefore, leak detection is a vital tool for the management of gas pipeline system around the globe. Low false alarm rate and accurate leak location is important part in preventing any incident or economic loss. The leak may harm surrounding people, increase the death risk and also decrease the efficiency of the system. Most of them have different advantages, disadvantages, and limitations. The cost of installment is also of the concern to the industry. Therefore, the solution of these problem must be robust with respect to the noise without losing the original signal.

1.2 Problem Statement

As discussed in previous sub-chapter, leak detection method is a popular research topic attracting researchers to develop efficient methods to quickly and accurately detect leak locations. A survey was done by Murvay and Silea (2012) stated that acoustic method is one of the popular method applied by the industry to detect leaks. Leak occurred due to disturbance of any feature in the system. Hole, crack and ruptures are examples of leak types. However, the difficulties are coming from the gas flow itself and these will lead to false alarm (Urbanek et al., 2012). In addition, the surrounding noise will also disturb the overall detection during collection of data. Hence, the decomposition of signal is poor due to high noise background. The pipeline materials also have different attenuation rate and the signal may attenuate in media. Thus, early detection can avoid any hazard to human and avoid the wasting of the media.

The crucial part is getting a more efficient and reliable leak detection for the pipeline network facilities. The collection of data may be difficult because of the problem in the pipeline. The signal is non-stationary, causing difficulties in detecting the leak, thus analysis methods include pre-processing, post-processing and analysis need to be done properly. Time frequency analysis is studied to identify and determine accurate leak location. This research will be conducting an acoustic leak detection method using signal processing analyser.

1.3 Project Objectives

This project aims to develop leak detection method with signal processing. In order to achieve the above goal, specific objectives are constructed as follow:

1. To evaluate the decomposition method for development of signal processing for leak detection application in straight and L-bend pipelines.

2. To analyse non-stationary analysis technique based on Hilbert transform to find the instantaneous phase and frequency of a signal.

3. To determine leak location and performance signal processing for the circular leak and L-bend in a pipeline network using experiment by calculating the percentage error.

1.4 Scopes of the Project

For the preliminary study, PVC pipe is chosen in order to define the suitable range of frequency of signal injection into the pipeline and the experiment will be conducted using Medium Density Polyethylene (MDPE) and Galvanized Iron (GI) pipes with specific length and natural air will be used as the fluid as it is safe to do laboratory experiment and also as cost effective. Straight and L-bend pipelines will be used in this experiment. A circular hole is simulated as the leak in the pipeline. The pressure of gas flow will be constant as to create background noise. Data collection will be done using DasyLab with special data acquisition model. The Ensemble Empirical Mode Decomposition (EEMD) will be used as the decomposition method and Hilbert transform (HT) will be applied to get instantaneous phase and frequency. These signal processing technique will be analysed using Matlab.

1.5 Thesis Organization

The rest of the thesis is organised as follows: Chapter 2 will specifically describe the literature review on the topic of leak detection method which is widely used in the worldwide. Different leak detection methods together with their advantages as well as disadvantages will also be reviewed. Several acoustic methods will also be discussed in details. Other than that, sound propagation in pipeline will be explained briefly to present fundamental of knowledge to the readers. The topic of signal processing will also be described in this chapter.

Chapter 3 will start by highlighting the methodology of this project. All the instruments used will be described with their respective figures for both hardware and software. A sub-chapter on experiment setup overview will be discussing on how to conduct the experiment while the computer simulation is done in order to simulate leak detection algorithm in Matlab.

The results and discussion analysis will be presented in Chapter 4. The result will show the benefit and efficiency of HHT method to detect leaks. The discussion of the results will start by selecting the best frequency injection and followed by discussion on the results of different pipe materials. The last sub-chapter will present the results of PVC pipe with L-bend for both without leak and with leak cases.

In Chapter 5, conclusions, research contributions and some general recommendations for future studies in this area will be stated.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A review of previous research efforts related to leak detection methods, sound propagation in pipeline and signal processing is presented in this chapter. This review starts with the definition of leak detection methods and their categories, followed by the fundamentals of sound propagation in gas pipelines including speed of sound and their behavior. Then, the chapter will explain on how sound wave injection into pipelines works. Finally, at the end of this chapter, an overview of signal processing starting from Fourier transform until Hilbert-Huang transform is discussed.

2.2 Leak Detection Methods

With the growth in global energy demand, oil and gas production focus on advance technology of leak detection method. The large quantities of medium transported means that a small percentage loss can give rise to events with considerable economic impact, environmental burden associated with wasted energy, and potential risks to public health.

A number of techniques have been developed for gas pipeline lead detection and can be split into software based method and hardware based method. The former consists of real time transient modelling (RTTM), mass volume balance, negative pressure wave (NPW), pressure point analysis (PPA), digital signal processing (DSP) and statistical method while the latter covers optical method, cable sensor, soil monitoring, vapor sampling, ultrasonic flow meters and acoustic as reviewed by Murvay and Silea (2012). Recently, a new method has been developed called the hybrid technique. Zhang et al. (2015) proposed a novel leak detection method both from software, RTTM and NPW.

2.2.1 Leak Detection in Gas Pipelines: Non-Technical Methods

Non-technical method is described as conventional method, using natural sense to detect the leak. Smell or visual effect of the gas maybe be detected at the leakage point in the pipeline. Examples of the method are soap bubble screening and trained dog. For soap bubble screening, the soap is sprayed around the piping joint or valves to detect the leak as shown in Figure 2.1. Aside from, trained dogs are used to detect leaks as they are very sensitive to smell (Kennedy, 2005; Quaife, 1993). Clearly, this method is cheap, and requires no special instrument but the disadvantages of the method is they require experience and meticulous persons to handle the job. However, this kind detection is only applicable for accessible pipelines and not for buried ones.

Figure 2.1: Warning sign of gas leaks using soap bubble screening method

2.2.2 Leak Detection in Gas Pipeline: Software Based Methods

Murvay and Silea (2012) had classified software based method as quite similar to indirect method. As the name states, the software algorithm is their main component. These software continuously monitor the changes in pressure, flow rate, temperature and other related paramaters in the pipeline. Next paragraphs will describe on individual software based method in details.

Real time transient modelling (RTTM) was discovered by Billman and Isermann (1984). They identified friction parameter in conjunction of cross-correlation of the output estimator error to present the leak detection and localization. Basically, RTTM uses three different equations which are conservation of mass, conservation of angular momentum and conservation of energy. This method can be run in all flow conditions including transient (Xu et al., 2013). Other than that, Morrow and Dickerson (2014) used RTTM through approximation of maximum variation observed in normal running. They analysed the flow and pressure deviation that happened in variation of leaks condition. Hafezi and Mirhosseini (2015) also used this technique to detect water leaks, together with cross correlation method of signal processing in order to detect the leak and find the effect of different size of leak. Even small leaks can be detected using this method, however the cost of instalment is quit expensive because of real-time data collection and the need for trained operators (Scott and Barrufet, 2003).

Next, the mass or volume balance modelling is based on the difference between the upstream and downstream of a pipeline. Liou (1996) and Parry et al. (1992) found that the imbalance between input and output of mass or volume can reveal the existence of leak. This method does not need any generation of high rate of changes in flow and pressure. Fukushima et al. (2000) extended this approach by using mass balance modelling along the pipeline based on transient flow equation. Civan and Balda (2013) applied mass-balance and transient flow models to detect leaks in liquid pipelines. Even though they need to use intensive measurements of all variables, they can estimate the leak location based on it. Other than that, Rougier (2005) used mass-imbalance approach with fully-probabilistic method. However, probabilistic methods need a considerable amount of computational power. Even thought this method is easy to install and has a relatively low cost, the limitation of this method is clear during the shut down, transient, and slack line conditions. In addition, through this method, detection of small leaks are time consuming. According to Doorhy (2011), approximately 60 minutes is needed to detect 1% of leak size.

Negative pressure wave or also known as rarefaction happens when leak occurs in the pipeline system. The leak produces a sudden pressure drop at both downstream and upstream. Based on Eq. (2.1) to (2.4), Silva et al. (1996) and Yang et al. (2010) explained that the leak location is calculated from the difference of time delay between the transducers. The principle of negative pressure wave is as shown in Figure 2.2.

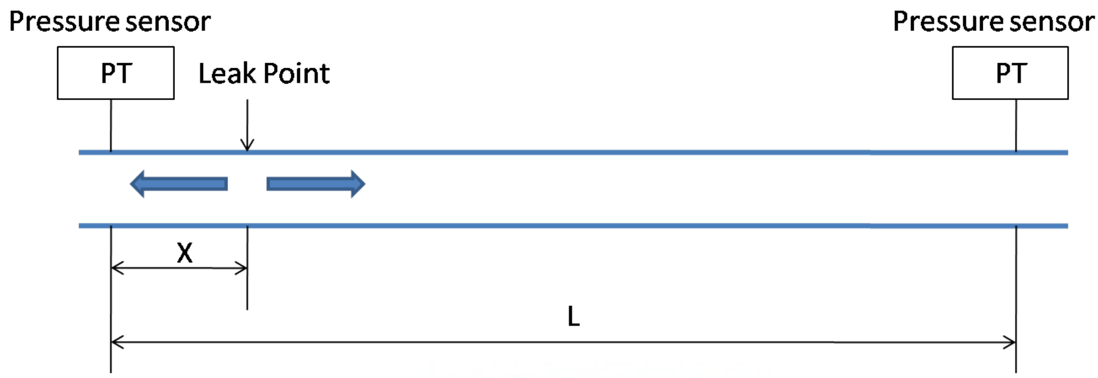


Figure 2.2: The principle of negative pressure wave leak location

Source: Yang et al., (2010)

$$t_1 + t_2 = L/v \tag{2.1}$$

$$t_1 + t_2 = \Delta t \tag{2.2}$$

$$x = t_1 \times v \tag{2.3}$$

$$x = \frac{(L + v \times \Delta t)}{2} \tag{2.4}$$

where;

L	=	length of pipeline (m)
x	=	distance between the leaking point and the front end point (m)
v	=	propagation velocity in the pipeline (m)
t	=	time when the wave is detected by the pressure sensors (s)

El-Shiekh (2010) observed that this method generates accurate leak location and fast detection. However, this method is not very suitable for long-range pipeline unless the amplitudes of pressure waves are further analysed.

Akib et al. (2011) claimed that pressure point analysis (PPA) is one of the popular warning system to detect leak. It is based on the fact that pressure inside the pipeline drops if the leak occurs. Using some statistical calculation pressure, the leak can be defined when the mean value of the pressure measurements decrease under cut off value. This method can detect leak rates less than 0.1 % of the flow but it is not a reliable leak detection technique during transient flow (Scott and Barrufet, 2003). Moreover, PPA can also produce false alarm as pressure drop is not unique to leak events even though the leak signature is correctly identified.

Another of detecting leaks method is using via digital signal processing (DSP). They strengthen the utilization of signal processing to analyse the flow in gas pipeline. Golby and Woodward (1999) applied this method in liquid pipelines but the same method is considered to apply for gas pipeline as well. Recently, new development by a company (ClampOn, 2014) and widely used for both liquid and gas pipelines. The principle behind this method is using passive acoustics (high-frequency noise) as method of operation and intelligent DSP electronic inside the sensor unit. The method detects a leak when the signature change drastically, while non-leak cases will show a stable pattern. During the first setup, if the leak already have in the pipeline, they cannot detect the leak after that setup except the leak becomes worse. There is no mathematical model approach used in this method, but it is definitely expensive, difficult to implement, retrofit and test.

Statistical analysis is a simple method without the used of any difficult mathematical model which makes it easy to implement. This method required the pressure and flow measurement at multiple locations along the pipeline in order to do the statistical analysis. According to Zhang and Twomey (2000), Shell developed a system called *ATMOS PIPE* which is incorporated with advance pattern recognition functions. They applied optimum sequential analysis technique to detect the changes in inlet and outlet of the pipeline. The result is quiet good because they can decrease false alarm rate and the reasonable cost of maintenance. Bagajewicz and Valtinson (2014) proposed a statistical method based on differentiation between two performance of model, no leak and one more with leak called as Generalized Likehood Ratio (GLR). This technique is user-friendly, robust and reliable to be used in different pipeline configuration. However, this technique lacks in term of estimating leak volume and high setup cost.

2.2.3 Leak Detection in Gas Pipeline: Hardware Based Methods

Hardware based methods use special transducer as the main tool to collect the signal data. This method is very straightforward in application but have their own analysis depends on the sensor and equipment used for detection.

Some findings show that optical method can be divided into two major categories which are passive and active detection methods. Both methods have their own advantages and disadvantages. Passive detection required a source and radiation to be emitted by the gas or relies on background radiation. The advantages are no laser required, very long range and multi-wavelength information. But, the advantages are it requires change of temperature and there is a probability of a weak signal making it difficult to detect the leak. In contrast to passive method, active method require the scannec area to be brightened using a source of radiation and the absorption or scattering caused by gas molecules above the surface is monitored using an array of sensors at specific wavelengths as explained by Ikuta et al. (1999). The advantages are the temperature does not need to be changed and strong signal. But, this active method requires laser, needs background signal, and generally only a few wavelengths can be detected as discussed by Reichardt et al. (2002).

Aside from these two methods, electric cable sensors can also be used to detect gas leakage in a pipeline system. Sandberg et al. (1989) developed a hydrocarbon sensing cable that can be installed along pipeline as shown in Figure 2.3. In order to detect the leak, the cable properties need to be monitored. The cable properties will change when there is a reaction occurring to in the materials used to build the cables. Example of cable properties are resistance or capacitance. The advantages of this method are it gives a fast response and is more sensitive than some other computational techniques. The disadvantages of using this technique are it requires high cost to implement the systems and it is quite difficult to retrofit this system to existing pipelines as explained by Murvay and Silea (2012). Other notable disadvantage is the difficulty in estimating the size of the leak.

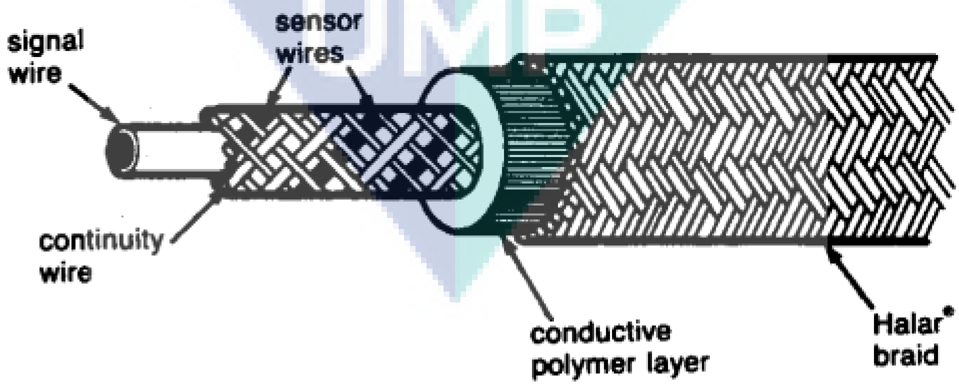


Figure 2.3: Hydrocarbon distributed sensor cable

Source: Sandberg et al., (1989)

Marrin and Kerfoot (1988) are among the first to use soil monitoring approached in the pipeline. Thompson (1987) patented a system for continuously monitoring for leaks in underground storage tanks as shown in Figure 2.4. Soil monitoring involves inoculating the gas pipeline with tracer compound (Lowry et al., 2000). If a leak occurs, the tracer compound will exit the pipe. In order to detect the leak, instrumentations such as dragging devices and probes need to be installed in the soil near to the pipeline. This is because the instrumentations will monitor the surface above the pipeline system. Murvay and Silea (2012) and Liu et al. (2005) discussed the advantages of using this technique including low alarm rate and high sensitivity. On the other hand, the disadvantages of using this technique are this technique requires high cost since trace compounds need to be added into the gas continuously during the process and this technique cannot be used for exposed pipelines.

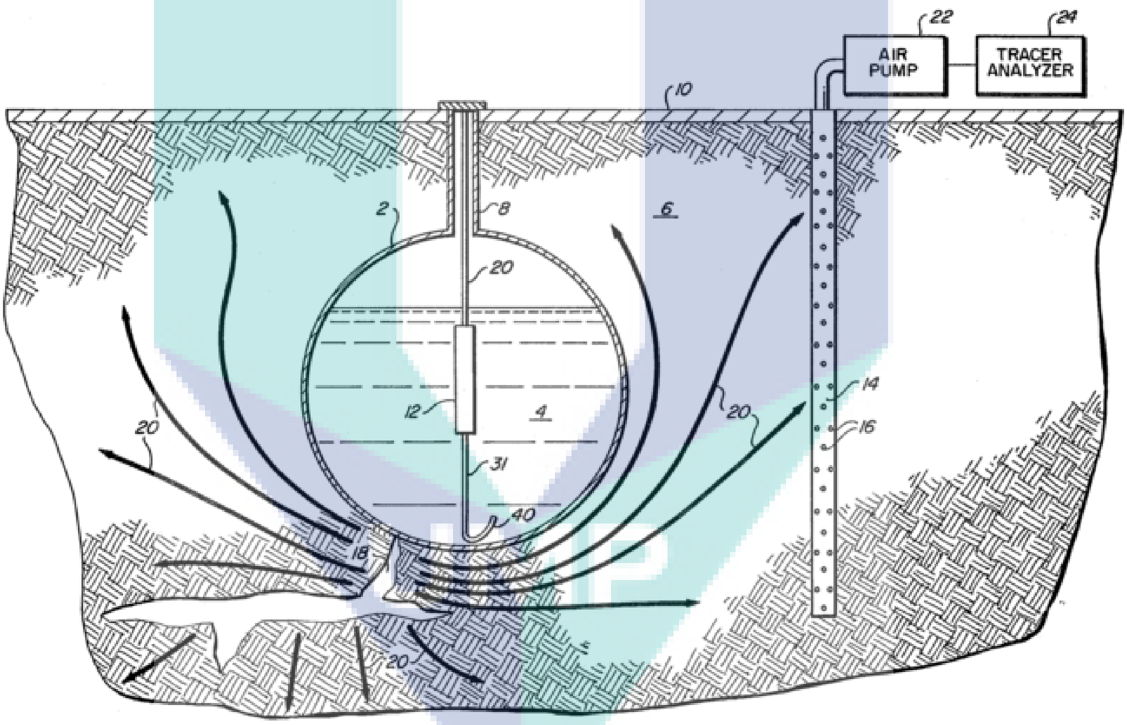


Figure 2.4: Cross-sectional functional diagram of the leak-monitoring system

Source: Thompson, (1987)

Compared to soil monitoring, vapour sampling method can be done through vapour monitoring system or by using mobile detectors by sampling the hydrocarbon vapours in the pipeline and it is a very direct method (El-Shiekh, 2010). The concentration of the gas will determine the size of the leak while the location of the leak can be determined by using a test gas that will be injected in the tube. This technique is suitable to detect small leaks and the detection rely on the frequency of the patrols. However, this method has a slower response time. Thus, it is not applicable to above ground or high depth pipelines. This method is often used for pipelines that are shorter in length and require high cost (Murvay and Silea, 2012).

Ultrasonic flow meters is considered new development and establishment in this area. This system works by considering that the pipeline is comprised of a series of segments designed by Controlontron. Two Site Stations which consist of a clamp-on flow meter, a temperature sensor and a processing unit are bounded in each segment. Volumetric flow rates, gas and ambient air temperature, sonic propagation velocity and site diagnostic conditions are measured in each Site Station. Master Station which computes the volume balance by comparing the difference in the gas volume entering and leaving each pipeline segment collect all the data obtained on Site Stations. Longer integration periods detect smaller leaks while short integration periods detect larger leaks. Murvay and Silea (2012) reviewed that this technique can locate leak with an accuracy of 150 m and another advantage is offered by the non-intrusive character of the electronic devices utilized. Retrofitting this technique to buried pipelines would be difficult and this is the downside of using this technique.

2.3 Acoustic Leak Detection

Leak detection and location in the gas distribution system based on acoustic method has been as a vital research topic both for academics and industry. Acoustic sensor can be used to detect the leaks in pipelines. Operators or intelligent pigs are needed to hold the device along the pipeline to inspect the leak. Placing the sensor too far will increase the risk of undetected leak while placing it too close will increase the cost. Lots of studies have been done in this particular area. Any leak detection method should be quick, accurate, cheap in cost and can be used in normal pipeline without interfering normal operation. Acoustic sensor is normally installed outside the pipeline network. Figure 2.5 shows the overall discussion in this subtopic.

Acoustic leak detection techniques have been studied since the 1930s. Rapid development was done by Watanabe and Himmelblau (1986) and its shows that sharp positive and negative pulse at a certain time using mathematical model of the pipeline acoustic. From this method, they proved that the location of leak is based on the present of sharp pulse or a step at certain time. After that, Rocha (1989) used pressure sensor to record the appearance of acoustic pressure waves. Brodetsky and Savic (1993) presented

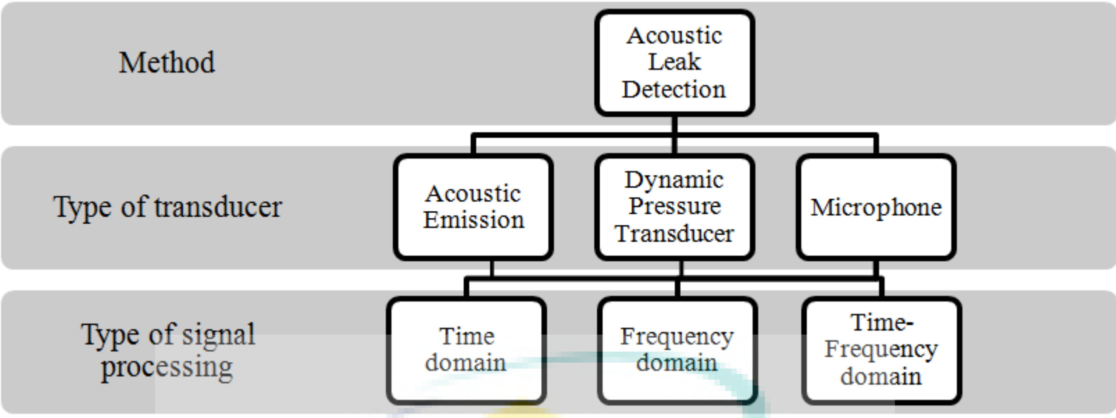


Figure 2.5: Acoustic leak

a new continuous acoustic leak detection system by using k-nearest neighbour classifier to distinguish leaks in underground high pressure gas pipelines. They applied piezoeletric transducer as sensor to detect the force along the pipeline. The standard sound source is produced by a steel ball, falling from 4 inches of height. Mostafapour and Davoodi (2013) used two acoustic emission sensors that transfer through the pipe wall to detect leaks. They removed the noise using wavelet transform and cross correlation algorithm. The result showed that the percentage error is only 5 %.

The technique uses pulse reflectometry involving the injection of sound pulse into the pipeline system and the resulting reflection will be recorded (Sharp and Campbell, 1997). Another study by Tolstoy et al. (2009) also used pulse reflectometry method to investigate pipe irregularities as shown in Figure 2.6. When a blockage is detected in a pipeline, the result shows that the nearer the source of pulse injection to the blockage, the domain strong effect appear and more scattering. Large blockage also gives strong effect compared to smaller ones, while pipe diameter and material will change the backscatter effect. Low frequency impulse is done by Loth et al. (2003) was used to detect leaks involving the measurement of two acoustic signals on each of a pipe segment. Aside from that, a study using cepstrum analysis was developed by using close and open solenoid valve. The time domain was obtained by identifying the delay time between initial wave and their reflections (Taghvaei et al., 2006).

Another experiment used buried pipeline under floors or in the walls of buildings as proposed by Yunus et al. (2006). They intended to provide arrangement information of the pipeline for the reinforcement purpose. Later, Yunus et al. (2008) extended the study in order to detect and locate leak using low cost and easy to implement acoustic method. They developed an experimental and simulation of gas pipeline leakage with

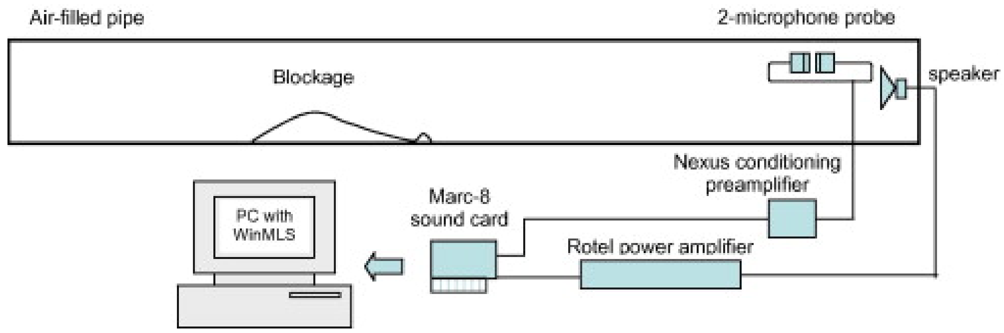


Figure 2.6: Schematic diagram of the acoustic experiment in the pipe

Source: Tolstoy et al., (2009)

different features consist of hole, L-bend, T-bend and crack type. Using Finite Difference Time Domain (FDTD), they presented the suitable frequency characteristic of the signal based on the features and successfully estimated leak location. They discovered the suitable frequency of injected sound is in range of 20-600 Hz for both circular leak and crack type while Murvay and Silea (2012) discovered this method can be used on new as well as on existing pipe network. But, high background noise condition will affect the actual leak. Urbanek et al. (2012) used wavelet filter to eliminate noise signal produced by echoes. This method is tuned by maximum value of kurtosis to present the leakage detection and their severity. They concluded that amplitude of echoes is directly proportional with size of hole and decrease with the distance from the hole because of the damping in the medium.

Shimanskii et al. (2005) mentioned that high-temperature microphones has been developed in nuclear power plants and has successfully detect leaks with sensitivity 0.23 m^3/h and also their accurate location. Papadopoulou et al. (2008) proposed a novel leak detection in single pipeline based on propagation of acoustic waves. The signal generated by an acoustic pulse generator is used to transmit the signal into the pipe. A microphone was then used to measure the transmission and reflection of this signal. The method is first conducted to a non-leak pipe to set the reference signature for the signal. With knowledge of speed of sound, the leak can be determined, however, it will become difficult when there is high background noise. Furthermore, a patented acoustic technique known as Acoustec that can be used to detect features such as blockage and leakage by injecting pressure pulse in the pipeline was developed by Wang et al. (2009b). Wang et al. (2009a) used the signal generated by an acoustic pulse generator to inject the input signal into the pipeline. The 100 Hz is transmitted signal amplified through the speaker into the pipeline and the microphone is installed at the same end as the loudspeaker to measure the transmission and reflection of the wave through the pipe. However, strong noise in the reflected signal blocks the detection of end pipeline location. So, they used matched filter to process the reflected signal the location of the pipe end is determined. In another test, a 800 Hz sound was injected into the pipe with a bend. The result showed that the pipe end can be detected yet there is no indicator of the bend on the tested pipe. Development in the signal analysis field is further improved with the additional of match filter to eliminate noise and this approach successfully in identifies features even in complicated arrangement with strong interference.

A recent study distinguishing between signals made by leak and background noise using time-frequency analysis together with location formula to increase accuracy (Meng et al., 2012). This new recognition and extraction method is very important to decrease the high false alarm rate and increase accuracy of leak location. As a result, acoustic leak signal is compared with the time domain analysis, contains waveform, amplitude, mean value, root mean square value, kurtosis, skewness and correlation analysis. From the analysis, kurtosis can be adopted to distinguish leak from other features in pipeline, while compressor signal can be distinguished by amplitude, waveform and kurtosis. The authors found that most signal of leak are in the range of 0-100 Hz. Santos et al. (2013) used acoustic method and neural artificial networks. The model used decomposition input of sound noises which contains different frequencies to determine the occurrence, magnitude and location of the leak. Kim and Lee (2009) concluded that time-frequency technique is the better analysis method compared to power spectral density (PSD). They used the time-frequency method to explain some of the features of wave propagation measurements made in gas pipes. In addition, time-frequency method can identify cut-off frequencies for acoustic modes in a circular duct.

Time-frequency analysis also can identify cut-off frequencies for acoustic mode in a circular duct. In the same time, Jia et al. (2012) developed an algorithm for gas pipeline leak detection based on Hilbert-Huang transform. They used acoustic wave measured using two sensors at different positions and the schematic diagram is shown in Figure 2.7. Leakage is detected by feature of acoustic signal extraction. Extensive experiments on real data proved the effectiveness of this new method. Bernasconi et al. (2012) performed some result of spectogram based on pressure signal in order shows the disturbance in the pipeline with development of new detection and classification algorithms. The Hilbert marginal spectrum for the signal could be acquired after Hilbert-Huang transform, which consists of two parts: empirical mode decomposition (EMD) and Hilbert spectral analysis (HSA) (Hedeng et al., 2012). Li et al. (2014) carried out a scheme based on cross time-frequency spectrum collected by using acoustic emission method.

In this study, acoustic method is the best method to do leak detection in straight

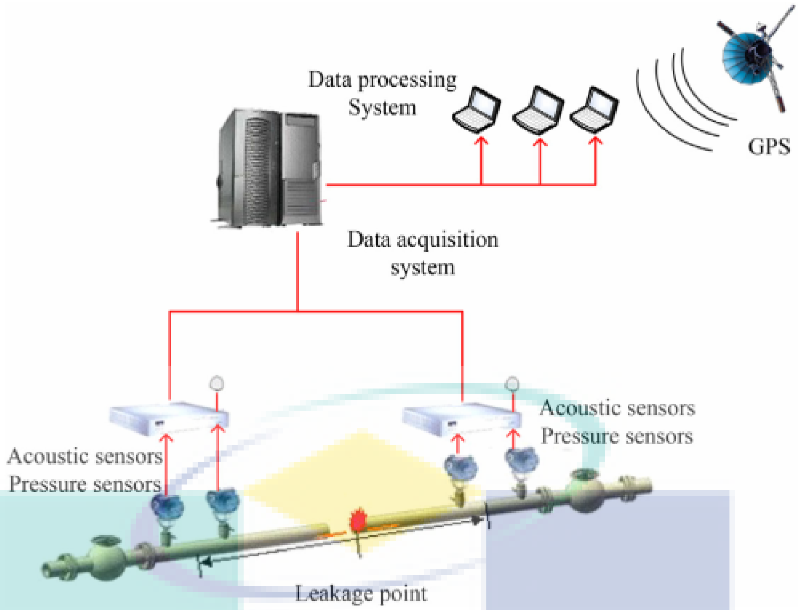


Figure 2.7: Schematic of an acoustic leak detection system

Source: Jia et al., (2012)

pipeline compare to others method. Acoustic method promises high detection rate and localization accurately and does not need complex mathematical model. However, the leak generates noise that will be picked up by acoustic sensor thus the most important thing is to minimize the background noise, as reported by Scott and Barrufet (2003) and Wang et al. (2009a). This method can be used on new as well as on existing pipe network. The advantages of this method compared with other method are fast detection and high sensitivity. In addition, this method also offer accurate leak location and low false alarm rate as discovered by Meng et al. (2012). But, high background and noise condition will affect the actual leak and also produce false alarm when the leak is too small, as highlighted by Wang et al. (2009b), Yunus et al. (2008) and Wang et al. (2009a).

2.4 Sound Propagation in Pipelines

As explained in previous sub-chapter, there are different types of transducer used in acoustic method. When dealing with acoustics, type of transducer and analysing method utilized are most important aspects. In this sub-chapter, the theory of sound propagation in pipeline will be discussed in details. To find the leak location, it is important to identify the exact speed of sound. In addition, the reflection of signal will determine the accurate time and differentiate whether defect or features in the pipeline.

Pressure balance in the pipeline system is interrupted when something blocked the flow. The disturbance may be caused by leakage, ruptures, crack or junction. Acoustic wave is generated by the friction of the wall of the pipeline. Three effects that occurred due to the incident wave as mentioned by Burn et al. (1999) and Beck and Staszewski (2004) are reflection, transmission and absorption (Figure 2.8). Reflection will also happen when there is change in the cross-sectional area of the pipeline (Sharp and Campbell, 1997) and their transmission as shown in Figure 2.9 (Papadopoulou et al., 2008). Dispersion is the phenomenon of speed change in frequency due to structural and geometric size. Meanwhile, absorption is determined by the material used. Tao et al. (2015) studied on simulation wave propagation within network pipeline system for several branch. When an acoustic wave is propagating towards the branch joint in one of the pipes, part of the signal will be reflected at the branch joint.

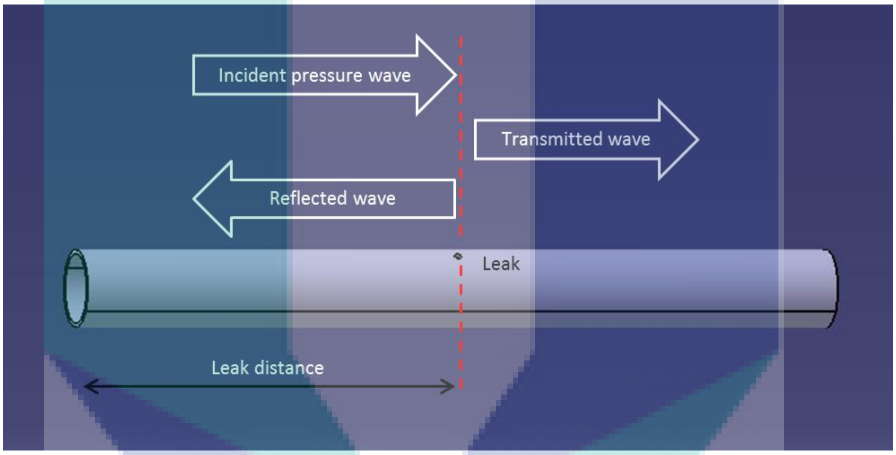


Figure 2.8: Conceptual wave reflections at a leak

Source: Colombo and Karney, (2003)

2.4.1 Speed of Sound

Air is a type of gas, and a very vital property of any gas is the speed of sound through the gas. As introduction, speed of sound is basically the speed of transmission of a small disturbance through the medium. Sound propagates through air as a longitudinal wave. Sound wave normally exhibit four types of phenomenons which are reflection, interference, refraction and diffraction. Basically, reflection angle is the same between incident and reflection.

Airborne sound is the sound which can spread only via the air. This can be de-

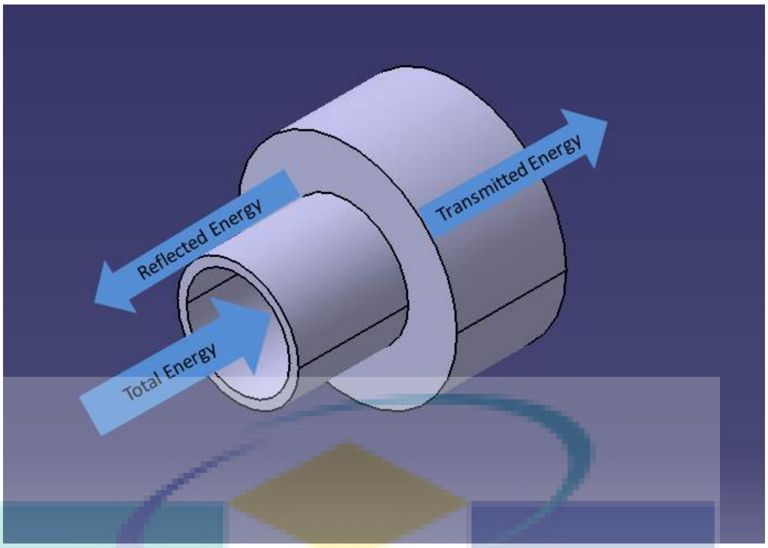


Figure 2.9: Acoustic reflection and transmitted energy in the pipe joint

Source: Papadopoulou et al., (2008)

tected, at least by the human ear, from 20 Hz - 20000 Hz. Airborne noise may also change into structure-borne and back to air-borne noise. This process is often called transmission of sound energy. The SI unit for speed of sound is meter per second (m/s) since the speed is measured by distance per unit time. In dry air at 20°C, the speed of sound is 343.2 m/s, as stated by Rienstra and Hirschberg (2003). In general, the speed of sound, c is given by the Newton-Laplace equation (see Eq. 2.5):

$$c = \sqrt{\frac{K_s}{\rho}} \tag{2.5}$$

where;

c	=	speed of sound
K_s	=	coefficient of stiffness, the isentropic bulk modulus (or the modulus of bulk elasticity for gases)
ρ	=	density (Kg.m^{-3})

For an ideal gas, K (the bulk modulus in equations above, equivalent to C, the coefficient of stiffness in solids) is given by:

$$K = \gamma . p \tag{2.6}$$

thus, from Eq. (2.5), the speed of sound is given by;

$$c = \sqrt{\gamma . \frac{p}{\rho}} \tag{2.7}$$

where;

γ	=	isentropic expansion factor or adiabtic index
p	=	pressure
ρ	=	density (Kg.m^{-3})

Using the ideal gas law to replace p with *nRT/V*, and replacing ρ with *nM/V*, the equation for an ideal gas becomes;

$$c_{ideal} = \sqrt{\gamma . \frac{p}{\rho}} = \sqrt{\frac{\gamma RT}{M}} = \sqrt{\frac{\gamma kT}{m}} \tag{2.8}$$

where;

c_{ideal}	=	speed of sound
R	=	molar gas constant (8.3145 J/(mol.K))
k	=	Boltzmann constant
γ	=	isentropic expansion factor or adiabtic index
T	=	absolute temperature
M	=	molar mass of the gas. The mean molar mass for dry air is about 0.0289645 kg/mol
m	=	mass of a single molecule

This equation applies only when the sound wave is a small perturbation on the ambient condition, and the certain other noted conditions are fulfilled, as noted below. Calculated values for c_{air} have been found to vary slightly from experimentally determined values.

With available value of γ=1.4000, R=8.314510 J/(mol.K), M_{air}=0.0289645 kg/mol, celcius temperature ϑ= T - 273.15, then;

$$R_* = R/M_{air} \tag{2.9}$$

and c_{ideal} is equal to:

$$c_{ideal} = \sqrt{\frac{\gamma RT}{M}} = \sqrt{\gamma \times R_* \times (\vartheta + 273.15)} \tag{2.10}$$

and

$$c_{ideal} = \sqrt{\gamma \times R_* \times 273.15} \times \sqrt{1 + \frac{\vartheta}{273.15}} \tag{2.11}$$

For dry air, where ϑ is the temperature in degrees Celsius (°C). This equation can be simplified into with Eq. (2.12) as below (in m/s):

$$c_{air} = 331.3 + (0.606°C^{-}1 \times \vartheta) \tag{2.12}$$

2.4.2 Absorption and Attenuation

Absorption is the conversion of the sound energy to other forms of energy. Part of the absorbed energy is transformed into heat and part is transmitted through the absorbing body. The energy transformed into heat is said to have been 'lost'. When sound from a loudspeaker collides with the walls of a room, part of the sound's energy is reflected and part is absorbed into the walls. Scattering is the reflection of the sound in directions other than its original direction of propagation. The combined effect of scattering and absorption is called attenuation. Ultrasonic attenuation is the decay rate of the wave as it propagates through material.

2.4.3 Reflection of Sound for Closed and Open End

The speed of sound in room temperature is about 343 m/s. The speed of sound is insensitive to the pressure because speed of individual molecules is not affected by the pressure. They crash into each other more often at high pressure, but between collisions they travel at a speed that depends only on the temperature, not the pressure. The average speed of molecules is proportional to the square root of the temperature, and inversely proportional to the square root of the mass of the molecules in the gas. The travelling pressure pulse in the pipeline with closed end will go through in the pipe and its direction reversed direction when reaching the end of the pipeline. This is as shown in Figure 2.10 using Ripple simulation. The sinusoid wave injected into this simulation is used to show the reflection of the wave when a pipeline have a closed end.

Besides that, the reflection of the sinusoid wave in open end is shown in Figure 2.11. The comparison between opened end (top) and closed end (bottom) shows the sign of the pulse reverse for the open end. The sound is not much emitted, and most of them is

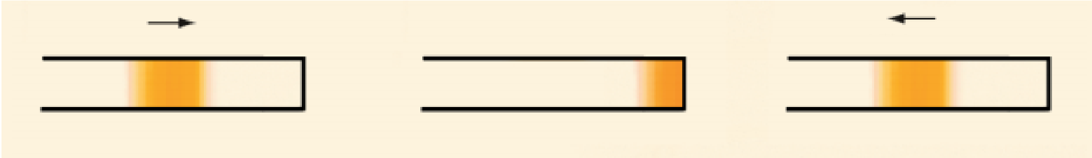


Figure 2.10: Reflection of sound in a closed end pipeline

Source: Heller, (2012)

reflects in the pipeline back. The other significant point is, the reflection will be slightly delayed and longer compared to closed end as portrayed in the vertical line as reference. At the end of the pipe, the air pressure remains the same inside the pipe until the pulse reaches the pipe end that the pressure pulse exists outside until it reaches the end; as the pressure exits the pipe, instead of finding lower pressure laterally as it did before, it now finds matched higher pressure outside. There is no sudden pressure release laterally, no impedance change. The entire pulse proceeds as if nothing happened; there is no back reflection inside the pipe at all.

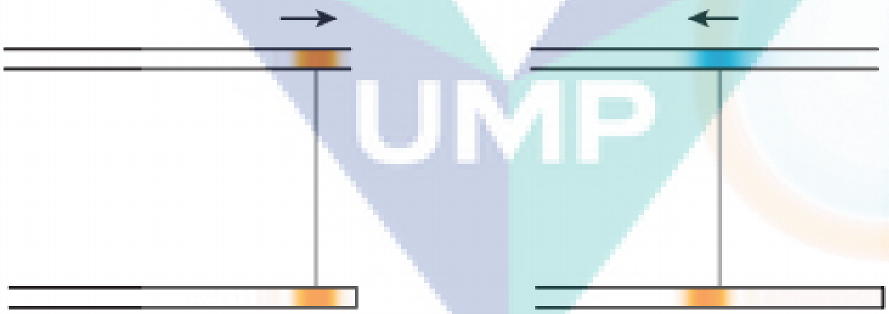


Figure 2.11: Reflection of sound in an open end pipeline

Source: Heller, (2012)

2.4.4 Reflection of Sound at Junction

In fact, the pressure pulse does not reflect just once, but many times, depending on the diameter of the pipe. Thus the narrower the pipe, the higher the impedance. Sound wave energy from one plane to another pass through the junction. Emanating from the floor plate flexural wave junction will create direct, flexural and distortional waves. Yunus et al. (2008) investigated the amplitude reflection for different features, L-bend, T-branch and leak as well. Even in complicated arrangement of pipeline, they successfully differentiated the features based on frequency characteristic reflected by the features and type of leaks. In this case, L-bend will be part of this study's experiment parameter.

2.5 Signal Processing

Signal processing is a combination of three major parts which are system engineering, electrical engineering and applied mathematics. It also deals with operations on or analysis of analogue to represent time-varying physical quantities. Signals include sound, electromagnetic radiation, images, and sensor readings. The goal of signal analysis is to extract information from the signal to reveal the underlying mechanisms of various physical phenomena. Precision and accuracy in the detection of gas leakage should be made a priority because it will reduce the cost of recovery and preventing mo serious accidents from happening. Researchers agreed that acoustics is one of the powerful technique to detect leakage and may be used together with popular signal processing techniques. Signal processing capabilities is emphasized in order to get fast and accurate leak location, so that the cost of losses will be reduced. Hence, transformation method such as Fourier transform (FT), Short Time Fourier Transform (STFT), Wavelet transform (WT) and Hilbert-Huang transform (HHT) is discussed. These approaches will be applied in frequency-domain and time-frequency domain.

2.5.1 Fourier Transform (FT)

Fourier Transform states that the sum of a specific set of sine waves is known as the frequency content of a signal. The sine wave is the only pure frequency wave and any distortion of this shape represents harmonics of some fundamental frequency. Thus, any wave no matter how oddly shaped, can be broken down into its component sine waves. Fourier Transform of a non-periodic signal produces a continuous transform. The Fourier transform is limited to stationary signals, signals that have the same frequency content for all times. In contrast, non-stationary signals require signal-processing methods that can quantitatively resolve changes in frequency content, as a function of time.

Fourier transform is the basic foundation in understanding more about wavelet transform. However, Fourier transform is not suitable for non-stationary signal which give different spectral components at different function apply. Fourier transfer is defined by Polikar (1996) as below,

$$x(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \tag{2.13}$$

f indicates the frequency and *t* indicates the time. From the function of the Fourier transfer, it is known that the equation is integrated over all times. The previous equation can be recovered from its spectral with the inverse Fourier transform as shown in Eq. (2.14).

$$X(f) = \int_{-\infty}^{\infty} x(f)e^{j2\pi ft}dt \tag{2.14}$$

Result of the integration can be divided into three categories. First category is when the result of the integration is large in value, the signal is dominant spectral component at frequency. Meanwhile when small value is the result of the integration, frequency will become the minor component. When the result is zero, it happened that it does not contain frequency. Since the limit of the integration is from negative infinity to positive infinity, thus no matter where in time the component of frequency appear, it will affect the result of integration which lead to the reason why Fourier transfer is not suitable for non-stationary signal. It is due to the signal has time varying frequency (Polikar, 1996).

2.5.2 Short Time Fourier Transform (STFT)

The Short Time Fourier Transfer (STFT) is when some portion of non-stationary signal is assumed to be stationary. It is assumed stationary by using a window to see the signals. Using STFT, signal is divided into small segments which then assumed to be stationary. However, there is some problem in STFT making it not suitable to be implemented. This issue is regarding to uncertainty principle.

Based on the STFT, only time intervals in which certain band of frequencies exists can be known. Thus, it leads to resolution problems. This is due to the window which is have finite length resulting to imperfect resolutions. Uncertainty principle comes handy when a choice is to be made between narrow window and wide window. Narrow window gives good resolutions but low frequencies meanwhile wide window is not good in time resolutions but with good high frequencies (Polikar, 1996). Therefore, both are not suitable to be used in non-stationary signals. Mathematically, this is written as:

$$STFT\{x(t)\}(\tau,\omega) = X(\tau,\omega) = \int_{-\infty}^{\infty} x(t)w(T-\tau)e^{-j\omega t}dt \tag{2.15}$$

where *x(t)* is the signal to be transformed and *w(t)* is the windowing function. X(τ,ω) is essentially the Fourier Transform of *x(t)w(T-*τ*)*, a complex function representing the phase and magnitude of the signal over time and frequency.

A disadvantages of FT is it gives a global energy-frequency representation of the data sequence. If the data is non-stationary, Fourier spectrum does not make any physical significance. Fourier cannot locate any frequency in time. STFT reduces frequency resolution, and it still imposes the stationary assumption in that region (Polikar, 1996). Eventhough STFT have the ability to decompose the signal into time-frequency domains, it still have its drawbacks when faced with Heisenberg uncertainty principle. This principle does not allow a high degree of resolution in both time and frequency domains simultaneously. This is because everything in the universe behaves like both a particle and a wave at the same time. Heisenberg uncertainty principle can be described as Eq. (2.16) below.

$$\Delta t \Delta f \geq \frac{1}{4\pi} \tag{2.16}$$

The problem with STFT is resolution. We might know at what time interval the frequency existed but not exact time. The window function is fixed for the entire signal which might not be the case in most application. Usage of a very narrow window helps the assumption of stationary but narrower window would not give a good frequency resolution. Therefore, there is a trade off between narrow window application and frequency resolution as shown in Table 2.1.

Table 2.1
STFT relationship between time and frequency resolution

Window size	**Narrow window**	**Wide window**
Time resolution	Good	Poor
Frequency resolution	Poor	Good

2.5.3 Wavelet Transform (WT)

For signal processing, wavelet transform is widely used in application of multi-resolution editing, signal filtering for noise, edge detection, marking reduction, data compression storage, recognition, enhancement and synthesis of speech. It is a powerful application tooland can be used to detect, localize, identify, classify, compress, store and analyse of power disturbance signals (Beck et al., 2006).

Wavelet transform or wavelet analysis is probably the most recent solution to overcome the shortcoming of the Fourier transform. The term "wavelet" is coming from small wave with finite energy, which has its energy concentrated in time or space. Wavelet has been developed from FT and decomposes a signal into set of basis function, which are obtained by shifted and scaled versions of a function called as "mother wavelet". In Figure 2.12, the basis function of wavelet transform (Daubechies-8 mother wavelet) is shown:

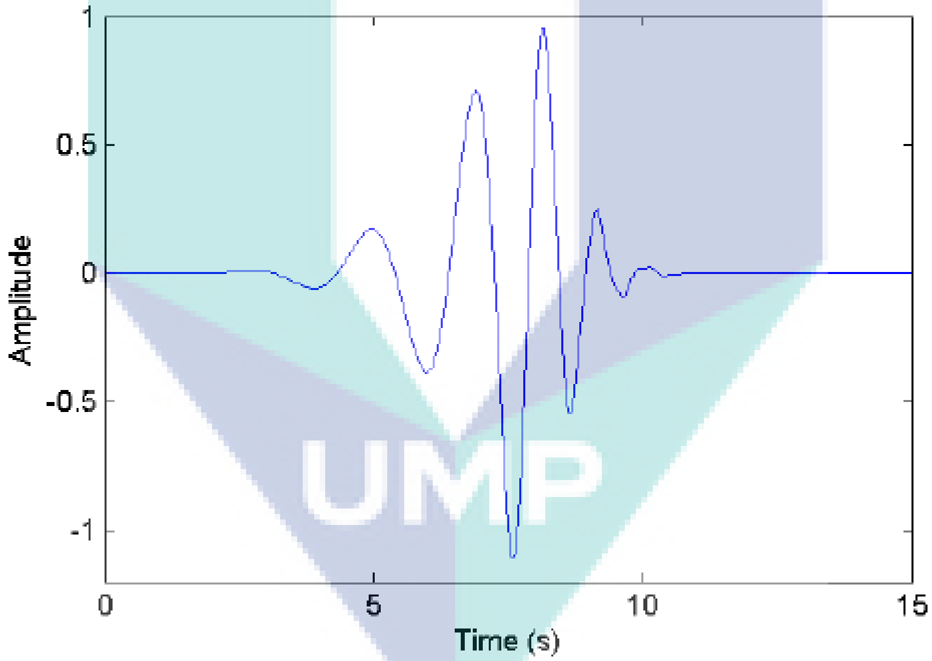


Figure 2.12: Daubechies mother wavelet

In wavelet analysis, the use of a fully scalable modulated window solves the signal-cutting problem. The window is shifted along the signal and for every position, the spectrum is calculated. Then this process is repeated many times with a slightly shorter (or longer) window for every new cycle. In the end the result will be a collection of time-frequency representations of the signal, all with different resolutions. Because of this collection of representations, multi-resolution analysis is performed. In the case of wavelets, it is normally do not speak about time-frequency representations but about time-scale representations, scale being in a way the opposite of frequency, because the term frequency is reserved for the Fourier transform.

Wavelet transform on the other hand is capable of providing time and frequency information simultaneously. For example, let a 1000 Hz signal is analysed, then filter it using high pass and low pass. After that, take the low past frequency and filter it again and repeat the process until no decomposition occur. This process will produce a bunch of signal and represent the same signal which is the 1000 Hz. From the result of decomposition, what frequency band exists at what time is known. However, there is uncertainty principle towards this result.

Uncertainty principle states that, the momentum and position of a moving particle cannot be known simultaneously. Thus, based on the result obtained, it will determine only spectral components to exist at any given time intervals since the frequency and time at certain point cannot be known (Polikar, 1996). Wavelet analysis can be either continuous or discrete. Discrete wavelet is used for signal decomposition and continuous wavelets are used for spectral analysis.

Continuous Wavelet Transform (CWT)

CWT is the alternative to STFT to counter back the resolution problem. CWT is defined as the sum over all time of the signal multiplied by the scaled and shifted versions of the wavelet function ψ. The CWT of a signal *x(t)* is defined as:

$$CWT(a, b) = \int_{-\infty}^{\infty} x(t)\psi^{*}{}_{a,b}(t)dt \tag{2.17}$$

y(t) is the mother wavelet, the asterisk in Eq. (2.17) denotes a complex conjugate, and a,b $\in$ R, $a \neq 0$ (R is a real continuous number system) are the scaling and shifting parameters, respectively. The basis functions are localized in frequency for both Fourier and wavelet transforms.

The most important difference between these transforms is that wavelet functions are localized in time and Fourier basis functions are active all the time. This localization feature, along with wavelets localization of frequency, makes wavelet to be suitable in different applications such as data compression, detecting features in signals and de-noising (Burrus et al., 1998).

Discrete Wavelet Transform (DWT)

CWT is highly redundant and its implementation may consume significant amounts of time and resources since in CWT, the scale and shift factors vary continuously over the full time frequency domains of the analysed signal. DWT has been introduced in order to overcome this deficiency and to speed up the Wavelet transform. In DWT, the scale parameter and translation parameter are no longer continuous but instead are integers. The wavelet functions used in DWT can only be scaled and translated in discrete steps.

Figure 2.13 shows the view based on time domain, frequency domain, STFT and Wavelet. For the time domain graph, the signal only shows the result in time and we loss the hidden knowledge about frequency while it is also a loss to frequency domain when we do not know the time. STFT give extra credit when this method can provide both time and frequency analysis but the resolution become the bigger problem.

As seen in Figure 2.13, STFT is divided into constant size of width and length. The time and frequency resolutions are determined by the width of the analysis window. So, the time frequency plane consists of squares in the STFT method. Compared to wavelet, the low frequency gives better resolution when the width is shorter while when the frequency is higher, the time resolution becomes longer and gives good resolution.

2.6 Hilbert Huang Transform (HHT)

As presented in the previous sub-chapter, non-linear and non-stationary signal cannot be analysed in the best way possible. There are many drawbacks to such method, for example FT needs linear and stationary signal, STFT with the poor resolution, and wavelet need correct selection of mother wavelet and also capturing those signal features which correlate well with the shape of the wavelet function, meanwhile it can ignore the other features.

Huang et al. (1998) recently developed the Hilbert-Huang transform as a new spectral analysis technique. This transformation is especially suited for analyzing non-linear and non-stationary data sequence as we discussed in previous sub-chapter. So far, the wavelet is the best method to analyse non-stationary signal but for low frequency signals, the time localization is poor while for high frequency signals, the frequency resolution is poor. Thus, with the development of HHT, the problem can be solved.

HHT consists of two main components which are empirical mode decomposition

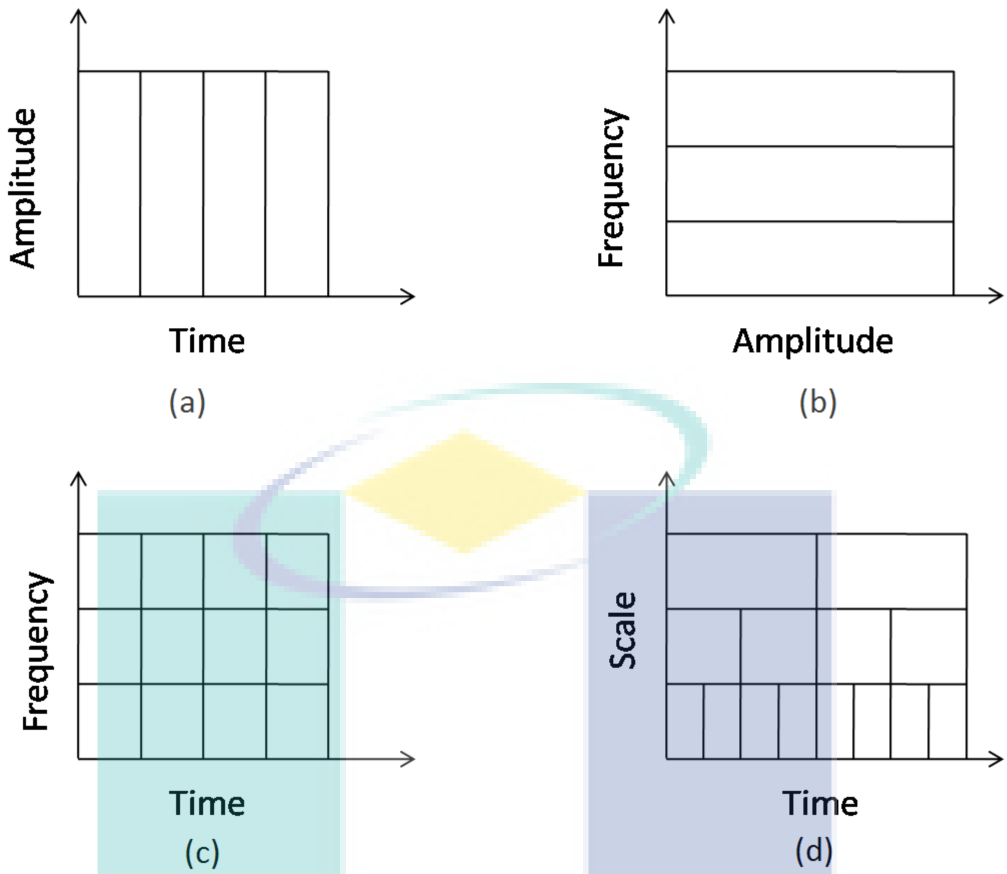


Figure 2.13: (a) Time domain, (b) frequency domain, (c) STFT and (d) wavelet view of signal analysis

Source: Polikar, (1996)

(EMD) and Hilbert transform (HT). This technique decompose any given signal as a set of nearly mono-component signals to a simple mode called as intrinsic mode function (IMFs). Huang et al. (1998) developed an iterative sifting process to extract the IMFs from a given data set. Once the IMFs are extracted, their Hilbert transform can be computed giving meaningful instantaneous frequencies. The process is continued until the residue becomes a monotonous function. The result is displayed by Hilbert spectrum (HS) in energy-time-frequency distribution.

The Hilbert transform can then be used to find the instantaneous frequency. The instantaneous frequency can give only one value at a time. The input signal thus has to be mono-component or narrow band. More than one oscillation will create nonsensical instantaneous frequencies. The data must have symmetric oscillations meaning that it must not have any trends. So a special class of functions is needed to have a meaningful instantaneous frequency.

One way to express the non-stationarity is to find instantaneous frequency and instantaneous amplitude. This was the reason why Hilbert spectrum (HS) analysis was included as a part of HHT. Huang et al. (1998) stated that HS presents the result in energy distribution over time and frequency. After performing Hilbert transform for each IMF, the data can be expressed as follow:

$$x(t) = \sum_{j=1}^{n} a_j(t) exp\left(i \int \omega_j(t) dt\right) \tag{2.18}$$

Various types of presentation can be made such as colour coded maps and the contour maps all with or without smoothing.

2.6.1 Empirical Mode Decomposition (EMD)

EMD algorithm attempts to decompose any signal into a finite set of functions and transform them into physical instantaneous frequency values. These functions are called intrinsic mode functions (IMFs). The algorithm utilized iterative sifting process which can subtract the local mean from a signal. Each IMF must fullfill two conditions as discussed by Huang et al. (1998):

1. Symmetric wave profile condition: for the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one; and

2. At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

Both condition have their own judgement. The first condition follows the Gaussian process which means that it is a requirement for narrow-band condition. It is to ensure the local maxima is always positive and local minima is always negative, respectively. The second condition modifies a global requirement to a local one, and is necessary to ensure that the instantaneous frequency will not have unwanted fluctuations arising from asymmetric waveforms.

The sifting process is a method to identify the IMF by their characteristics in time and scale based on the data given, and decompose data without involving predefined function or time window size. The sifting process can be compressed as follows:

1. Determine the minimum and maximum (local extreme) of the signal, x(t) and connect them by cubic spline to form the upper and lower envelope.

2. Calculate the mean, m(t) as half of the between the upper and lower envelopes.

3. Subtract the local mean from the signal, d(t) as an IMF, *d(t)=x(t)-m(t)*.

4. Repeat the process of iteration on the residual m(t) until the residual is too small and represent the trend.

This process is repeated happen until the final residue is a monotomic function. The last extracted IMF is the lowest component of the signal. Figures 2.14 to 2.18 show the plotted IMF as illustrated by Huang et al. (1998). Basically, IMF can have variable amplitude and frequency as a function of time to represent a simple oscillatory mode. The sifting process is useful for two things; a) to eliminate the riding waves and b) to make signal profiles more symmetric. Figure 2.14 presents the raw data of test which include non-linear and non-stationary signal.

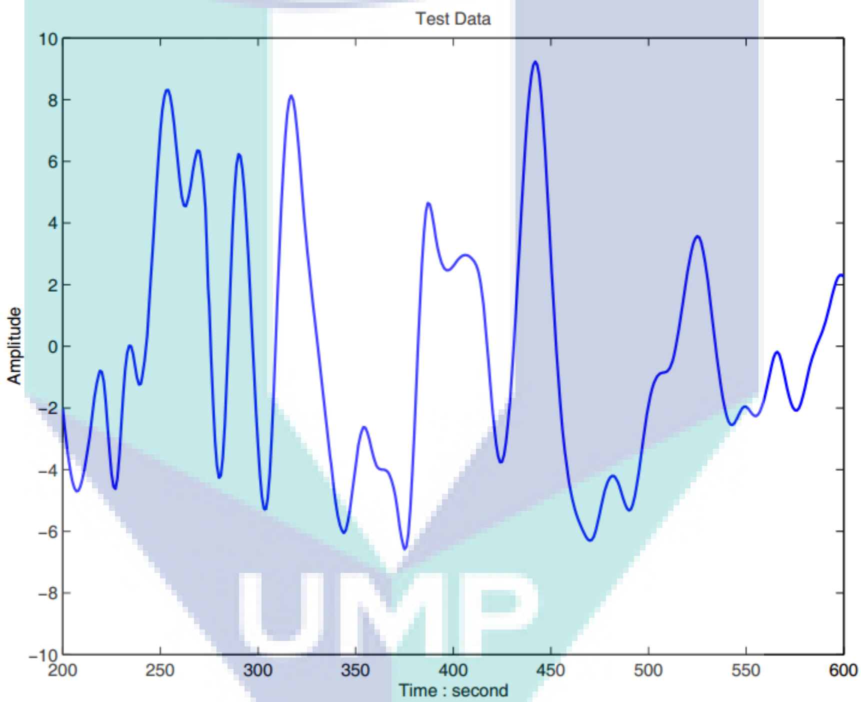


Figure 2.14: The test data

Source: Huang et al., (1998)

The mean, m_1 as shown in Figure 2.15 designated with the h_1 is the first component of IMF. The upper and lower envelope should cover all of the data as mentioned in the sifting process previously. The result of h_1 with comparison to test data shows in Figure 2.16.

$$h_1 = x(t) - m_1 \tag{2.19}$$

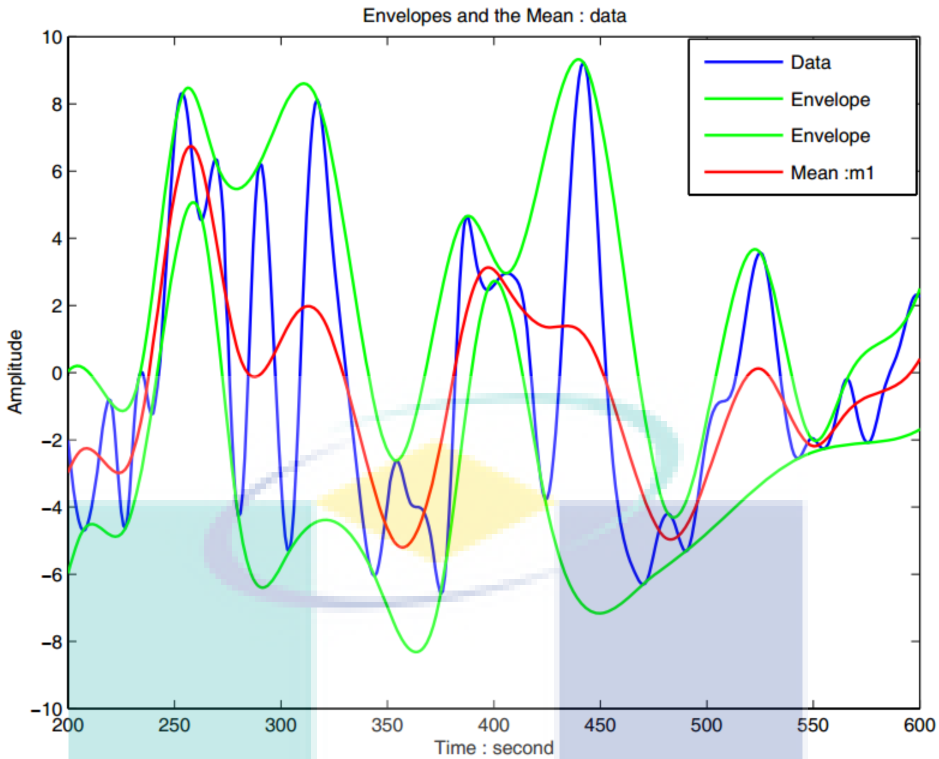


Figure 2.15: The local maxima and minima used to develop upper and lower envelope (green), mean data (red) based on test data (blue)

Source: Huang et al., (1998)

The new extrema produced in each h and the sifting process has been repeated as many time possible to reduce the extracted signal into an IMF. In fact, with repeated siftings, the sifting process can recover signals representing low-amplitude riding waves.

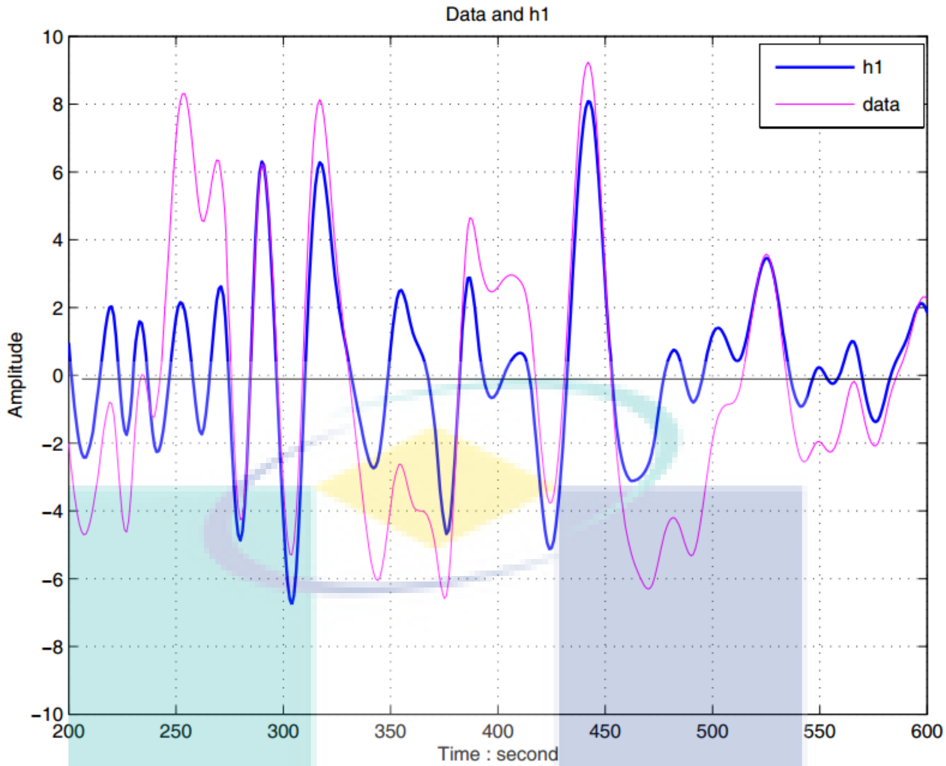


Figure 2.16: The test data (pink) compared to h1 (blue)

Source: Huang et al., (1998)

Figure 2.17 shows repeated data used to get the first IMF. The test data becomes h_1, and after sifting, h_1 became new data designated as h_2. This step treated as the data:

$$h_{11} = h_1 - m_{11} \tag{2.20}$$

The process is repeated up to k times, and h_{1k} becomes an IMF;

$$h_{1k} = h_{1(k-1)} - m_{1k} \tag{2.21}$$

and the first IMF c_1 as shown in Figure 2.18 is defined as:

$$c_1 = h_{1k} \tag{2.22}$$

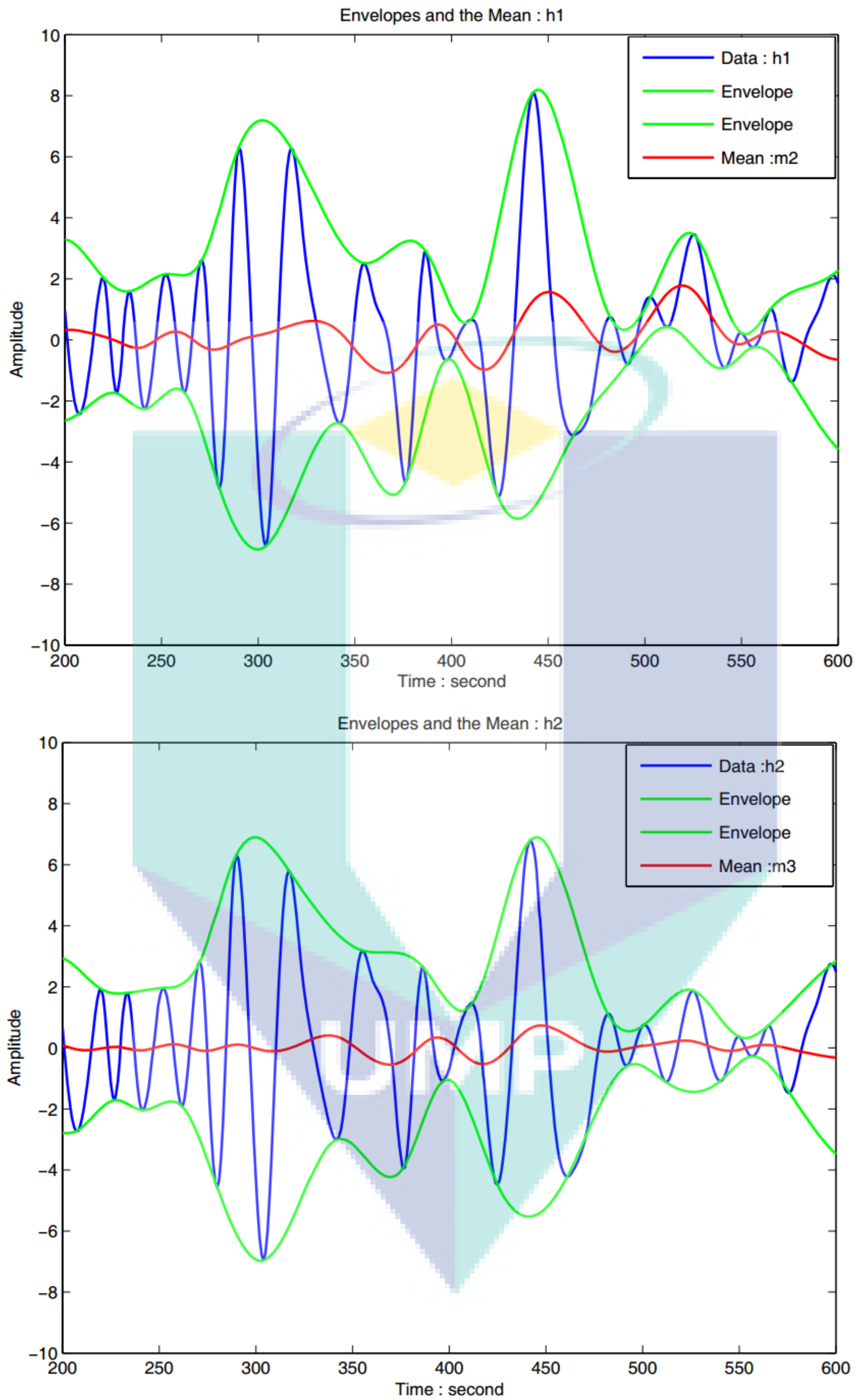


Figure 2.17: Repeating sifting steps with h1 and m2 (top) and repeated sifting steps with h2 and m3 (bottom)

Source: Huang et al., (1998)

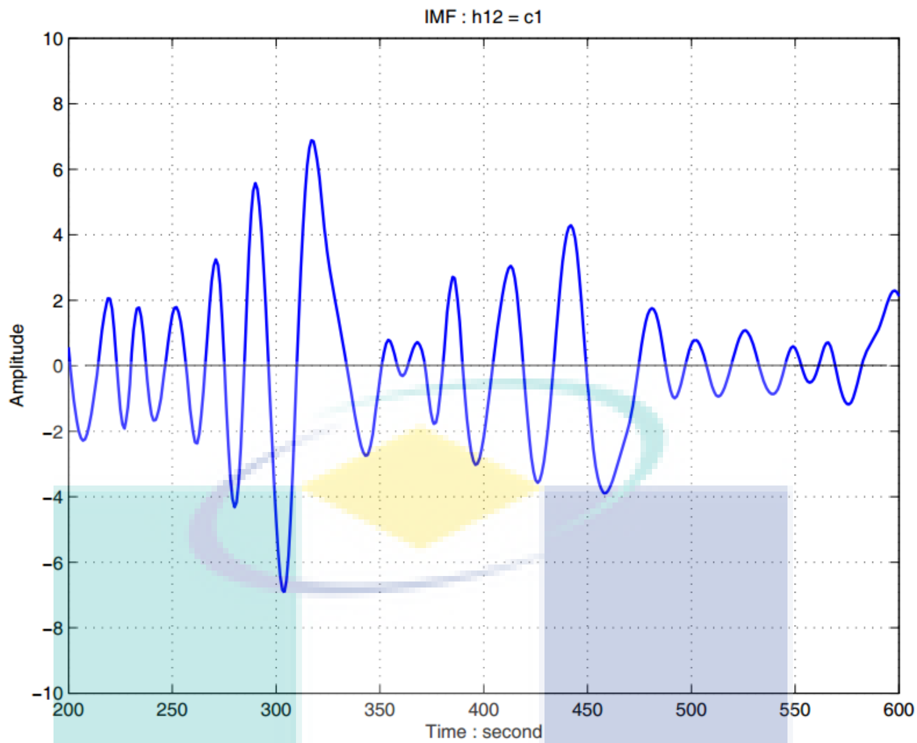


Figure 2.18: The first IMF, c_1 after 12 steps

Source: Huang et al., (1998)

2.6.1 *Stopping Criterion*

The most appropriate and common stopping criteria are designed to avoid over iterating. The selected stoppage criterion is defined as follows:

$$SD = \sum_{t=0}^{T} \left[\frac{\left| h_{1(k-1)}(t) - h_{1k}(t) \right|^2}{h^2_{1(k-1)}(t)} \right] \tag{2.23}$$

A typical value for sum of difference (SD) can be set between 0.2 and 0.3 as suggested by Huang et al. (1998). The sifting process should be stopped when the number of zero crossings is equal to, or differs by at most one from the number of extrema for S successive siftings steps. According to an empirical guide (Huang et al., 2003), the range of S-number was found to be between 3 and 5.

After the sifting process, c_1 can be separated using below equation, while r_1 will be treated as new signal and repeated sifting process take place.

$$X(t) - c_1 = r_1 \tag{2.24}$$

$$r_1 - c_2 = r_2, ..., r_{n-1} - c_n = r_n \tag{2.25}$$

The sifting process can be stopped by any of the following predetermined criteria: either when the component, c_n, or the residue, r_n, becomes so small that it is less than the predetermined value of substantial consequence, or when the residue, r_n, becomes a monotonic function from which no more IMF can be extracted. Even for data with zero mean, the final residue can still be different from zero; for data with a trend, the final residue should be that trend. By summing up Eqs. (2.24) and (2.25), we finally obtain:

$$X(t) = \sum_{i=1}^{n} c_i + r_n \tag{2.26}$$

A flow diagram of EMD process shows in Figure 2.19 and the signal is completely decomposed with the last residue, ideally does not contain any extrema points. This means that it is either a constant or a monotonic function.

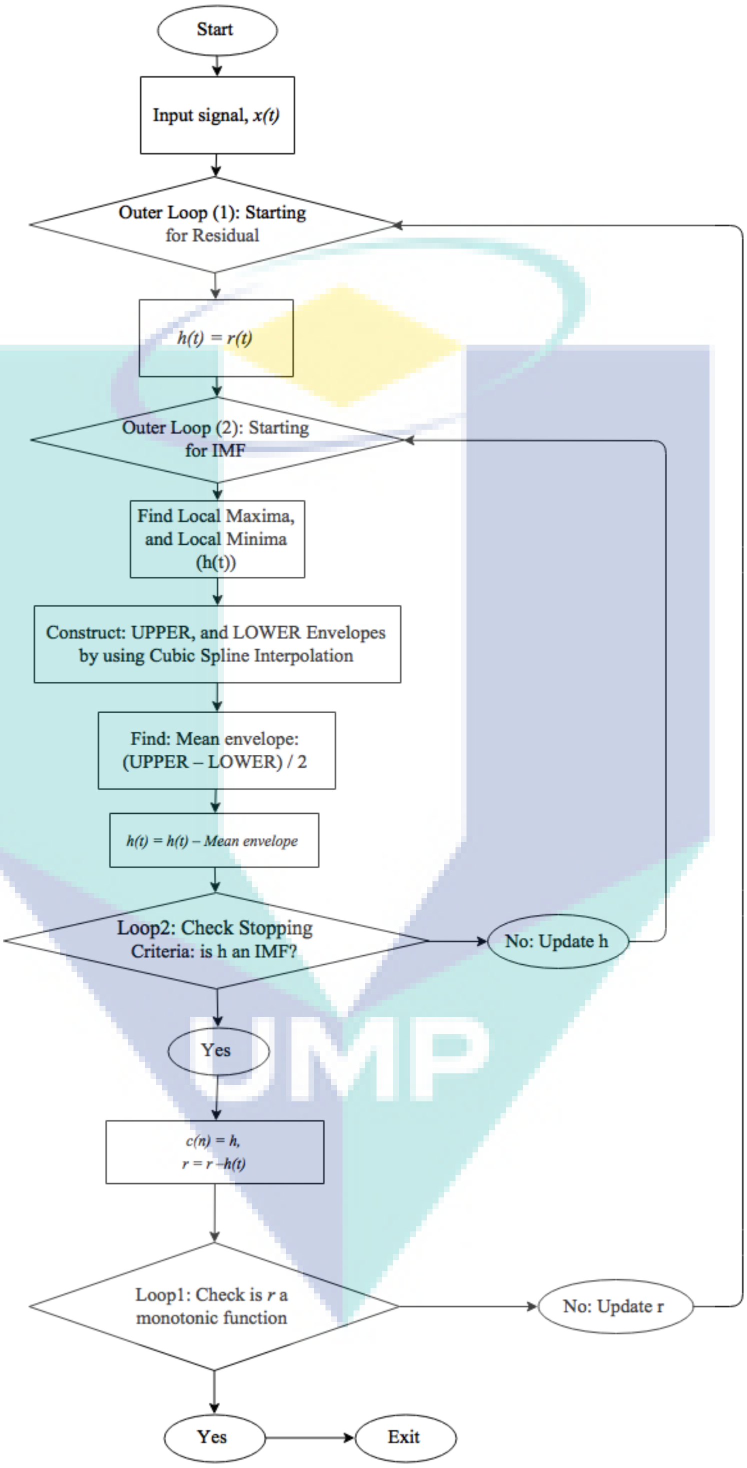


Figure 2.19: Flowchart EMD

2.6.2 Ensemble Empirical Mode Decomposition (EEMD)

In EMD, the sifting process can only extract IMFs which differ in frequency by more than factors of 2. This situation is called as dyadic filter, so that this problem contribute to mix-mode problem (Flandrin and Goncalves, 2004). Mode missing occurs when two or more different modes of oscillation appear in a single IMF. The highest frequency and lowest frequency components of the signal clearly belong to different modes of oscillation but in mode mixing they are spread over all extracted IMFs. Mode mixing not only causes serious aliasing in any subsequent IMFs, but can cause individual IMFs to be devoid of physical meaning (Huang and Wu, 2008; Wu and Huang, 2009).

The added white noise will occupy the entire time frequency space and the different parts of the signal will automatically be projected onto proper scales of reference established by the white noise, thus eliminating mode mixing.The individual IMFs are, of course, very noisy but the ensemble mean of a number of corresponding IMFs will leave only the signal, as a collection of white noise cancels each other out in a time space ensemble mean (Wu and Huang, 2004). However, adding more noise to already contaminated signals will not produce cleaner results. The realization of the original contaminated noise remains the same over all trials and therefore cannot be eliminated through averaging.

To overcome the mode mixing problem, a new noise assisted analysis method, called ensemble empirical mode decomposition (EEMD), was adopted instead of EMD, as proposed by Wu and Huang (2009):

1. Add finite amplitude noise to the original signal.
2. Decompose signal into a finite set of IMFs using the EMD sifting method described previously.
3. Repeat steps 1 and 2 with different noise data sets.
4. Average the ensemble of extracted IMFs to average out the noise and obtain mean IMFs.

2.6.3 Hilbert transform (HT)

Hilbert transform of *x(t)* produces time-domain signal. Eq. (2.27) displays the Hilbert transform *y(t)* which also can be written for any function of *x(t)*.

$$H[x(t)] = y(t) = \frac{PV}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \tag{2.27}$$

PV denotes as Cauchys principle value of the integral. Byron and Fuller (2012) determined that an analytical function can be formed with the HT pair, *z(t)* and *y(t)* as shown in Eq. (2.28).

$$z(t) = x(t) + iy(t) = a(t)e^{i\theta(t)} \tag{2.28}$$

where $a(t)$ is the instantaneous amplitude equals to:

$$a(t) = \sqrt{x^2(t) + y^2(t)} \tag{2.29}$$

and $\theta(t)$ is a phase function of the z(t):

$$\theta(t) = arctan(\frac{y(t)}{x(t)}) \tag{2.30}$$

The instantaneous frequency can then be written as the time derivative of the phase, as shown in Eqs. (2.31) and (2.32). Note that the analytic function *z(t)* is the mathematical approximation to the original signal *x(t)*.

$$\omega = \frac{d\theta(t)}{dt} \tag{2.31}$$

$$f = (1/2\pi)\frac{d\theta}{dt} \tag{2.32}$$

One advantage obtained with the representation in Eq. (2.32) is that frequency can be determined at any given time *t*, since frequency can be calculated by differentiating the phase angle with respect to time as described by Huang and Attoh-Okine (2005). The Hilbert transform forms the basis of the definition of an analytical signal and provides a unique way of defining the imaginary part so that the result is an analytic function.

Fourier transform (FT) seems to be limited compared to the wavelet and the HHT in the analysis of non-linear and non-stationary signals. The wavelet transform has been the best available non-stationary data analysis before the introduction of the Hilbert-Huang transform. However, the analysis of the signal has proven that the HHT offers a better time and frequency resolutions than wavelet transform and allows a better physical interpretation of the signal content. The Hilbert-Huang transform turns out to be a new revolutionary nonlinear and non-stationary signal data analysis method.

The combination of the ensemble empirical mode decomposition (EEMD) and the associated Hilbert spectrum (HS) has proven to be versatile and robust in analysis of non-linear and non-stationary data. Table 2.2 presents the comparison between three transform which are FT, WT, and HT. The application of the Hilbert transform on the extracted IMFs allows the creation of an energy-time-frequency representation, the Hilbert-Huang spectrum, characterized by a high time and frequency resolutions. It is the first local and adaptive method in time-frequency analysis. Therefore, Hilbert transform seems to be the favourite candidate among available spectral analysis tools.

Table 2.2
Comparison between FT, WT and HT

Type	**Fourier Transform**	**Wavelet Transform**	**Hilbert Transform**
Basis	A prior	A prior	An adaptive
Frequency	Integral transform: Global	Integral transform: Regional	Integral transform: Local
Presentation	Energy-Frequency	Energy-Time-Frequency	Energy-Time-Frequency
Non-linear	No	No	Yes
Non-stationary	No	Yes	Yes
Uncertainty	Yes	Yes	No
Harmonics	Yes	Yes	No

2.7 Summary

The study of leak detection in this chapter have covered the type of techniques commonly used in gas pipeline. Acoustic is one of the method that is recently developed because of their fast detection time and accurate localization. Other than that, this chapter presents the basic concepts associated with propagation of wave. The reflection caused by disturbance may be due any features or leak itself. The reflection of the wave was analysed using signal processing technique such as FFT, STFT, WT or HHT. However, the accurate leak location can only be determined using advance signal processing such as HHT, with improvement via decomposition method by EEMD. With knowledge of speed of sound, the leak can be identified and localized. Hence, K-chart below (see Figure 2.20) shows the research approach and the gap of this research.

Based on this figure, the detection is divided into two major working fluid which are liquid and gas. The study is meant to perform research in gas pipeline in both type of features which are the junction and straight pipeline. This research seeks to compare the outcome obtained from both of them. For experimental work, the hole-leak type is chosen.

There are three type of sensor usually used in this experiment. However, microphone is chosen over the dynamic pressure transducer or acoustic emission. The selection of sinusoidal wave is better chirp signal for obtaining the result in time-frequency analysis. Wavelet, STFT and HHT are the analyzer used for comparison purpose before EEMD is chose as type of decomposition method in order to detect, localize and identify the leak.

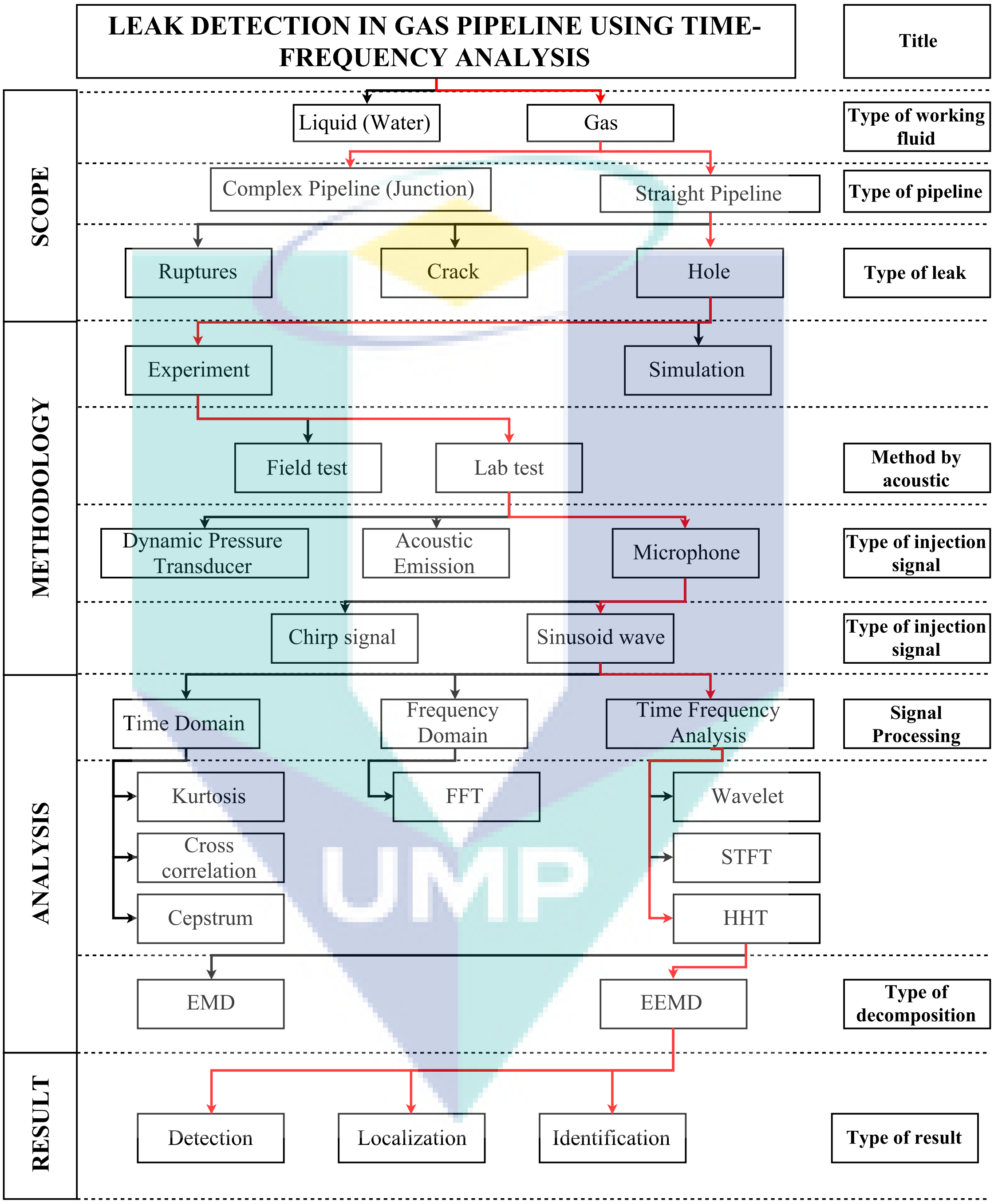


Figure 2.20: K-chart of research approached

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will discuss on the research flow chart and also the pipe materials used in this experiment. The material used in this experiment are Polyvinyl Chloride (PVC), Medium-Density Polyethylene (MDPE) and Galvanized Iron (GI) pipes. The next issue that will be discussed is on sensor overview and characteristics, characteristics of instrumentation (speaker) used, and both software and hardware data acquisition (DAQ). All data collected will then be discussed. The procedures used to conduct the experiment is explained and shown using various illustrations. Some numerical simulation were done on the synthetic data using Fast Fourier transform (FFT), Short Time Fourier transform (STFT), Wavelet transform (WT) and Hilbert Huang transform (HHT) to validate the algorithm.

3.2 Flow Chart

To achieve the objectives of the project, flow chart of methodologies used were drawn for as a guide in ensuring that this project is in the correct direction and becomes successful. Figure 3.1 shows the flow chart of this project. This project was carried out strictly according to the flow chart to ensure the project's efficiency and effectiveness.

In this study, the experiment is conducted using three type of materials: PVC, MDPE and GI. PVC is normally used by previous researchers to study acoustic leak detection (Urbanek et al., 2012; Yunus et al., 2008; Papadopoulou et al., 2008). The test rig model setup involved the connection of a compressor (fan) to direct gas flow into the pipeline. For the pre-limininary study, the frequency of sound injection is selected based on performance displayed by the Hilbert spectrum (HS). This study is analysed by using

Hilbert-Huang transform (HHT). 100 Hz, 500 Hz, 1000 Hz, and 2000 Hz of sinusoid wave is injected into the PVC pipeline. And the result of suitable frequency is applied for other experiments.

After the suitable sound frequencies have been determined, the experiment starts with data collection for all three materials used. At this stage, data for each material is collected using Dasylab with special worksheet in order to obtain the best signal. The data is decomposed using EEMD, and then the selection of IMFs is gathered and analysed using HT. These elements are important to obtain sharp resolution and accurate leak location. The final result is presented in HS to show energy-time-frequency distribution. The leak location is summarized into a table and percentage error is calculated to show the successful distance achieved.

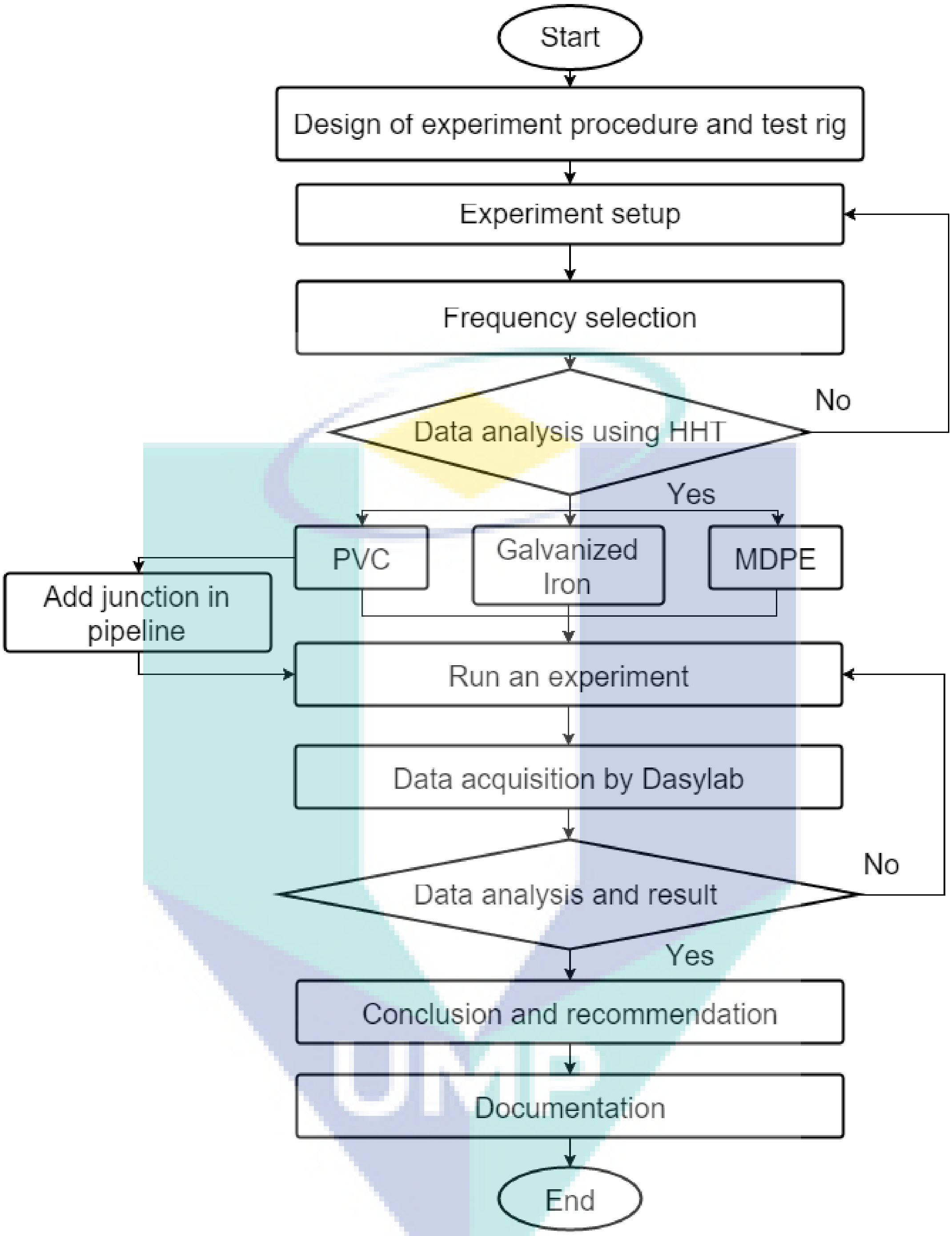


Figure 3.1: Flowchart of research study

3.3 Pipe Material

Several different materials were used in this study in order to observe the level of difficulties of signal obtainment. MDPE is considered as soft material which can absorb high frequency sound injection, whereas PVC stood in the average level. GI pipe is considered as hard material, and expected to produce high signal noise because of the low sound absorption of this material. In the industry, the most commonly pipe is steel, PVC is used for laboratory purpose and MDPE is also used for low gas pipeline (Majid and Mohsin, 2012).

3.3.1 Medium-Density Polyethylene (MDPE)

MDPE pipe is widely used in gas distribution system and also fittings, sacks, shrink film, packaging film, carrier bags, and screw closures (Ghazali et al., 2012). They are easy to handle and fold around. The corrosion resistance is tough and highly reliable even in aggressive soils. Because of their light weight, this makes it much easier to load, transport, handle and install. It has excellent resistance to subsidence, traffic vibrations, point leading, marshy ground to UV rays and also UV stability.

3.3.2 Polyvinyl Chloride (PVC)

PVC is one of most widely produced synthetic plastic polymer and they come in two forms which are rigid and flexible. The rigid form of PVC is often used in the pipe construction (Papadopoulou et al., 2008). PVC is often chosen as the piping material because of its lightweight quality, low cost and also requires minimum maintenance.

3.3.3 Galvanized Iron (GI)

Galvanized iron pipe are widely used in water or gas pipeline network especially for long distance. The term galvanized comes from the zinc coating used for the pipe. The barrier and galvanic protection is used in order to prevent corrosion from occurring. Galvanized pipes are widely used to convey natural water due to Zn coatings that are normally very corrosion resistant to natural waters. This material is categorized as a hard material which has the ability to absorb only a small portion of the energy of the wave traveled in it. This presents an advantage to the sensor used since it could detect a large portion of the wave reflected from the leak point.

In this project, these three materials were used for the experiment to compare the different result in HHT. The specification of MDPE, PVC and GI pipe is shown in

Appendix A. Different type of material is depends on their absorption rate. Hence, the different result will obtain in this project.

3.4 Instrumentations Characteristic

For accurate leak detection, a microphone with high accuracy was used. The reflection signal is collected by this sensor in the pipeline before data acquired by Dasylab. The characteristics of this microphone will be discussed in this sub-chapter.

3.4.1 Microphone

The microphone that was used in our experiments is a PCB Piezoeletronics with model number 378B20 as shown in Figure 3.2. This specific model is a small sized and high sensitivity transducer for making absolute sound measurements over the frequency range of 7 Hz to 6300 Hz at 1 dB and 3.15 Hz to 12500 Hz at 2 dB. This microphone is suitable to use for low ranged frequency and compatible for this experiment since the sound injection tested vary from 100 Hz to 2000 Hz. The sensitivity of this microphone is 47.89 mV/Pa.

Other than the sensor, others instrumentations were also used in this experiment in order to acquire data and drive the signal to the host PC and store it before post processing was done. These instruments will be discussed in this section.

3.4.2 Speaker

The speaker used in this project is a multimedia speaker system. It is a portable speaker which uses the latest ABS engineering plastic material. It uses USB interface and fully supports the Windows operating system. Figure 3.3 shows the speaker used in this experiment. The specifications of the speaker are as in Table 3.1.

Table 3.1
Multimedia Speaker System specifications

Properties	**Value**
Frequency Response	90 Hz - 20 KHz
Rated power	4 x 3W
Signal to Noise Ratio (SNR)	$\geq$ 85 dB
Size measurement	150 x 83 x 75 mm

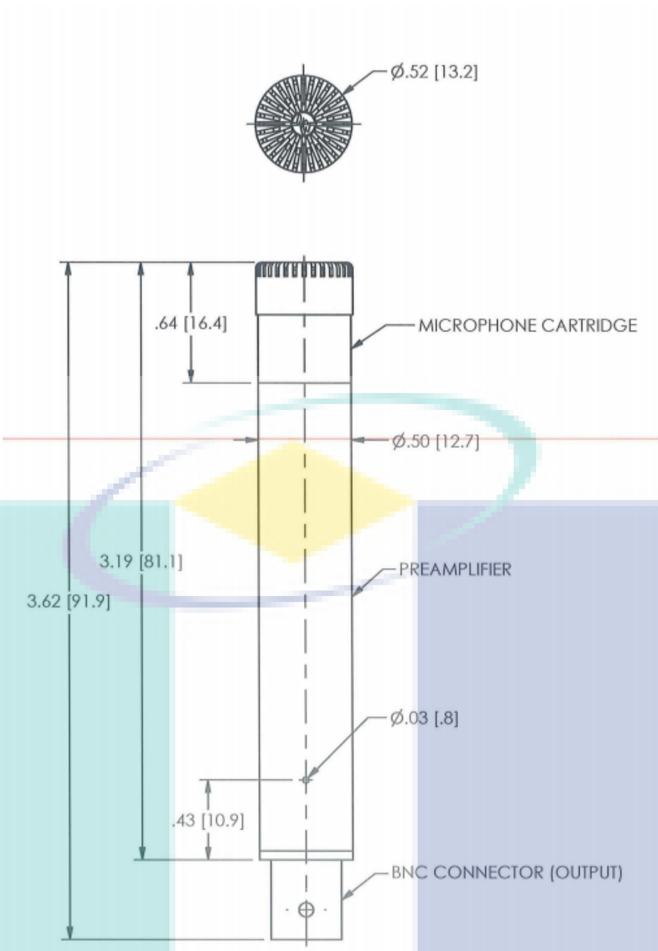


Figure 3.2: Microphone schematic diagram

Source: *www.pcb.com*

Figure 3.3: Speaker used in this experiment

3.4.3 Data Acquisition (DAQ) Hardware

The data acquisition hardware that is used in this project will be discussed in this section. For DAQ purpose, the signal is driven to a *National Instruments* USB-4331, 51.2 kHz maximum sampling rate and 24 bit analog input. This device works together with Dasylab software.

The USB-4331 delivers 100 dB of dynamic range signal conditioning for accelerometers and microphone which consists of four analog input channels with a single analog output as shown in Figure 3.4. The entire analog input channel simultaneously acquire data at rates from 2 to 102.4 kS/s. The channel also include anti-aliasing filters that automatically adjust the sampling rate which is suitable for any application of frequency response audio test.

Figure 3.4: All four analog input channels and the single analog output

The *National Instruments* is completed by NI-DAQmx as the hardware driver. The interface of NI-DAQmx is shown in Figure 3.5 below. The configuration is set based on the input and output of the experiment. The sensitivity is set based on the specifications for the transducer which is the microphone. Sound pressure is used as analog input. Sampling was performed simultaneously across the sound pressure channel at 51.2 kHz, the highest rate for analog output channel, to minimize discretization error.

3.4.4 Data Acquisition (DAQ) Software

The DAQ software that was used in this experiment is DASYLab which works with NI-DAQmx device as shown in Figure 3.6 and their description in Table 3.2. DASYLab is a powerful monitoring and control application that does not require any programming to be done. It offers real-time analysis, control and the ability to create custom

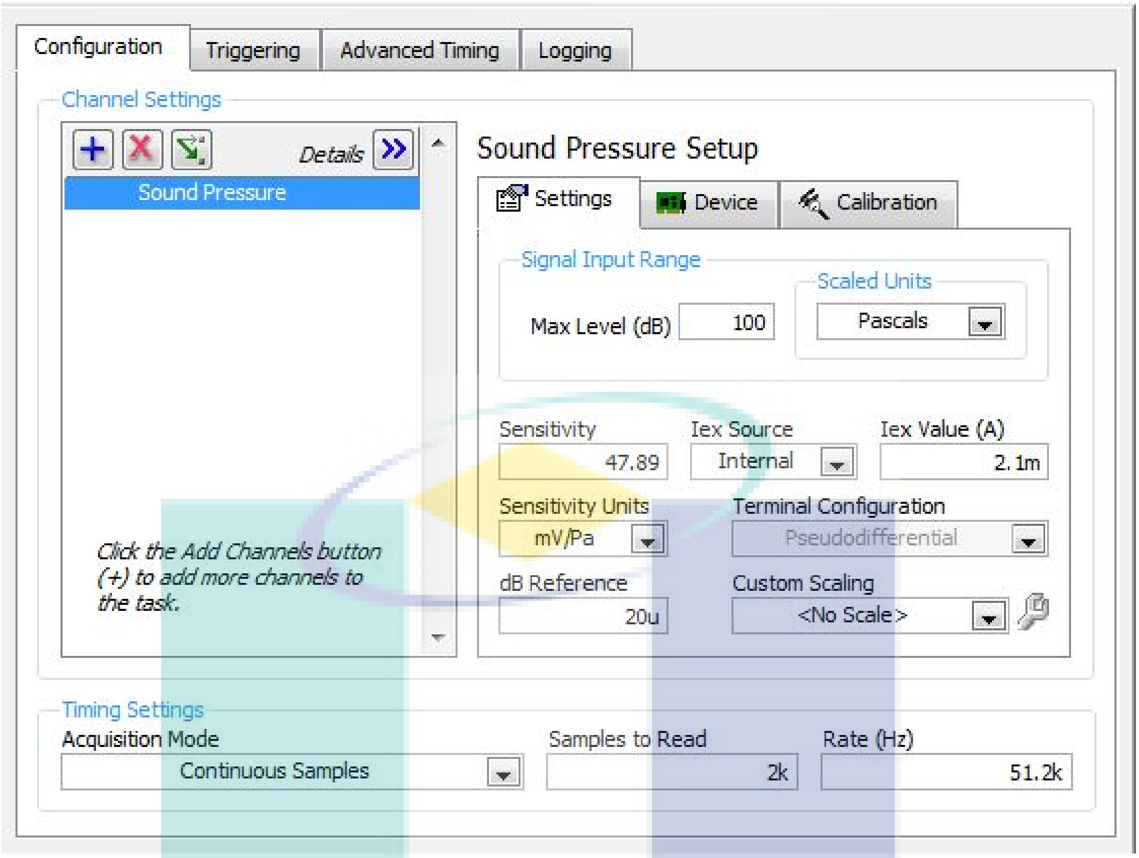


Figure 3.5: NI-DAQmx interface

graphical user interface with wide range of options. This software also offers modules to perform Fast Fourier transforms (FFT), digital filtering, logical operations, etc.

Table 3.2
Description of functional icons during data acquisition process

Feature	Description
Task DAQ	Analog input with sampling rate of 20 kHz
Data trigger	Trigger on absolute value; within the limits. Thus, specifies the upper lower limit and pre/post trigger data
Relay	Control channel with one input signal.
FFT	Calculate and analyse the discrete spectrum of a signal.
Y/t chart	High-speed scope display for fast data with a wide range of display options.
Write data	Write data to floppy/hard disk files; supports DASYLab, IEEE-32-bit, ASCII, Diadem and other formats.

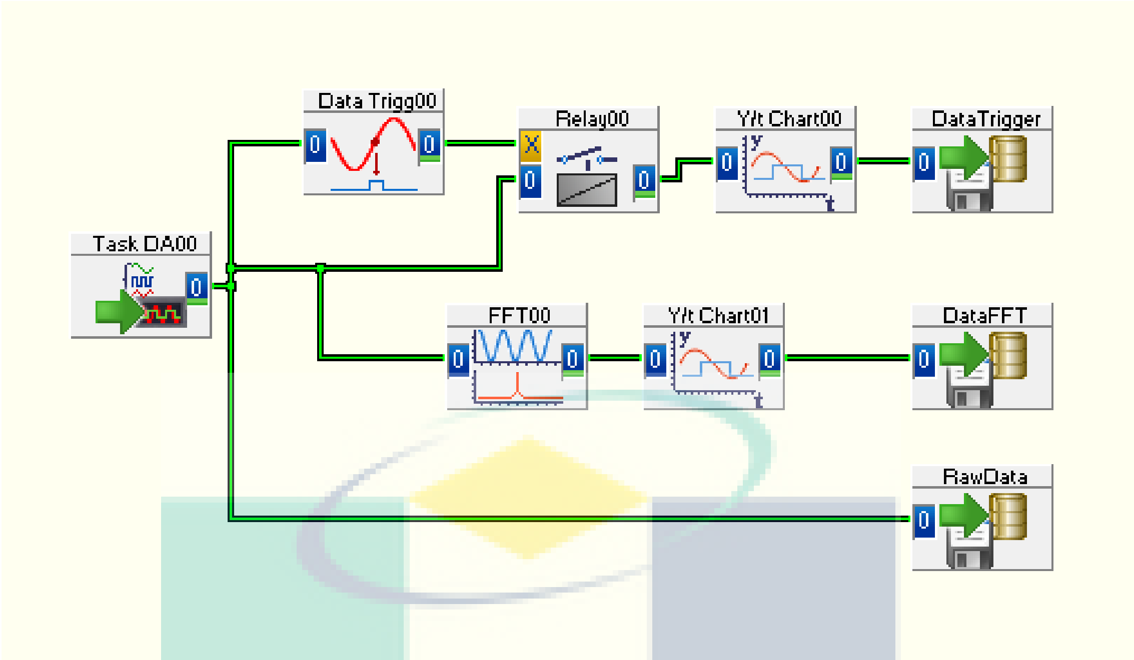


Figure 3.6: DASYlab interface

3.5 Experimental Setup Overview

The schematic diagram of the experiment setup is shown in Figure 3.7. It consists a pipeline with same diameter of 2 inches and a fan to blow the medium along the pipeline. In order to simulate a leak, a small circular hole with 10 mm diameter was drilled 4 meter from the inlet as shown in the red circle in Figure 3.7. Urbanek et al. (2012) studied that different size of hole contribute to the different results of amplitude. The peak of amplitude increase significantly with the size of the hole while the amplitude is decrease with the distance from the hole due to the damping in the analyzed medium.

The same setup is used for different materials as mentioned before. However, further investigation involving L-bend pipe was done by on PVC pipe only. The PVC pipeline was added with an L-bend pipe as its additional feature as shown in Figure 3.8. The length of PVC pipe is 5.8 meter, after the additional of 1 meter of L-bend, the total length is 6.8 meter. For significant test, three times of data collection is repeated and validated by t-Test statistical analysis. The p-value is 0.0043 which is good for the data consistency.

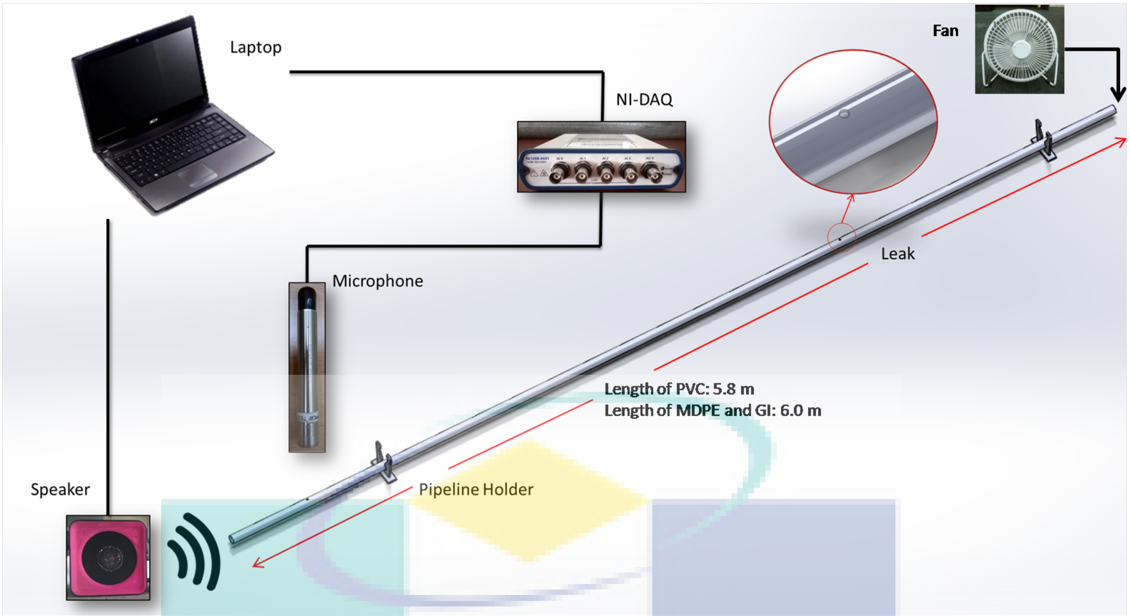


Figure 3.7: Schematic diagram of pipeline experiment.

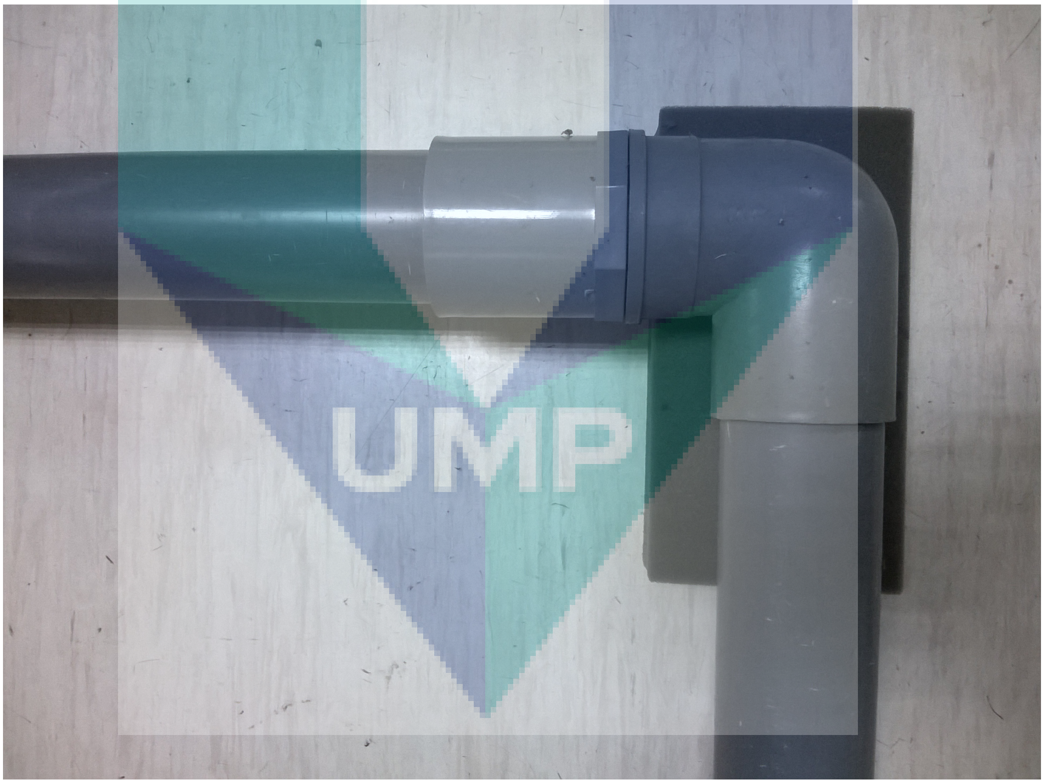


Figure 3.8: L-bend attached to the PVC pipe

3.5.1 Signal Acquisition

Basically, gas pipeline system contains high pressure flow. However, in this case, the study was concentrated to low pressurised pipeline. Low pressurised condition was created by a fan and sine wave was injected through a speaker that was connected to the laptop in order to amplify the sound. To measure the sound pressure signal, a microphone is installed at the beginning of the pipeline as shown in Figure 3.9.

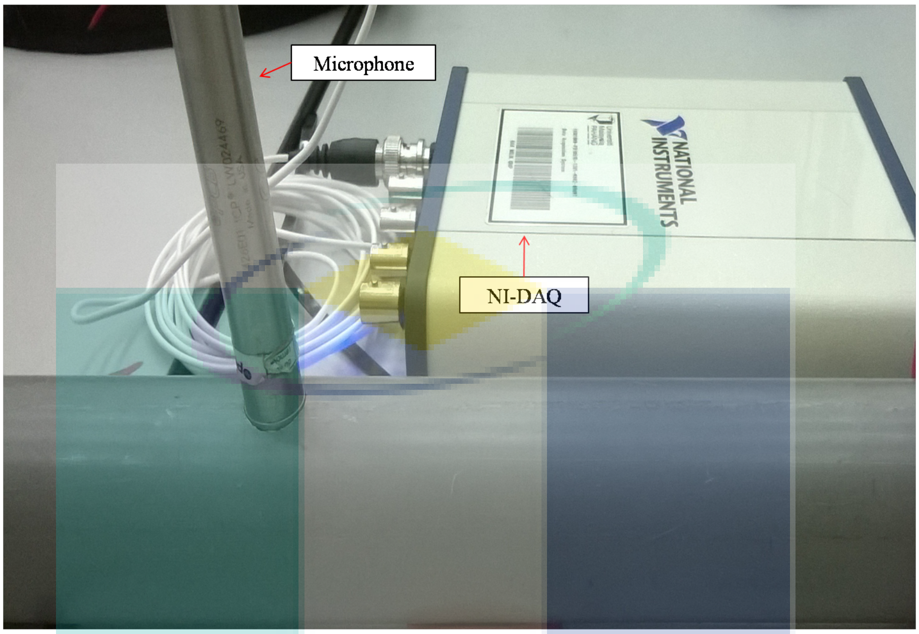


Figure 3.9: Microphone attached to pipe

In the experiment, the microphone was connected to the *National Instruments* USB-4331 as the input source while the output was connected to a personal computer to acquire the data using DASYLab. The personal computer is also connected to the speaker to amplify the sound of selected frequency. The preliminary study was conducted to investigate the suitable frequency to be used in the experiment and discussed in Section 4.2.

3.5.2 Calibration Speed of Sound

As the temperature room is maintained at 29 °C, the speed of sound can be determined. Using Eq. (3.1), the speed of sound is 348.6 m/s. To be precise on this number, a calibration is conducted to ensure the exact speed of sound. Experiments were conducted at a low pressurized and to get the accurate location of the leak, the wave speed of the pipeline had been calibrated by measuring the time taken for generated sine wave to travel from the inlet to the boundary of the pipeline and back to the measurement point. The calculation is shown as follows (Papadopoulou et al., 2008):

$$c = \frac{2s}{t} \tag{3.1}$$

where;

s	=	distance (m)
c	=	speed of sound (m/s)
t	=	time (s)

The Leak Location Error equation (LLE) is as shown in Eq. (3.2).

$$LLE = (\frac{AD - MD}{MD}) \times 100\% \tag{3.2}$$

where;

AD	=	Analysed distance
MD	=	Measured distance

At the distance of 5.8 m, and t = 0.0332 s as shown in Figure 3.10, the speed of sound was calculated as 349 m/s. This speed of sound is applicable for all pipe material including PVC, MDPE and GI. Summary of experiment specifications is presented in Table 3.3.

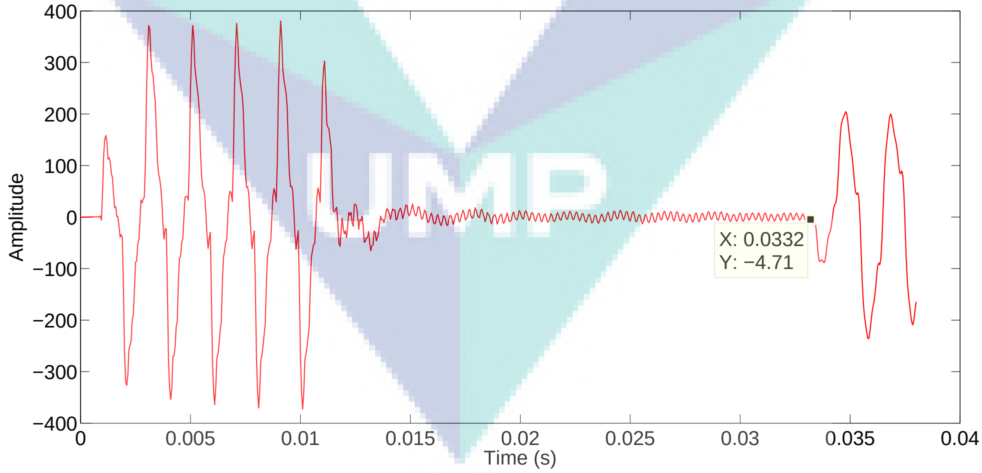


Figure 3.10: Data of signal during calibration

Table 3.3
Experimental specification

Feature	Description
Material	PVC, MDPE and GI
Speed of sound	349 m/s
Sampling rate	20 kHz
Block size	8192 Hz
Duration of sound injection	0.01 s
Frequency of sound injection	500 Hz
Diameter of pipeline	2 ”
Length of pipeline	PVC (5.8 m), MDPE and GI (6.0 m)
Hole diameter	10 mm
Pipe thickness	PVC (1.8 mm), MDPE (6.3 mm) and GI (4.1 mm)

3.5.3 Experimental Procedure

Experimental procedure for all materials conducting in this study is as follow:

1. The pipe is setup in as Figure 3.7.
2. The leak on the pipe is closed.
3. Sine wave is injected into the pipe through the speaker connected at the inlet of the pipe.
4. The transmission and reflection of the sine wave measured by microphone as the sensor and collected by Dasylab software.
5. Step 3 and 4 is repeated twice.
6. The data stored in the Dasylab is analysed using Matlab software.
7. The experiment is repeated with hole to simulate leak.

3.6 Numerical Simulation to Test Algorithm

In order to show the efficiency of the ensemble empirical mode decomposition (EEMD) and Hilbert transform (HT) techniques, a simple relevant signal is validated. Consider a simple sine wave with two frequencies and presence of impulse at certain time. The impulse represents the irregularity in the signal which can be considered as the reflection of the leaks or feature in the pipeline system. The HHT was tested by using synthetic data to validate the algorithm. The signal with different frequency and amplitude is defined by Eq. (3.3).

$$x(t) = 5sin(2f_1t) \quad when \quad 0 < t \leq 1.0s$$
$$x(t) = 10sin(2f_2t) \quad when \quad 1 < t \leq 2.0s \tag{3.3}$$

where f_1 is equal to 20 Hz and f_2 is 30 Hz. Both signals were combined with impulse at two places which are at 0.4 s and 1.6 s as shown in Figure 3.11. At 1.0 s, the amplitude is increased and as well as the frequency. Other than that, the changes of amplitude represent the reflection of repetition by the signal when the sound signal is injected.

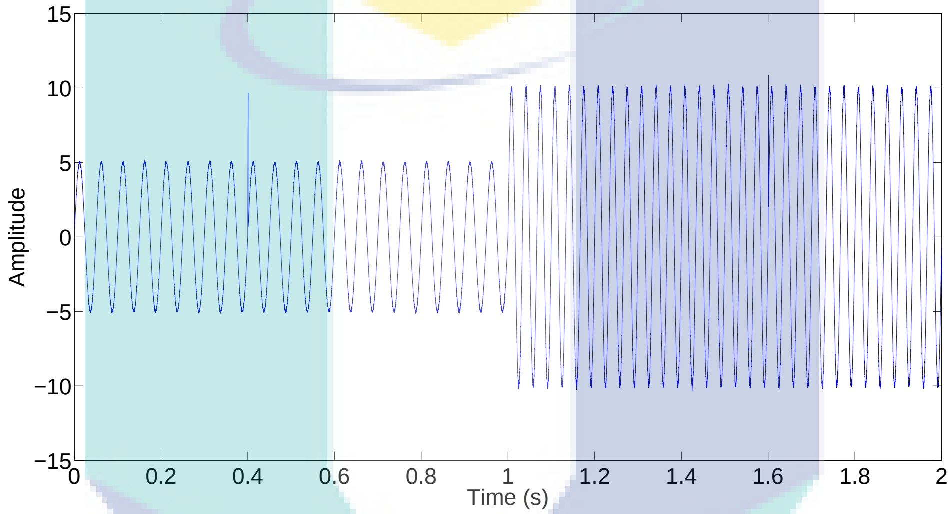


Figure 3.11: Time domain of the synthetic 20 Hz and 30 Hz signal

This signal has been selected in order to show the ability of the EEMD and EMD to separate the different frequency components as well as to identify the irregularities present in the signal. From Figure 3.12, both frequencies can be clearly seen in the frequency domain based on signal present in time domain as shown in Figure 3.11 previously.

3.6.1 Empirical Mode Decomposition (EMD) and Ensemble Empirical Mode Decomposition Analysis (EEMD)

The signal was analysed using two main different decomposition, EMD and EEMD to show their ability. As mentioned by Huang et al. (1998), the unwanted ripple is shown in the bottom part of Figure 3.13 as displayed by Hilbert spectrum. It is attributed to inaccuracies introduced by the spline fitting procedure used in the algorithm. It will happen in the EMD analysis as shown in Figure 3.13.

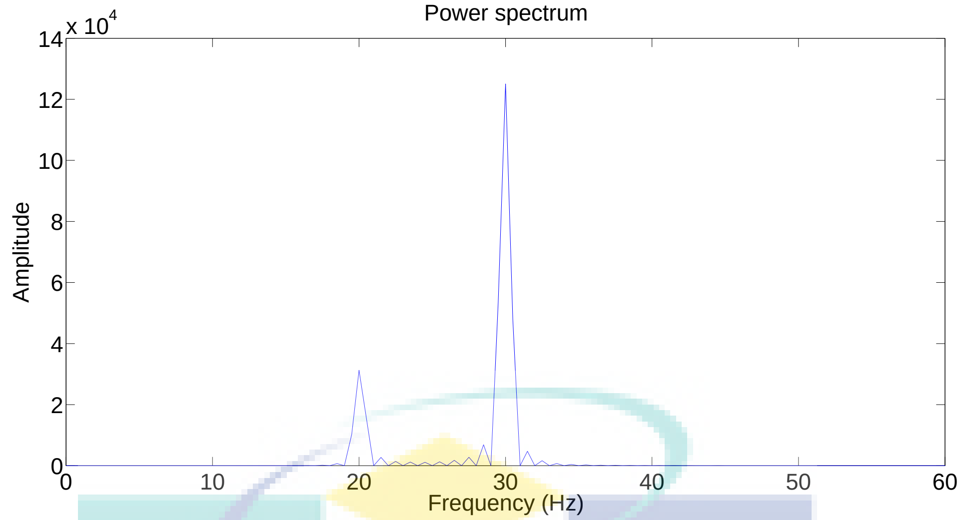


Figure 3.12: Frequency domain of the synthetic 20 Hz and 30 Hz signal

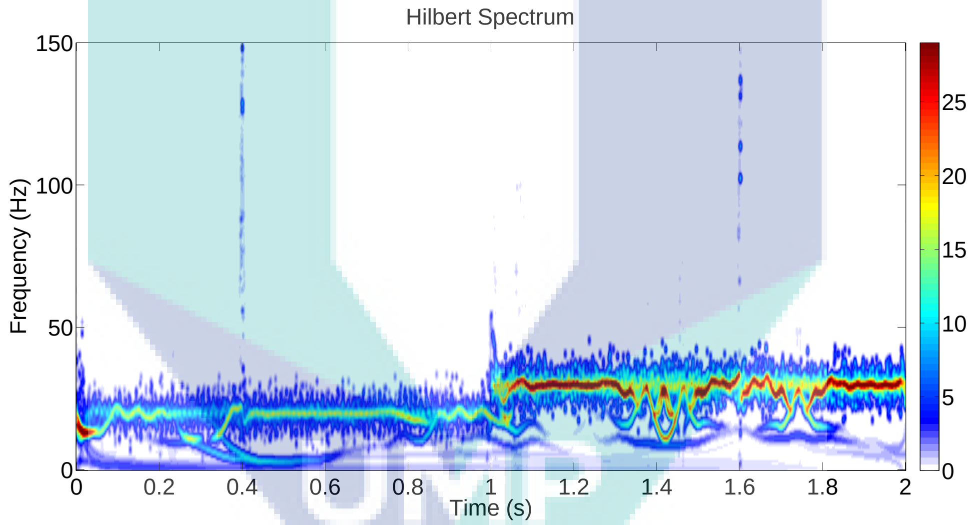


Figure 3.13: Hilbert spectrum of synthetic signal using EMD

Due to drawbacks of EMD, EEMD is implemented to get better result. The EEMD analysis was done using this synthetic signal which is yield eleven IMFs and residue of the signal as shown in Figure 3.14. In this case, the ratio value of the standard deviation of the added noise is 0.2 and the ensemble number of EEMD is 10. Wu and Huang (2009) suggested that the amplitude of the noise should be about 0.2-0.4 standard deviation of the amplitude of the raw data. However, according to Li (2011), since there is no equation to help choosing the right white noise amplitude, there are some basic rules that could be followed.

In Figure 3.14, IMF1 to IMF6 indicate the irregularity based on frequency given since the amplitude is high. The EEMD has shown some spikes at 0.4 s and 1.6 s. Meanwhile, IMF7 to IMF11 are considered meaningless in this analysis since there are no spike present. Thus, the power of EEMD is demonstrated through this example and proven its capacity to extract embedded and hidden feature in the signal where Fourier transform fails to do so. The IMF was transformed to the time frequency analysis to show the frequency at a certain time.

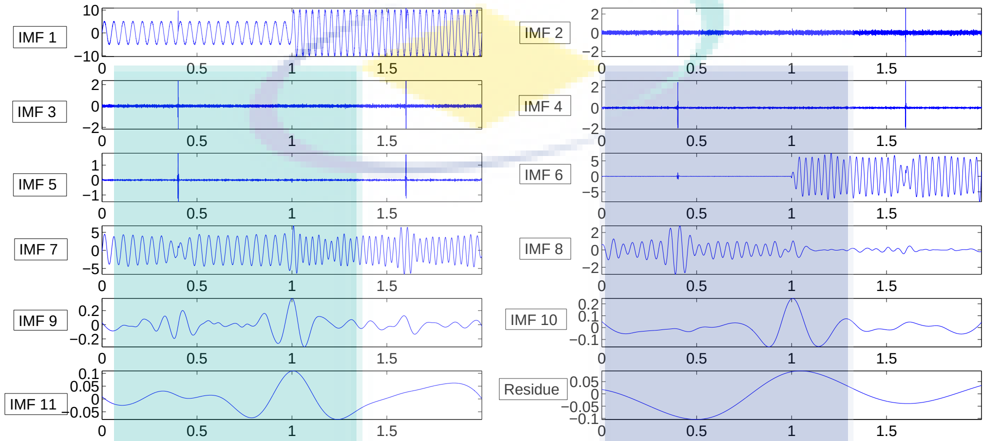


Figure 3.14: 11 IMFs and residue of the synthetic signal

With all selection of IMFs, Figure 3.15 shows both frequencies of 20 Hz and 30 Hz. The irregularity clearly shows at 0.4 s and 1.6 s. This plot provides a high resolution time frequency detailing on the time and frequency. In addition, the frequency is well split out at 1.0 s, as per frequency signal given. This move is made in order to provide excellent result for leakage detection in the pipeline and the location can be calculated based on the speed of sound and time delay from this plot. As a result, it is now possible to represent the result in Hilbert spectrum (HS).

The HS provides a high resolution time frequency representation and gives details about the nature of the sine wave and the impulses. These two frequencies and two impulses can be exactly determined with accurate time duration. In addition, the discontinuity that appears in the impulse is well localized in time. The ripples also can be eliminated by EEMD.

3.6.2 Comparison with Another Methods

The synthetic signal was also compared with another time-frequency method to highlight the advantages and disadvantages of both methods. Wavelet analysis is another

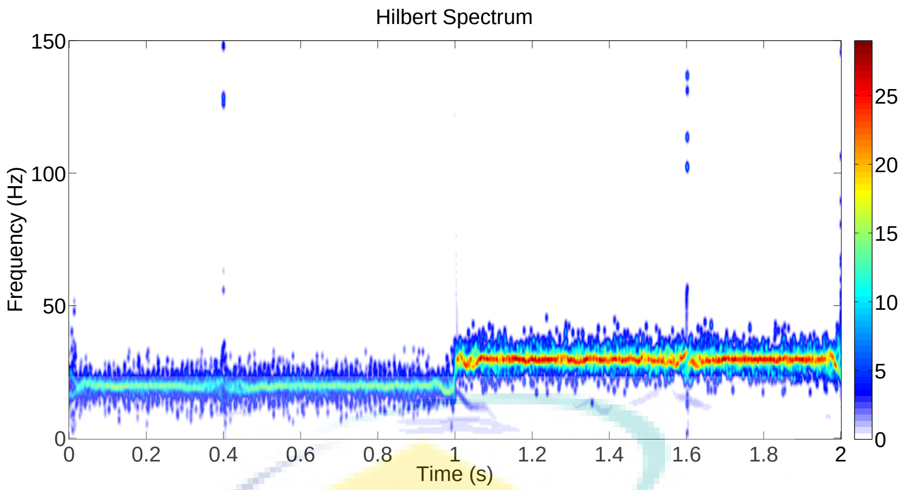


Figure 3.15: Hilbert spectrum synthetic signal using EEMD.

good option for non-stationary and non-linear data analysis. Figure 3.16 shows the scalogram with standard Morlet wavelet type analysis. The wavelet analysis is also a powerful method to show frequency at certain time. Based on the scalogram, the irregularity cannot be seen clearly. The frequency resolution is not so good but the two frequency components can still be identified. The resolution is too broad and inaccurate. So, using this method, the limitation of wavelet is underlined.

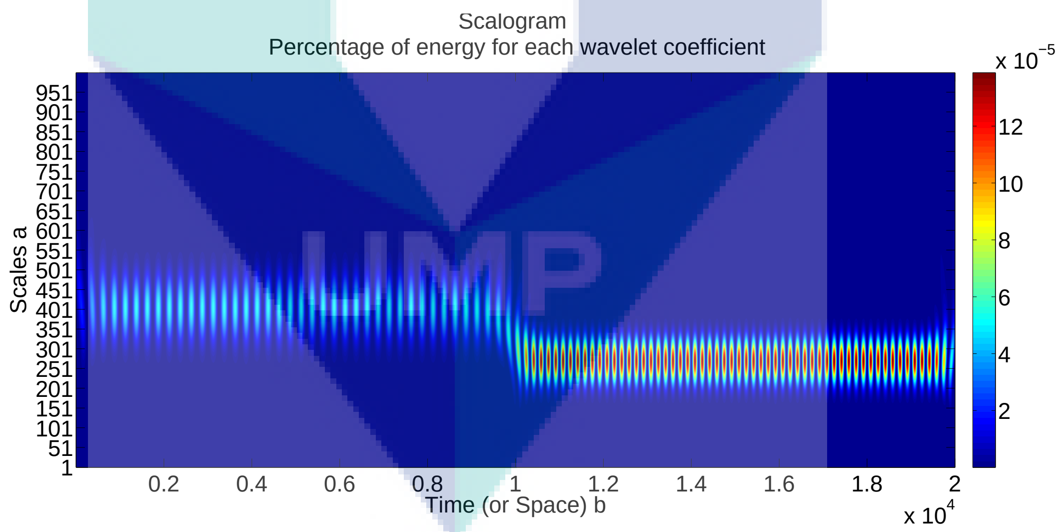


Figure 3.16: Scalogram of synthetic signal in Morlet as mother wavelet

The spectrogram corresponding to the STFT for the synthetic signal is shown in Figure 3.17 below. A random window size has been chosen that is one quarter (N/4) of the signal length. The spike can be detected at 0.4 s and 1.6 s but unfortunately, the frequency exist throughout the time window . It cannot be said for sure at what time the spike happened due to this inaccuracy. The time of first impulse occurred at 0.3 s to 0.42

s and the second impulse happened around 5.8 s to 6.2 s. Compared to HHT, the sharp time impulse shows the better result. Obviously, it fails to show the precise time.

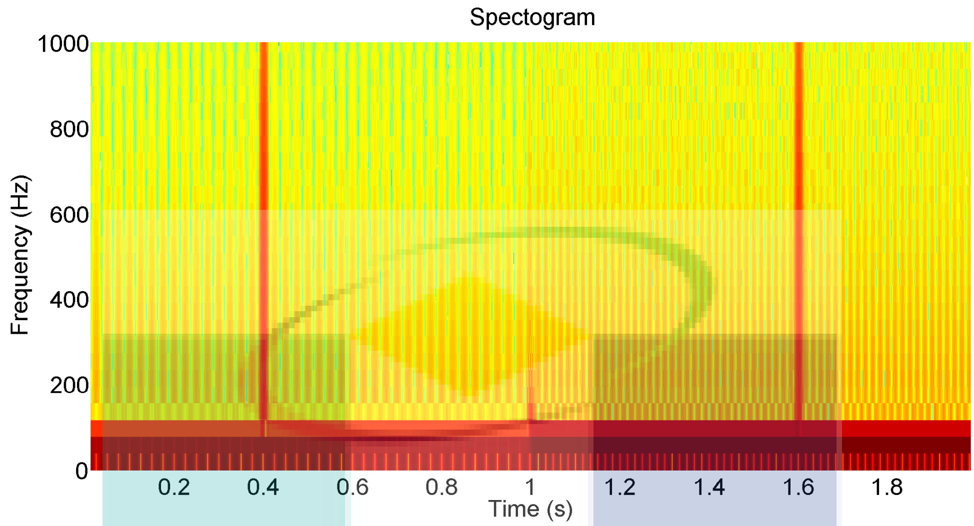


Figure 3.17: Spectrogram of synthetic signal with N/4

Even though FFT and STFT is easy to implement, these methods are not suitable for non-linear and stationary signal (Huang et al., 1998). Only WT and HHT is able to analyse both signals. Time-frequnecy resolution of STFT is limited by the Heisenberg principle. This principle implies that one cannot achieve high temporal resolution and frequency resolution at the same time. The performance of STFT is highly dependent on the window size. For the purpose of the work on looking into reflections for leak detection, both temporal and spatial resolutions are important. WT is allowed the filters to be constructed for stationary and non-stationary. However, WT needs to be operated using a suitable mother wavelet.

Thus, another advantage of HHT over WT is in terms of high time-frequency resolution. HHT has proven to be versatile and robust in analysis of non-linear and non-stationary data (Wu and Huang, 2009). Although the test by Wu and Huang (2009) obtained good results and new insights by applying HHT for various data such as numerical study of classical non linear equation systems and data representing natural phenomena, it still lacks a strong theoretical background as well as an analytical formulation. In fact, the capability of HHT in revealing physical meaning of the data has only been recently proven empirically. Table 3.6.2 shows the summary of advantages and disadvantages of FFT, STFT, WT and HHT.

Table 3.4
Comparison of different method for signal processing

Method	FFT	STFT	WT	HHT
Advantages	Easy to implement		Features extraction	
		Can be used for non-stationary signal	Non-stationary data analysis	Can be used for all type of signal
			Multi-resolution	High time-frequency resolution
			Basis function obtained by sifting and scaling a particular function	Both local and adaptive method in frequency analysis
			Analytic form for the result	Suitable for non-linear and non-stationary data analysis
			Allow filters to be constructed for stationary and non-stationary	Sharper spectrum
				Adaptive data driven basis
Disadvantages	Not appropriate for non-linear and non-stationary signals	Non-adaptive	Leakage generated by the limited length of the basic wavelet function	Lack of theoretical analysis
	Feature extraction is impossible	Time-frequency resolution limited by the Heisenberg principle	Non-adaptive nature	No mathematical formulation
			Unable to resolve intra wave frequency modulation	No physical meaning of some IMFs

3.7 Summary

In summary, this chapter outlined the methodology and analysis for the leak detection method in gas pipeline in order to achieve the objectives of this study. In Section 3.2, the flowchart explained the process utilized in this experiment in an easy way. In Sections 3.3 to 3.6, the hardware and software parts of the study were explained with figures included. These sections are very important for the next chapter. After that, the experiment setup was explained to show the connection between hardware and software parts as explained previously. In Section 3.7, some numerical simulation are introduced among the time-frequency analysis. With drawback of WT and STFT, HHT is chosen to be the signal processing method in this study. To test the ability of HHT based on EEMD method of decomposition, a synthetic signal was used and analysed using several algorithms and compared to common signal analysis method. From that point, we can conclude that EEMD is the best analysis method to detect leak in gas pipeline as was demonstrated in Hilbert spectrum. Later work will show on how these methods can be applied to real networks.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this section, the results of analysis using different materials and different methods are discussed. Firstly, a preliminary study was done to select the frequency of sound to be injected into the pipeline. Next, the result of the study on PVC, MDPE and GI pipelines will be discussed with and without the present of leak. The results were then demonstrated using Hilbert spectrum and discussed briefly in the next section. The percentage error was calculated and shown in their respective tables.

4.2 Preliminary Study: Frequency Selection

This preliminary study is done to select the suitable frequency to be injected into the pipeline. It is difficult to identify the location of the pipe end from the time domain figure because of high level of noise. Based on the theory, the high frequency component of acoustic signal attenuates quickly, while the low frequency component can propagate a longer distance. Since the range of 20-600 Hz is the range for chirp signal input used by Yunus et al. (2008), the suitable range is needed to find the best value of frequency sinusoid wave. Urbanek et al. (2012) found that the signal concentrated at 600 Hz for circular leak. This study was expected to use the same frequency for both features, circular leak and L-bend.

The experiment was conducted using two different conditions which are no leak and leak pipeline. 100 Hz, 500 Hz, 1000 Hz and 2000 Hz of sinusoid wave was injected into the pipeline. The wave was injected for 0.01 s via the speaker. The duration is quite short because of the short pipeline and to avoid multiple reflection (Yunus et al., 2008). The signal obtained reveals the occurrence of signal in the pipeline from 0 s to 0.015 s.

The speed of sound is assumed as 349 m/s, calibrated before running the experiment as explained in Section 3.5.2. The distance for sound injected is calculated at 2.7 m and outlet at 5.85 m. The results are as shown below and in all of the experiments performed, the energy distribution is treated as consistent (0-120). Figures 4.1 to 4.4 shown the different spectrums based on different frequencies tested.

Figure 4.1 illustrates the spectrum of 100 Hz sinusoid wave injected into the pipeline. The crowded signal is not focused on 100 Hz but scattered up until 1100 Hz. The signal start to diminish after 0.015 s, equals to 2.7 m. The sinusoid wave is expected to stay at 100 Hz sinusoid wave from 0 m to 2.7 m but the signal spiked at certain distance. Therefore, this sinusoid wave cannot detect any existence of feature. For leak condition, the distribution appear at 4 m (in red circle) as leak location simulated in the pipeline. However, the energy is not so strong and may be loss. Even though the leak is able to be detected, this sinusoid wave is considered as a fail attempt because it is unable to present accurate frequency. In this case, two options are available whether to use low frequency, or shorter time duration should be employed (Wang et al., 2009b). Since the length of pipeline is only 5.8 m, the second option is considered better. That is why 100 Hz is not chosen to be the sinusoid wave injected for the next experiment.

Next instead, 500 Hz sound was injected into the pipeline and the results are as shown in Figure 4.2. The figure below shows the signal pipelines both with and for without leak condition. This baseline between with leak and without leak is important to prove the occurrence of leaking in the pipeline. Based on Figure 4.2 (a), the waves start to spike at 0.00989 s equivalent to 1.725 m and the residue signal still occur in the pipeline and collided each other until they reached the outlet at 0.0332 s equivalent to 5.8 m even though the signal is scattered. This clear image is very important in order to get accurate leak location. Moreover, the ripple problem caused by EMD (Huang et al., 1998) is solved using EEMD method. EEMD method is able to eliminate the noise using white noise added during the analysis. Thus, the signal becomes clearer when the noise is eliminated. The energy is also strong and good enough to calculate the accurate leak location with good resolution in Hilbert spectrum.

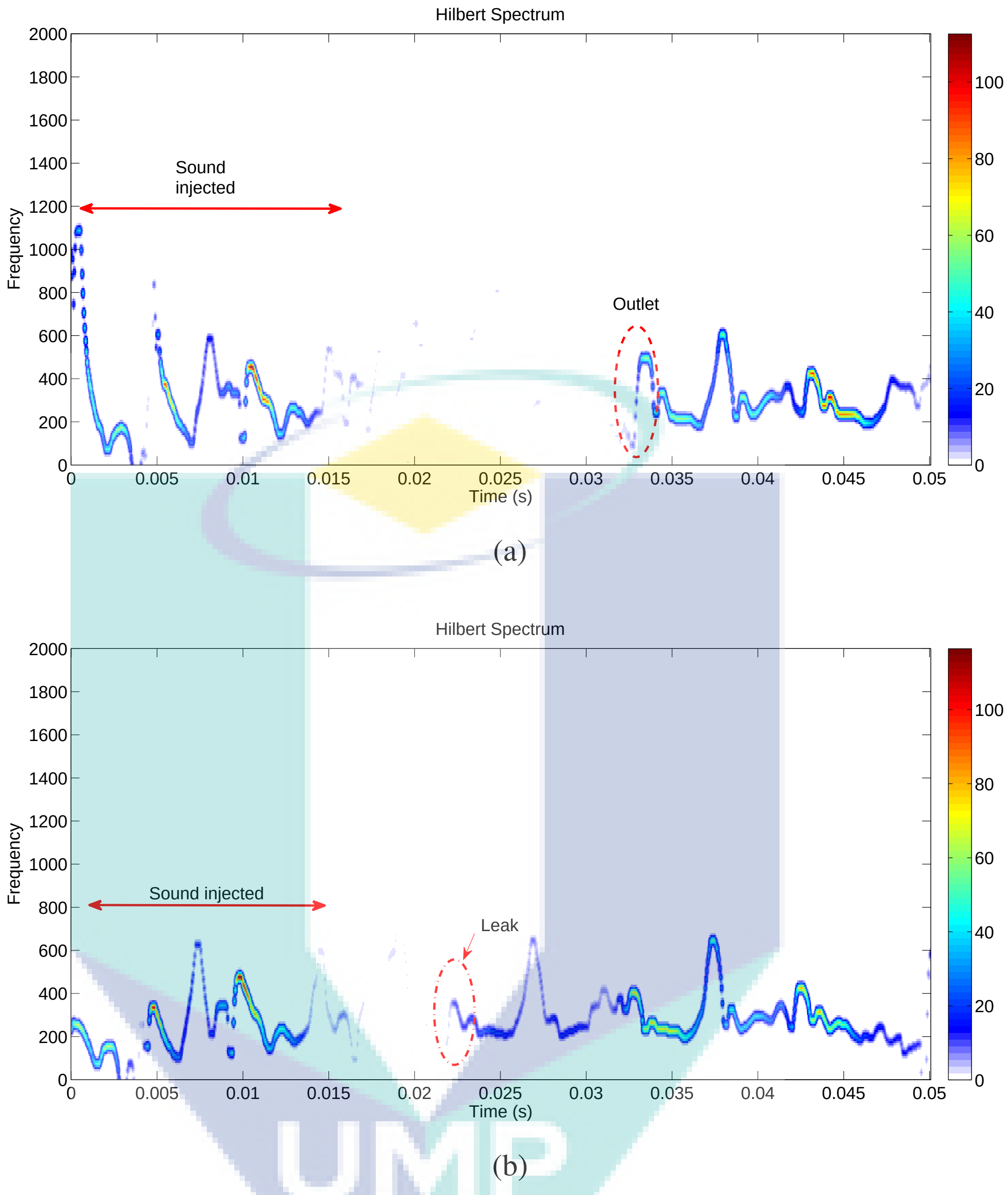
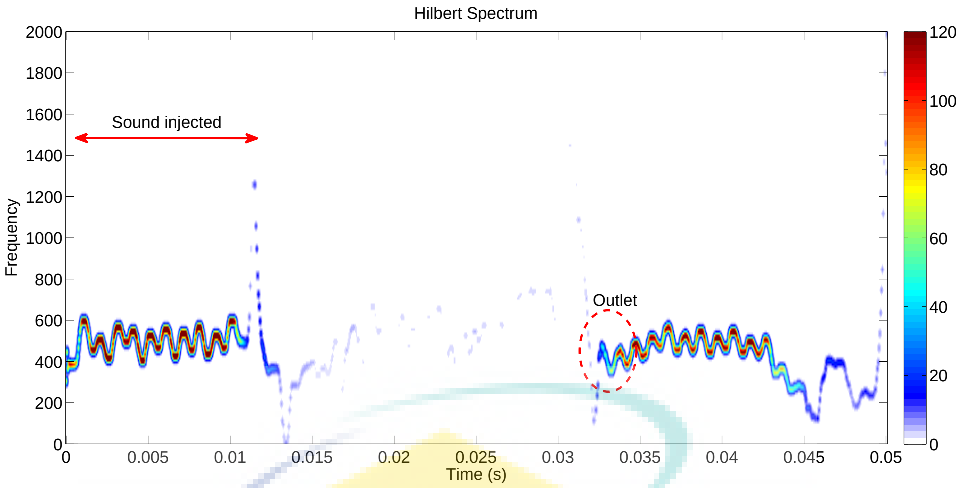
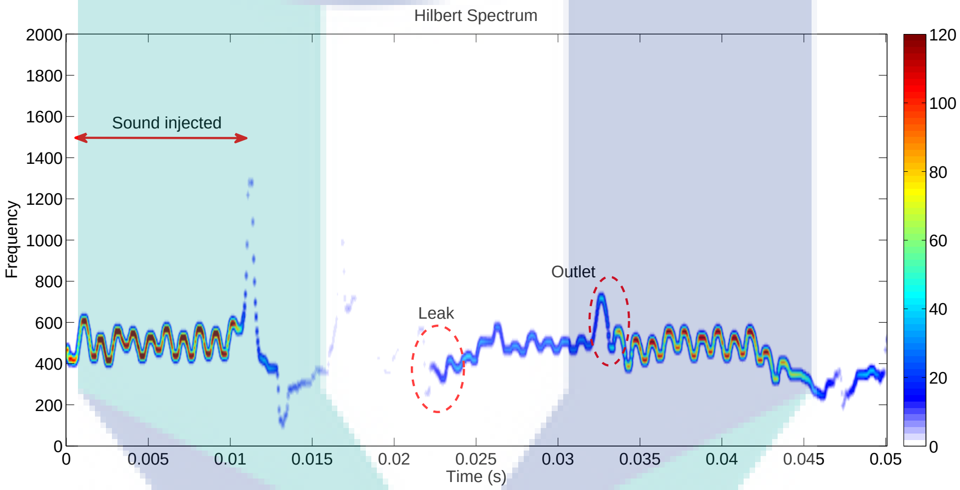


Figure 4.1: 100 Hz sinusoid wave with (a) no leak and (b) leak conditions

Figure 4.3 shows the signal from 1000 Hz sinusoid wave and the EEMD results obtained. The signal tend to attenuate quickly when higher frequency is used while low frequency component can propagate for a longer distance (Meng et al., 2012). The leak occurred at 400-500 Hz even though 1000 Hz was injected into the pipeline. The low energy can lead to signal loss. In addition, high frequency is not needed due to the short length of the pipeline. It is proven that 1000 Hz is not suitable to be injected in the actual experiment.



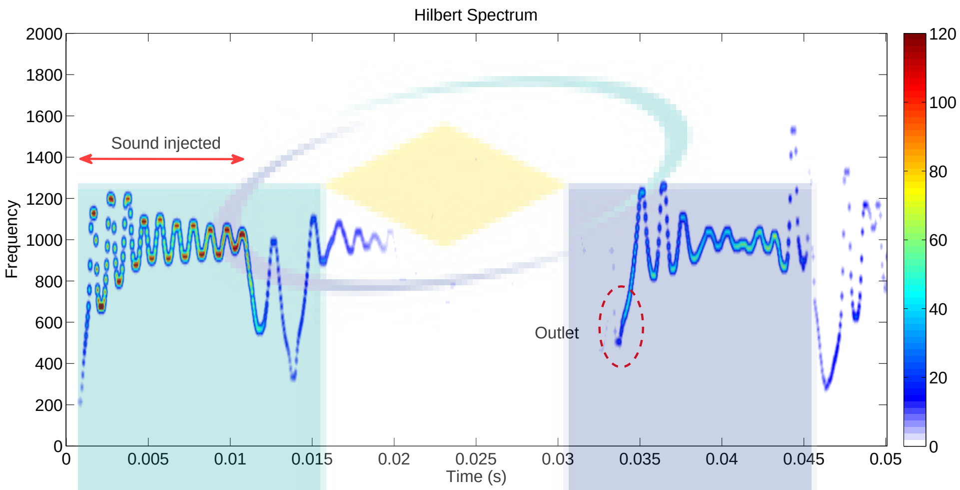
(a)



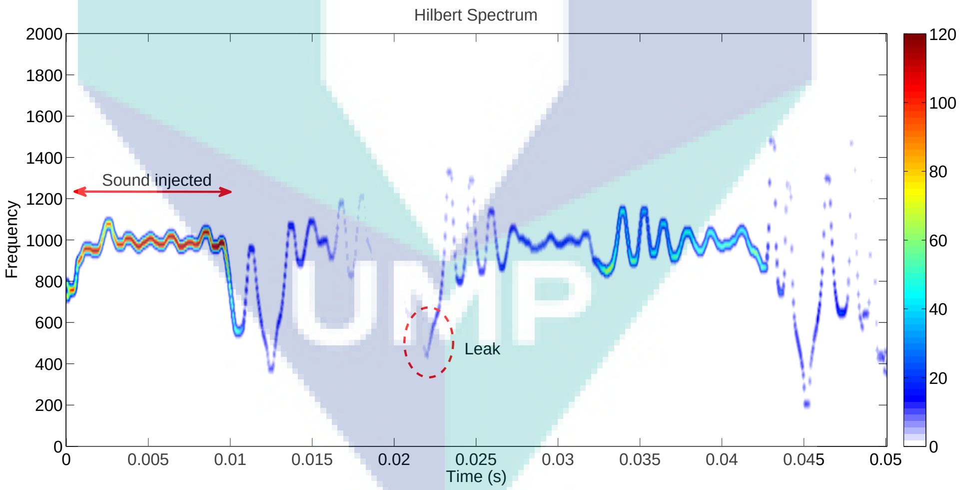
(b)

Figure 4.2: 500 Hz sinusoid wave for (a) no leak and (b) leak conditions

The same situation happens to 2000 Hz of sinusoid wave as shown in Figure 4.4. The frequency reached up to 1800 Hz only and the signal was lost and the leak location cannot be determined eventhough a baseline case of the without leak condition was used to be compared with leak condition. The Figure 4.4 (a) shows the appearance of outlet pipeline. However, the leak and outlet does not appear in the leak condition experiment (refer Figure 4.4 (b)). It has been proven that high frequency propagates quickly compared to lower frequency (Ingard and Singhal, 1974).



(a)



(b)

Figure 4.3: 1000 Hz sinusoid wave for (a) no leak and (b) leak condition

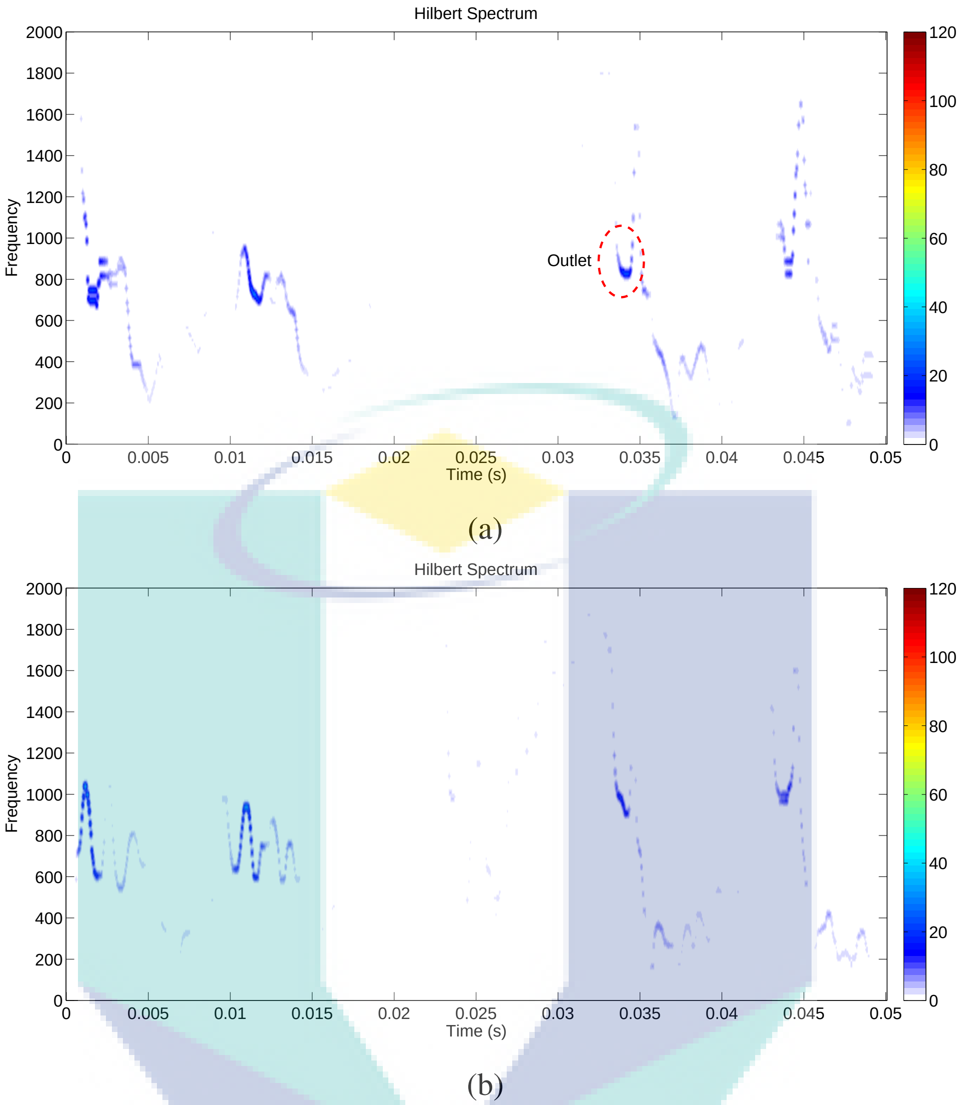


Figure 4.4: 2000 Hz sinusoid wave for (a) no leak and (b) leak condition

The results show that based on the observation, the best frequency is 500 Hz. A clear spectrum is important for the next experiment. The selection of 500 Hz for the sound injection is based on the signal's clear spectrum, high energy, consistency of the result and suitable for short pipeline length.

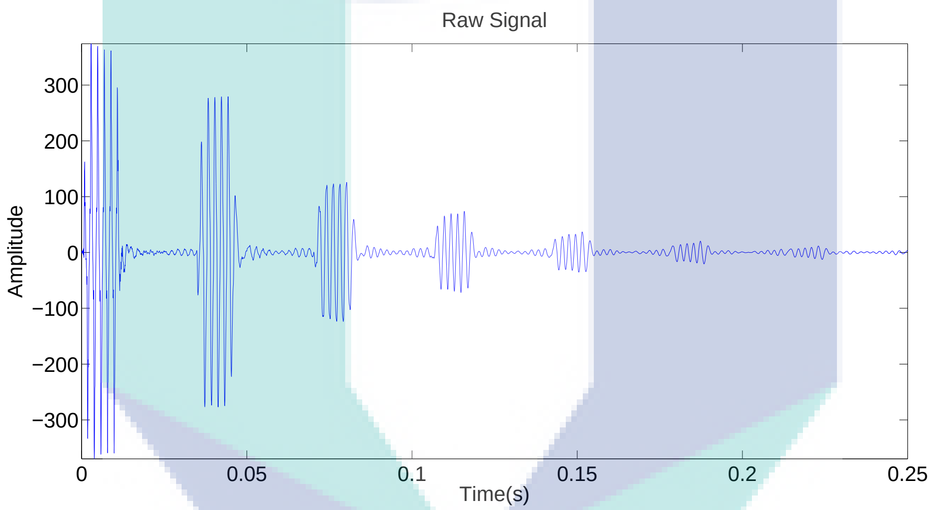
Table 4.1
Result summaries

Frequency (Hz)	**Observation**
100	Low energy
500	Clear spectrum and high energy
1000	Too wide resolution
2000	No indicator to locate the leak

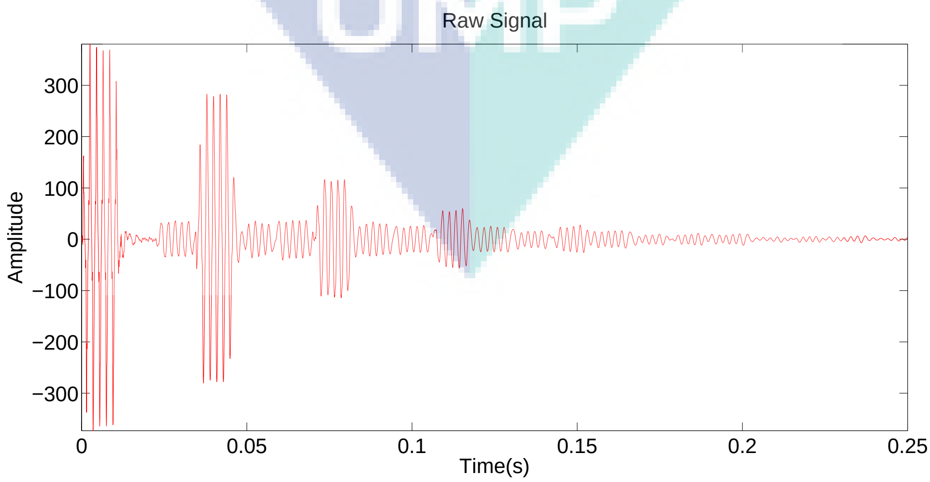
4.3 Experiment Results

4.3.1 MDPE Pipeline

The first experiment used MDPE pipeline to test the signal. As mentioned earlier, MDPE is a soft material. This material tends to absorb the sound injected, making the reflection signal becomes difficult to retrieve after the signal is inserted. The data will be analysed in the same way as PVC and GI pipelines which were tested using FFT and HHT. Figure 4.5 shows the signal from the MDPE pipeline for both conditions. Basically, the result is the same as MDPE but there is a difference in the difficulty to capture the data since the absorption rate for MDPE is higher compared to PVC and GI.



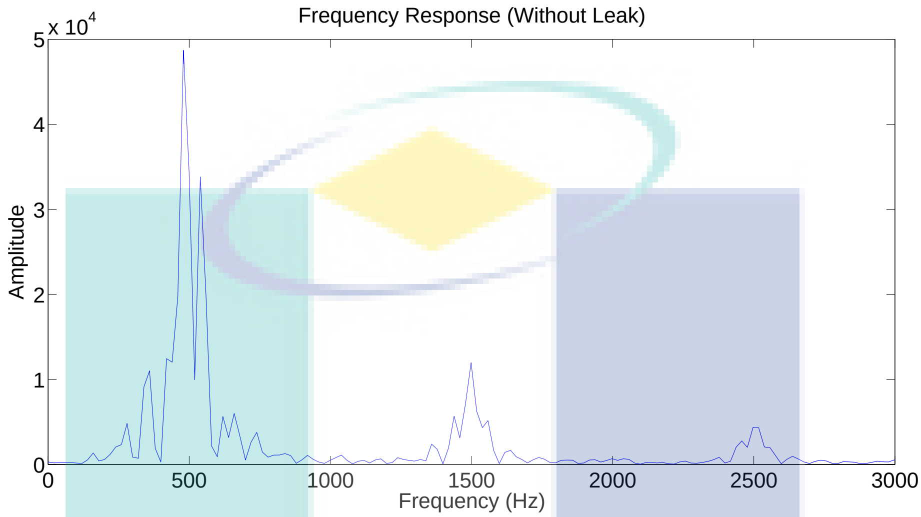
(a)



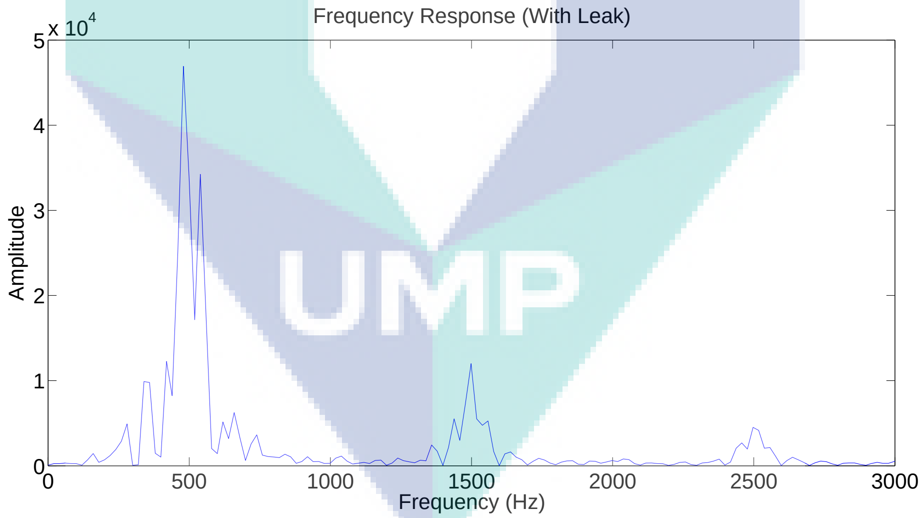
(b)

Figure 4.5: Signal data of MDPE pipeline for (a) no leak and (b) with leak condition

As expected, outcomes from FFT did not present any meaningful results. The results just showed the existence of signal frequency but do not show the leak data nor the location as portrayed in Figure 4.6. The spike at 1500 Hz and 2500 Hz is reflection for injection we give before which means did not give any meaningful result. In this case, time is vital for the calculation of location as mentioned in Eqs. (3.1) and (3.2).



(a)



(b)

Figure 4.6: FFT analysis of (a) no leak and (b) with leak for MDPE pipe

The signal data of the MDPE pipeline was analysed using EEMD for decomposition process as presented in Figure 4.7 before it was displayed in the Hilbert spectrum. The decomposition looks the same for both conditions with a notable difference in component IMF4 because that is where leak is located. Figure 4.8 presents the EEMD analysis for leak condition in MDPE pipeline. IMF4 shows the existence of wave at 0.023 s.

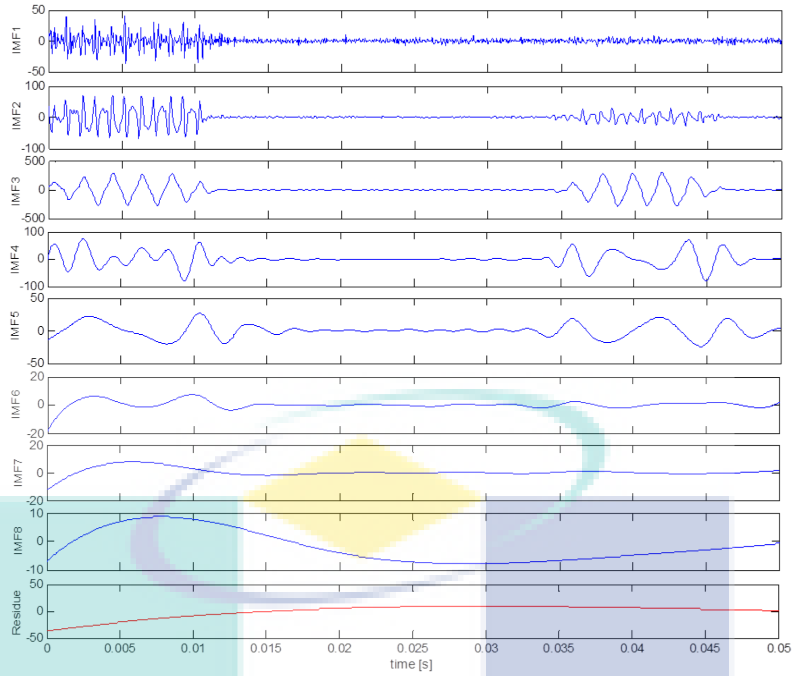


Figure 4.7: IMF without leak condition for MDPE pipeline

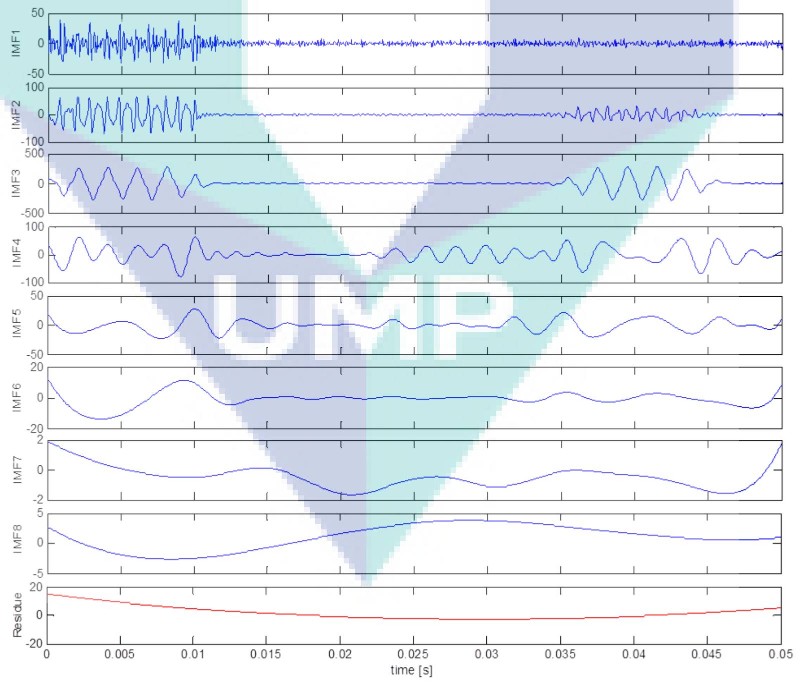


Figure 4.8: IMF leak condition for MDPE pipeline

The selection of IMF4 to IMF7 data signal was analysed in HT as presented in Figure 4.9 to Figure 4.11 for both conditions. Figure 4.9 shows a spike at 0.018 s, which is equivalent to 3.193 m to indicate the sound injected finish in the pipeline while another spike at 0.033 s equivalent to 5.671 m corresponding the outlet of the pipe. Next, repeating the experiment with leak condition, the result was completely different. The signal appears at 0.022 s, reflected to 3.839 m when converted to distance as shown in Figure 4.10. This corresponds to the leak location. Furthermore, the injected sound finished at 0.019 s, which equals to 3.316 m while the outlet was determined at 0.035 s, which is equivalent to 6.055 m. It is simpler to convert from time into distance by multiplying the time taken for wave to travel by the speed of sound divided by two. In this case, the speed of sound is considered as 349 m/s, which is similar with other materials.

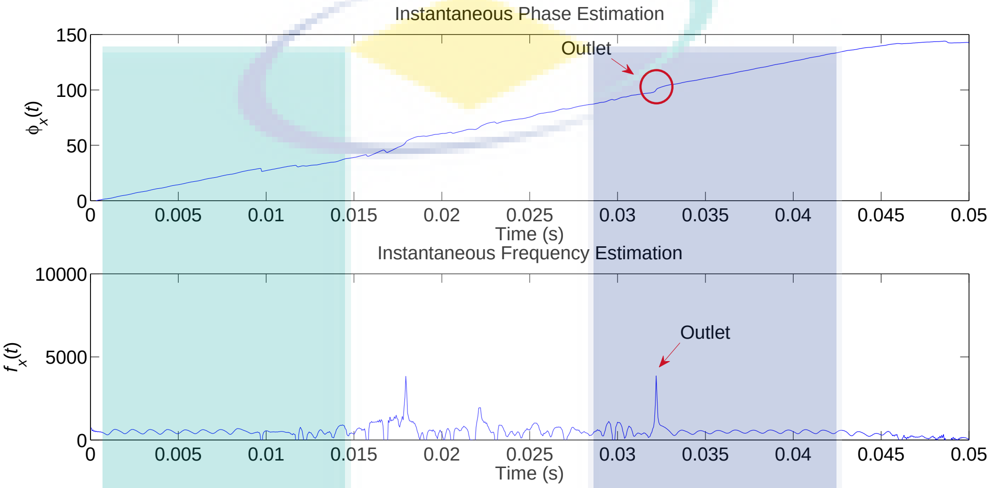


Figure 4.9: Instantaneous phase and instantaneous frequency with no leak condition for MDPE pipeline

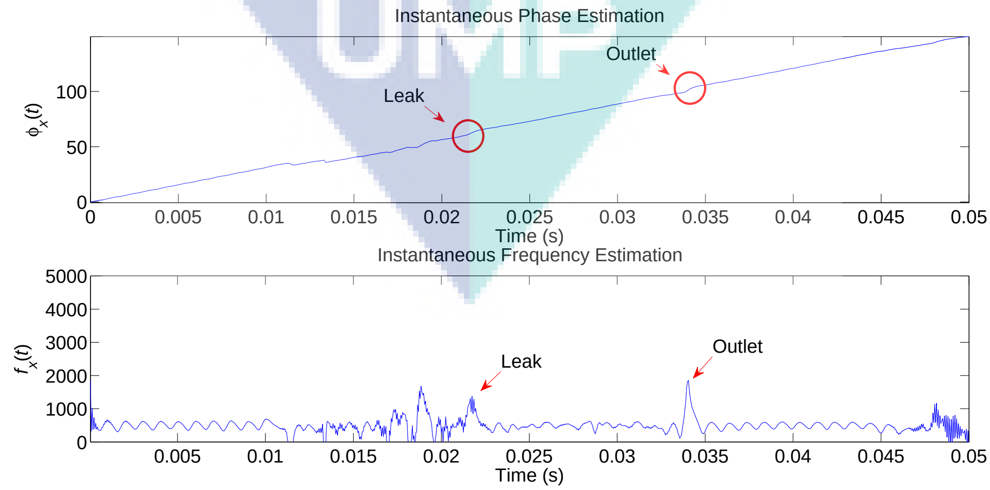


Figure 4.10: Instantaneous phase and instantaneous frequency with leak condition for MDPE pipeline

Figure 4.11 shows the Hilbert spectrum of signals for both conditions. The analysis using IMF4-IMF7 were to be further examined using this method. In Figure 4.11 (a), the sound injected is displayed from 0-0.01 s which equal to 1.745 m. The spike occurs at 0.033 s which equal to 5.759 m in distance to show the outlet position. In Figure 4.11 (b), the injected sound re-occurred at 0.023 s (3.926 m) which proved that the leak occurred there and the spike that appeared at 0.034 which equivalent to 5.950 m is proved as the outlet location.

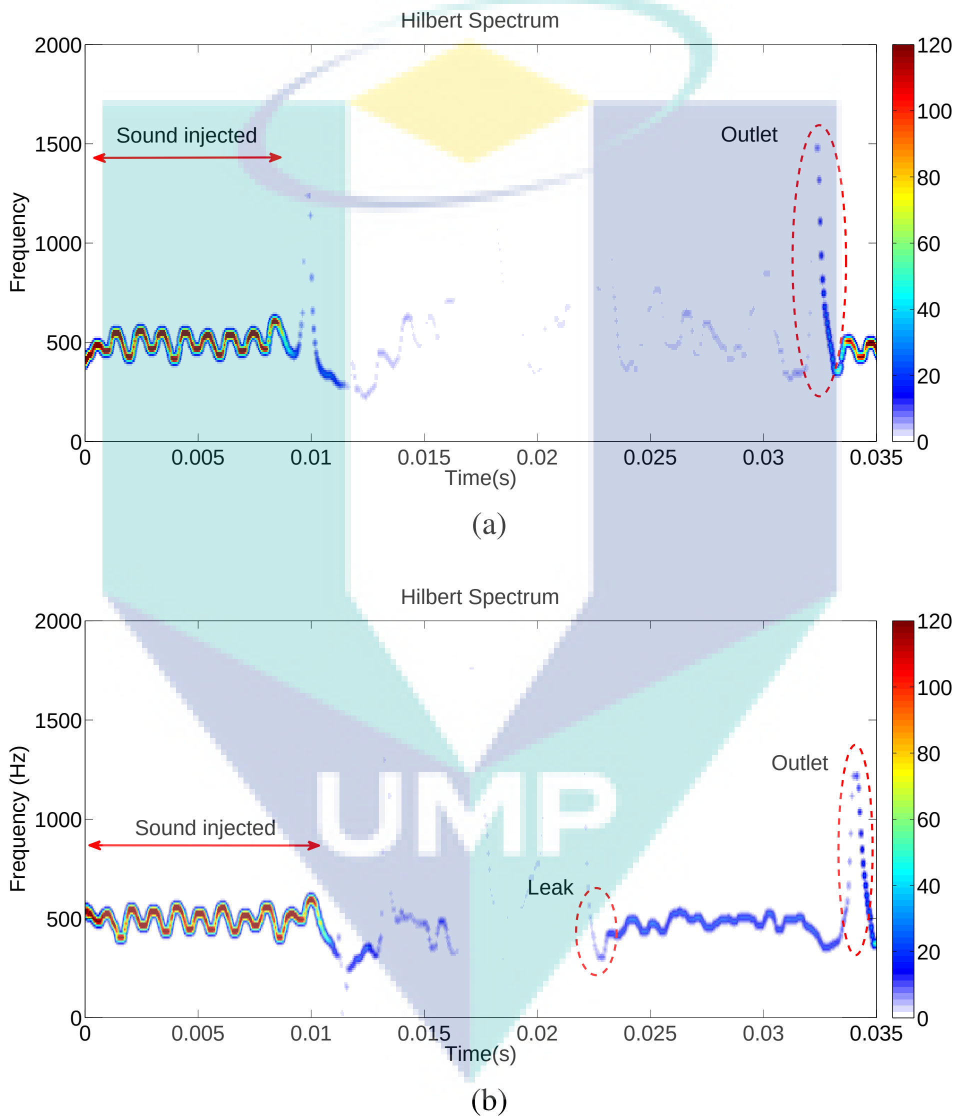


Figure 4.11: Hilbert spectrum of IMF4-IMF7 results for (a) no leak (b) with leak condition

Table 4.2 presents the result for MDPE tests and their location error. In general, the results verified that HHT can provide simple and clear results in indicating the leak location with acceptable error. The highest error is 1.850 % which is below than 5 % (Mostafapour and Davoudi, 2013).

Table 4.2
Results of the tests with and without leak condition in MDPE pipe using HHT

Test	Analysed Distance (m)		Measured Distance (m)		Error (%)	
	Leak	Outlet	Leak	Outlet	Leak	Outlet
1	3.926	6.055			1.850	0.917
2	4.005	6.075	4.000	6.000	0.125	1.250
3	3.956	6.063			1.100	1.050

4.3.2 PVC Pipeline

Figure 4.12 shows the raw data collected by DASYlab. 20 KHz of sampling frequency was used in this case and 500 Hz of sinusoid wave was injected for 0.01 s. The blue signal represents the no-leak condition and red colour represents the leak condition signal. The distance of the reflection point is calculated by multiplying the time delay corresponding to the peak by the speed of sound in the pipe system which is 349 m/s and halving this value to count the return journey.

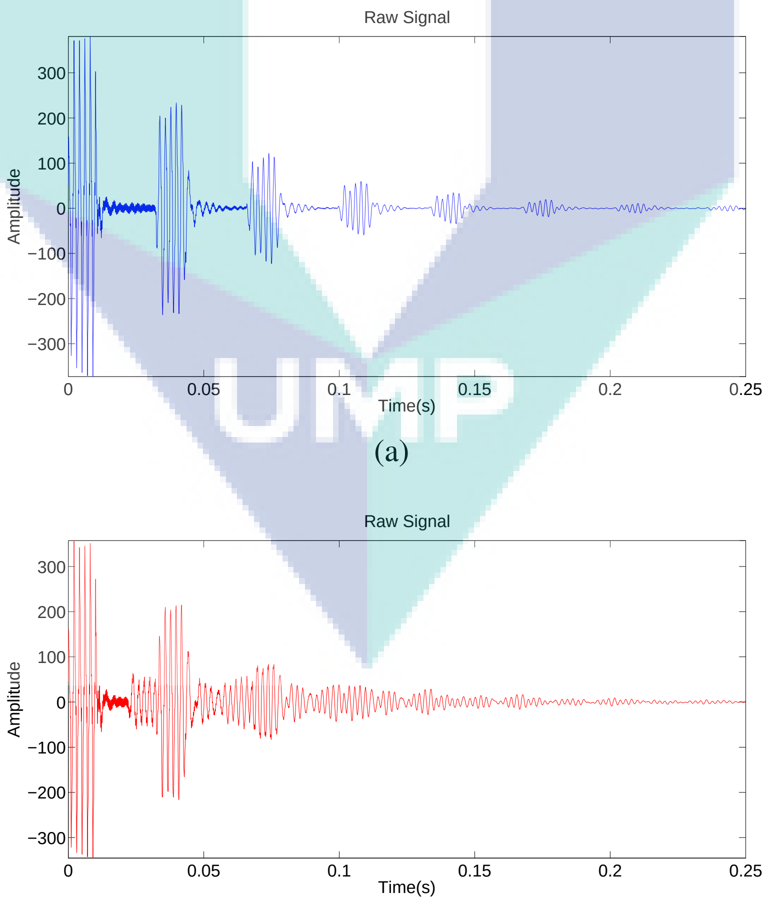
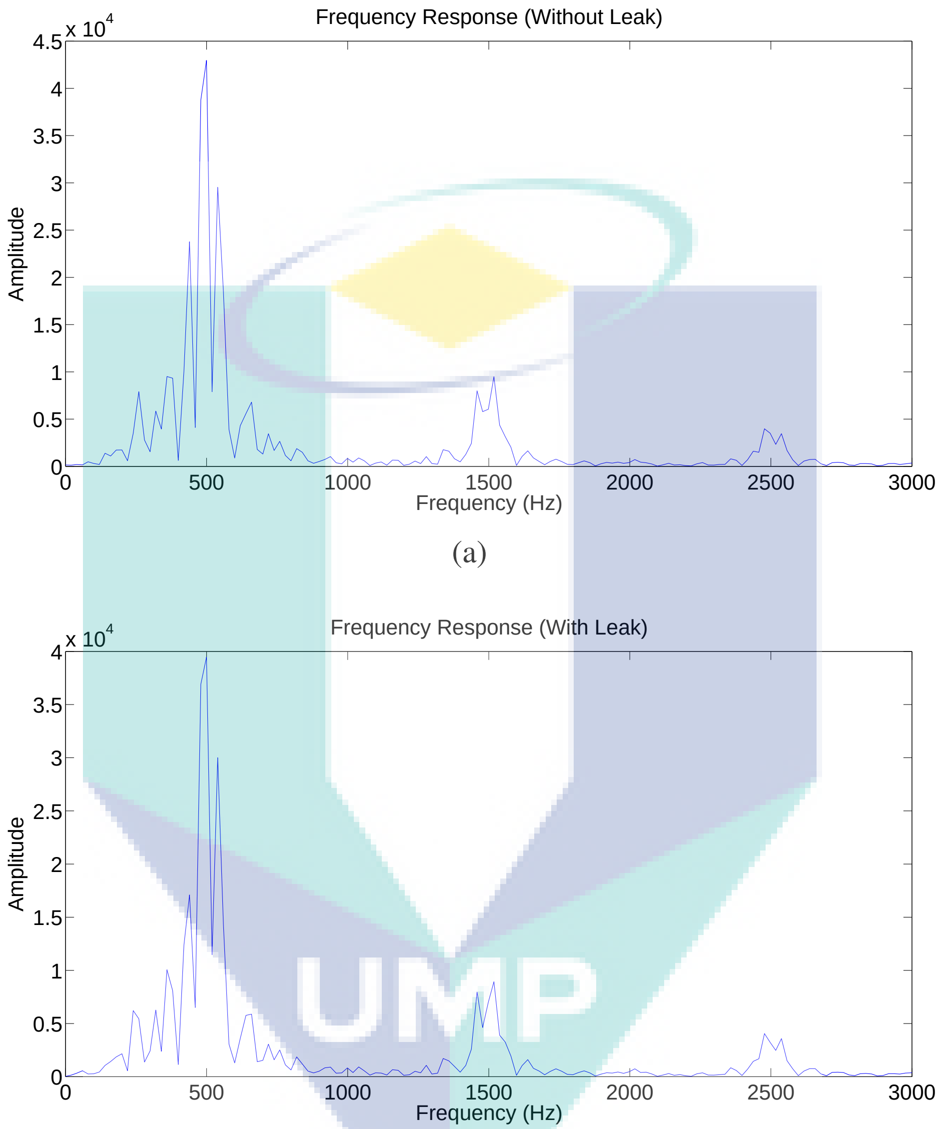


Figure 4.12: Signal data of PVC pipeline for (a) no leak (b) with leak

The signal test in FFT is shown in Figure 4.13. Both conditions show the same results and the difference between leak or no-leak condition cannot be differentiated. It is proven that FFT cannot be used to determine the present of leak and leak location at all.



(a)

(b)

Figure 4.13: FFT analysis (a) no leak and (b) with leak

The signal has been decomposed using EEMD into eight IMF from high to low frequency as shown in Figures 4.14 and 4.15. The last component shows the residual of signal and then the signal has been analysed using HT. Decomposition happens from high frequency to low frequency. IMF1-IMF3 consist mostly of the noise and was ignored with regard to the HT analysis while IMF8 and the residue contain the basic response of the signal. Therefore, all of these IMFs have been removed and IMF4-IMF7 were selected to generate a signal without noise and shown in HS.

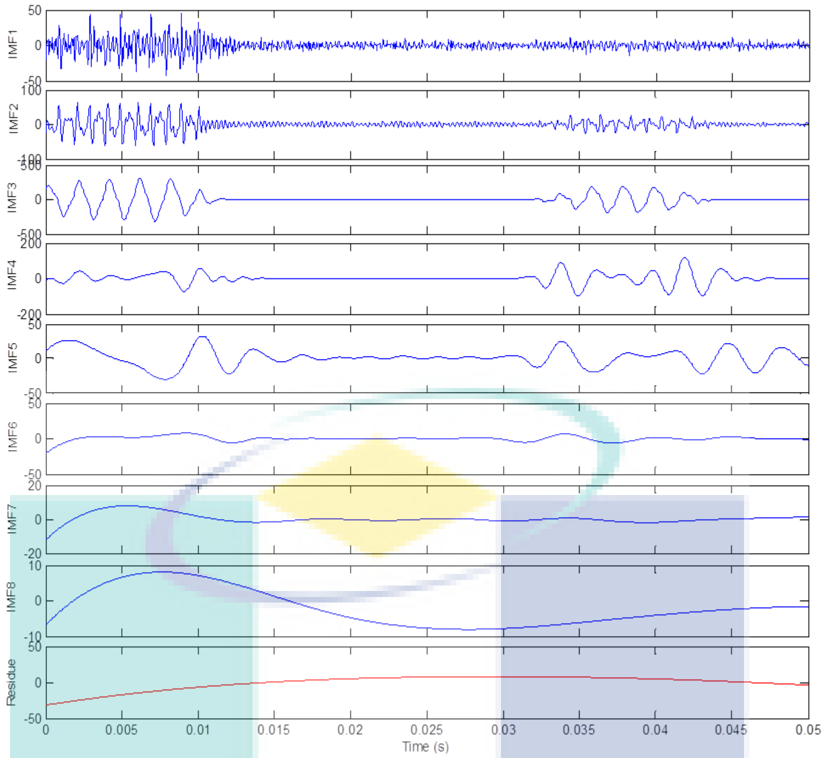


Figure 4.14: IMF without leak for PVC pipeline

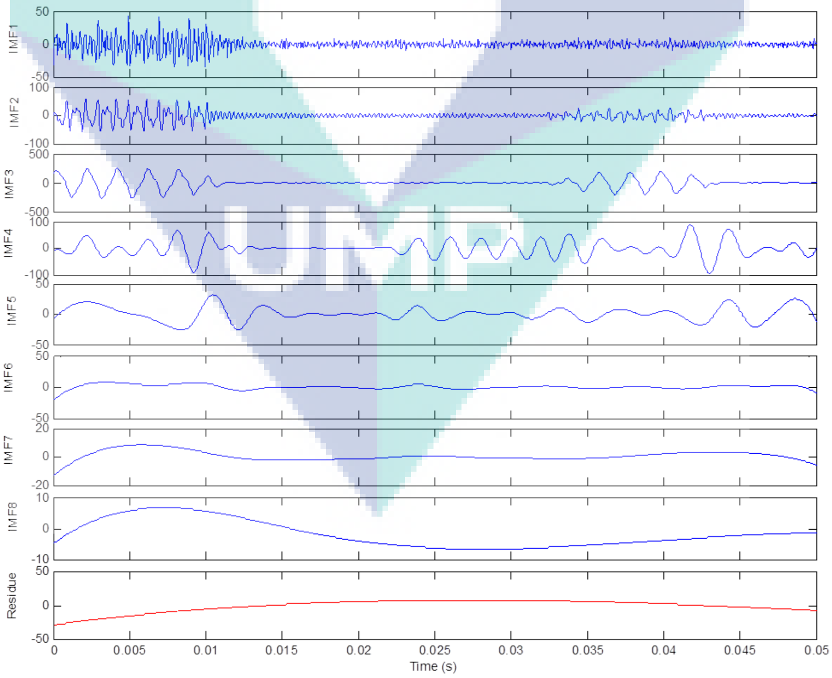


Figure 4.15: IMF with leak condition for PVC pipeline

The selection of IMF4-IMF7 was then analysed using the HT of the signal without leak as shown in Figure 4.16. The outlet was calculated as 0.031 s in time and after being converted into distance, the result is 5.410 m. The real outlet was located at 5.800 m. However, the sound that was injected cannot be detected in this instantaneous frequency and phase. Besides, we can see the different results between leak and no-leak conditions where the reflection of the signal exist approximately at 0.021 s (see Figure 4.17). At this point, we multiply the number with the speed of sound (349 m/s) by dividing it by two, resulting 3.691 m, which corresponds to the distance of the leak location from the measuring section. The outlet was calculated at 0.031 s and after converted to distance gives 5.471 m.

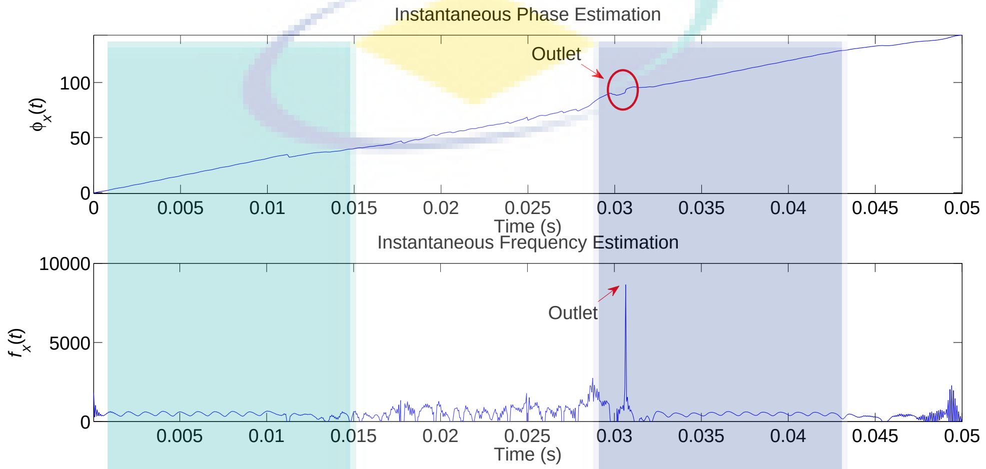


Figure 4.16: Instantaneous phase and instantaneous frequency without leak conditions for PVC pipeline

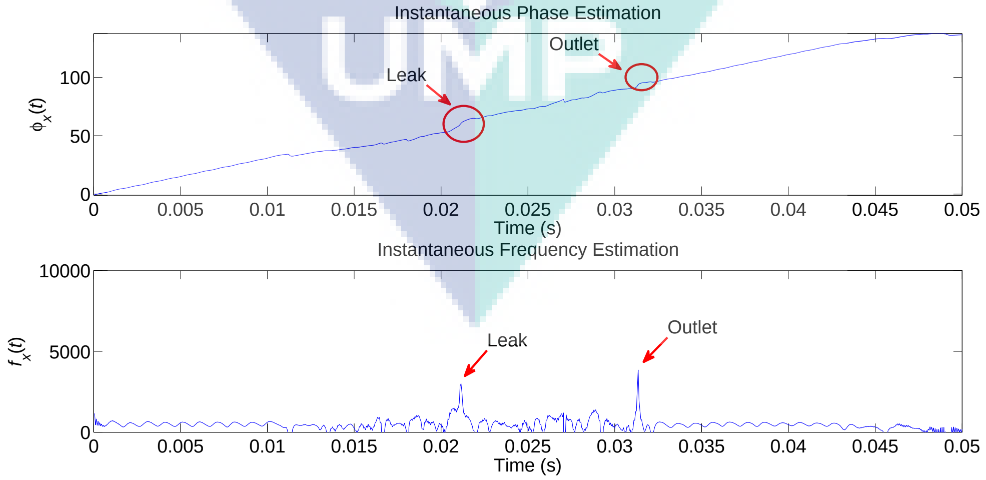
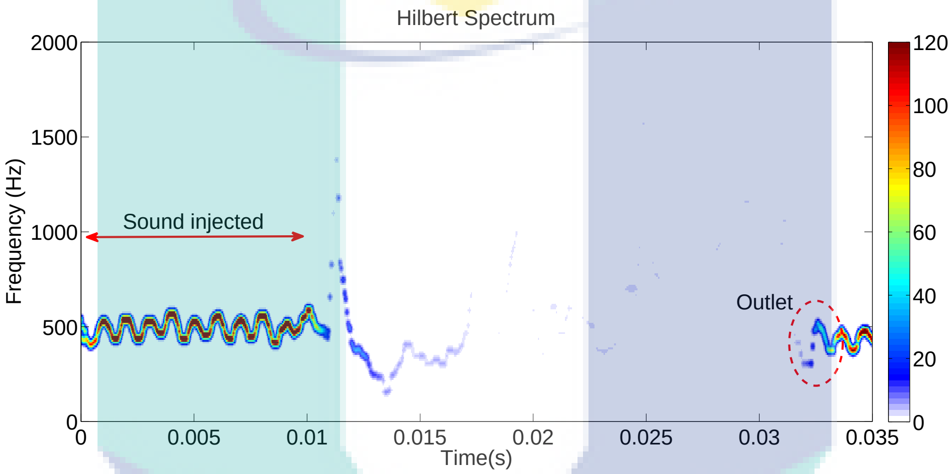
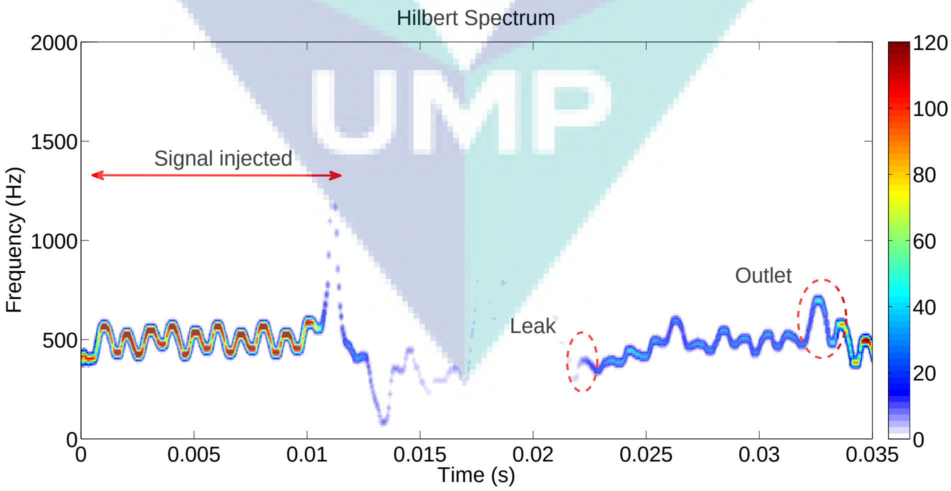


Figure 4.17: Instantaneous phase and instantaneous frequency with leak for PVC pipeline

The experiment data from the rig described above was then analysed to be displayed in Hilbert spectrum (HS). The signal with the leak location at 4 m from the measuring point was generated and the obvious difference between leak and without leak can be seen in HS as shown in Figure 4.18. As for the without leak condition, the frequency of 500 Hz at 0.0331 s is equivalent to 5.776 m indicating the pipeline outlet. Figure 4.18 (b) shows the spike ends at 0.017 s which equals to 2.967 m displaying the occurrence of the injected sinusoid wave that was given before. The energy distribution is a fixed constant, 0-120. When signal was injected into leak pipeline condition, the signal drop early compared with no leak condition because of the echoes or reflection of the sound itself. The reflection gathered at 0.0225 s which is equivalent to 3.926 m proven the occurrence of leak. The error for the leak location is 1.844 %. The outlet for leak condition experiment is determined at 0.0343 s which equals to 5.985 m with 3.196 % of error.



(a)



(b)

Figure 4.18: Hilbert spectrum of IMF4-IMF7 results for (a) no leak and (b) with leak condition for PVC pipeline

Table 4.3 presents the results of the test conducted in PVC pipeline. The results indicate that this technique is successful in locating leak in pipeline system with acceptable errors. The error for PVC pipeline is around 1.375 % to 2.200 % for leak while 0.362 % to 3.196 % for outlet. As informed previously, the leak location is detected at 4 m and at the outlet (length of pipeline) which is at 5.8 m.

Table 4.3
Results of the tests with and without leak condition in PVC pipe using HHT

Test	Analysed Distance (m)		Measured Distance (m)		Error (%)	
	Leak	Outlet	Leak	Outlet	Leak	Outlet
1	3.926	5.985			1.844	3.196
2	3.945	5.834	4.000	5.800	1.375	0.586
3	3.912	5.821			2.200	0.362

4.3.3 GI Pipeline

The GI pipeline of 6 m in length was used in this experiment. The signal is similar as other pipe materials as shown in Figure 4.19. The pipeline without leak condition is used as a baseline to be compared with the one with leak condition. The sound was injected for 0.01 s and the reflection of the sound seventh times of repetition before the sound was completely lost. This is because of the sound absorption from the material and the amplitude of sound will decreased.

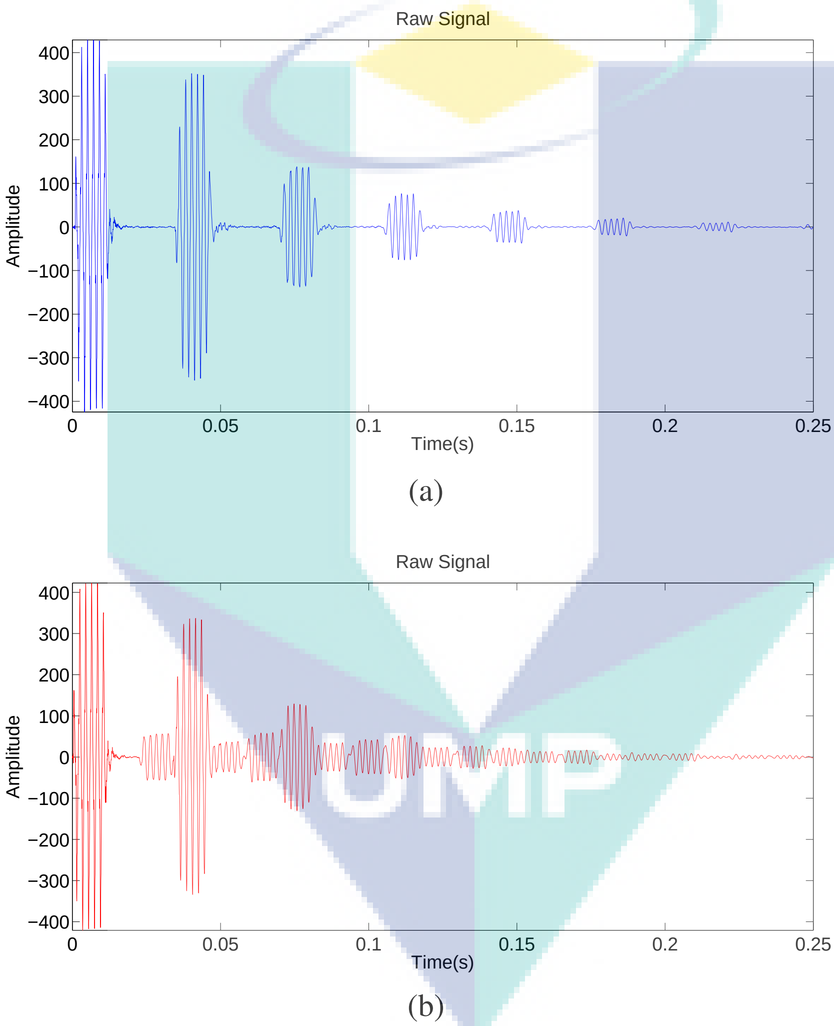
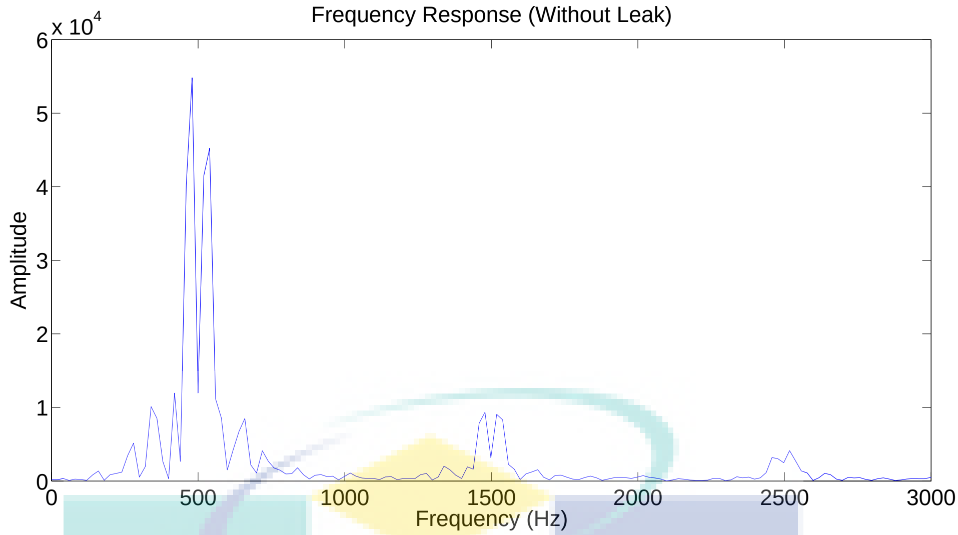
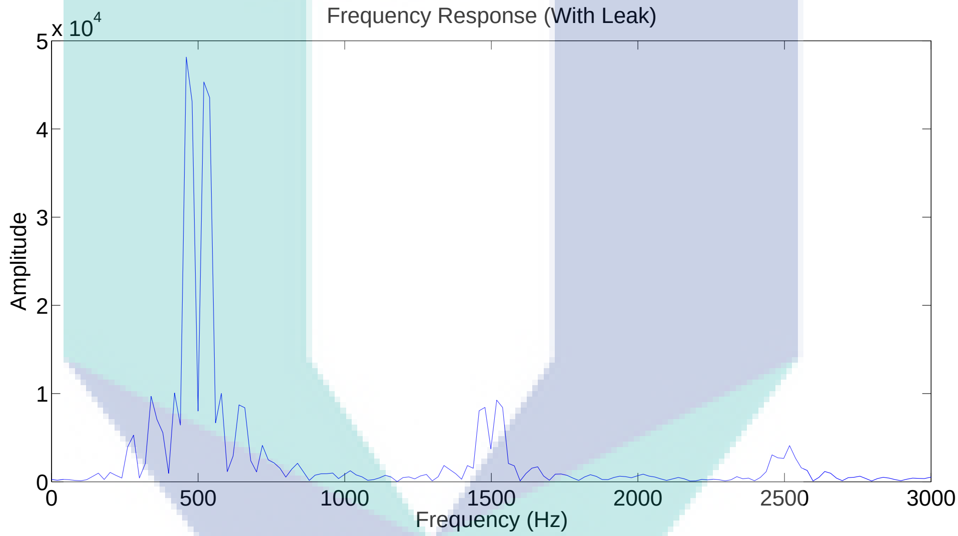


Figure 4.19: Signal data of GI pipeline for (a) no leak and (b) with leak condition

Figure 4.20 shows the FFT results for the GI pipeline. As explained previously, the FFT results is not suitable in extracting results of leak location since time is not included in its frequency domain.



(a)



(b)

Figure 4.20: FFT analysis for (a) no leak and (b) with leak condition

The same data was analysed in EEMD as shown in Figure 4.21 is for without leak condition while in Figure 4.22 is for with leak condition. IMF1 to IMF3 is removed since there is no useful meaning for the analysis. Only IMF4 to IMF7 is counted as signals to be analysed in the HHT afterwards. The decomposition happens from high frequency to low frequency. The disturbance occurred at 0.023 s which is equivalent to 3.926 m as shown in Figure 4.22 proving the leak location.

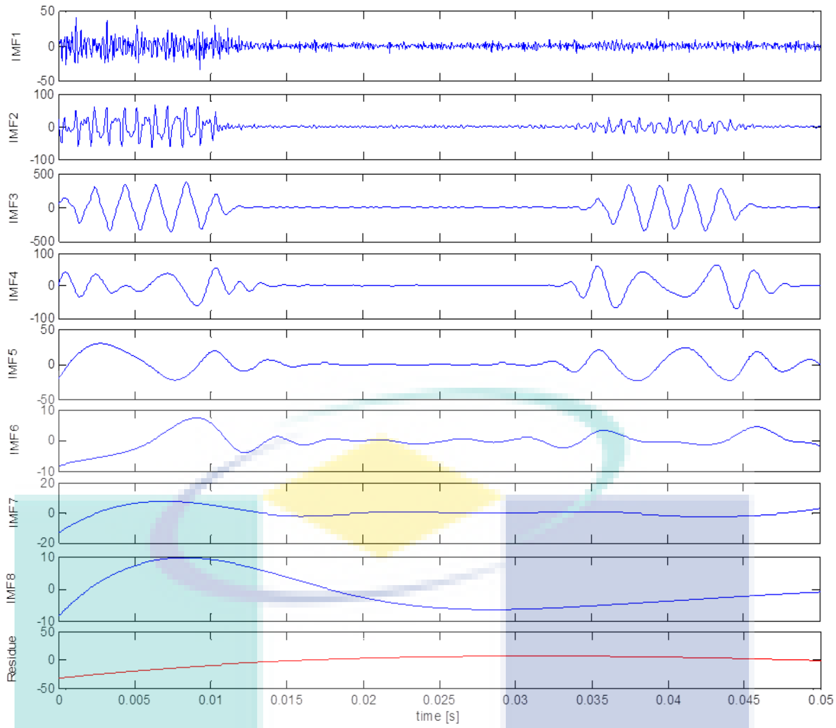


Figure 4.21: IMF for without leak condition in GI pipeline

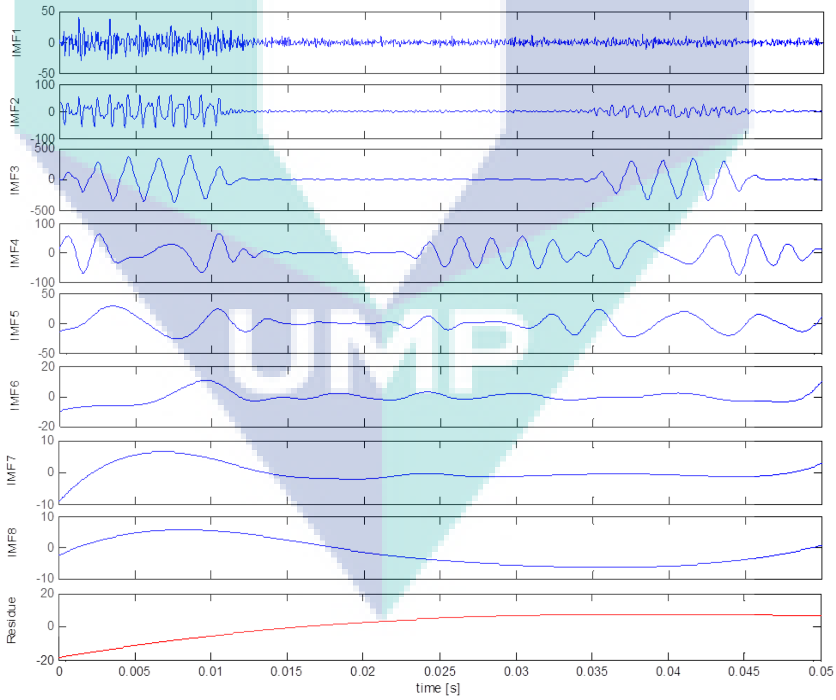


Figure 4.22: IMF for with leak condition in GI pipeline

The results for instantaneous phase and frequency is not good for GI pipe as unwanted spikes appeared as shown in Figure 4.23. The main possible reason of getting this bad instantaneous frequency is because of the absorption rate of the material itself. GI pipe is considered as hard material where the sound is not being absorbed if compared to PVC and MDPE. The results considered the last spike as the outlet which is at 0.032 s which is equivalent to 5.593 m and the location of error is 6.783 %. For leak condition of GI pipeline, the instantaneous phase and frequency is shown in Figure 4.24. From the figure, the leak occurs approximately at t = 0.022 s (3.769 m) and outlet is at t = 0.034 s (5.942 m). Again, an unwanted instantaneous frequency appears at t = 0.016 s and considered to happen due to the sound has been finished being injected. However, the results is still valid since the selection the IMF in the next process is applied to prove the leak location.

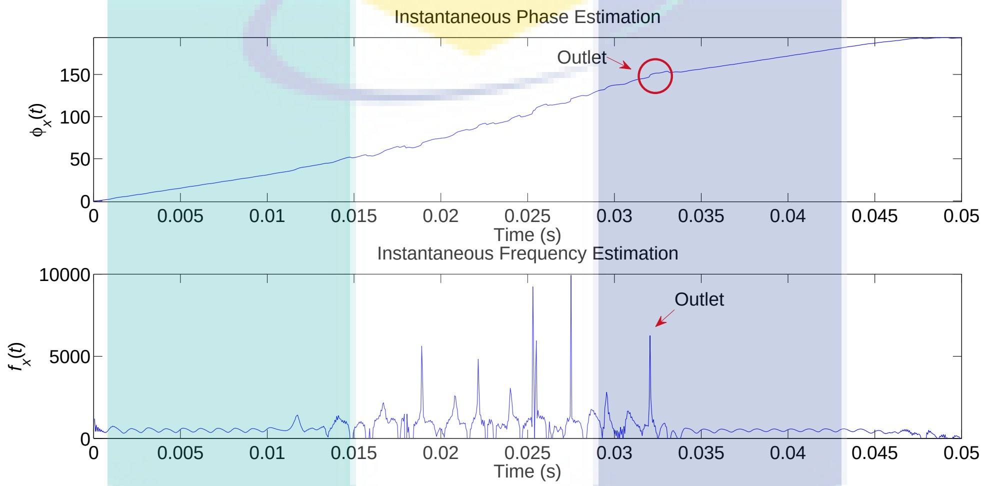


Figure 4.23: Instantaneous phase and instantaneous frequency without leak for GI pipeline

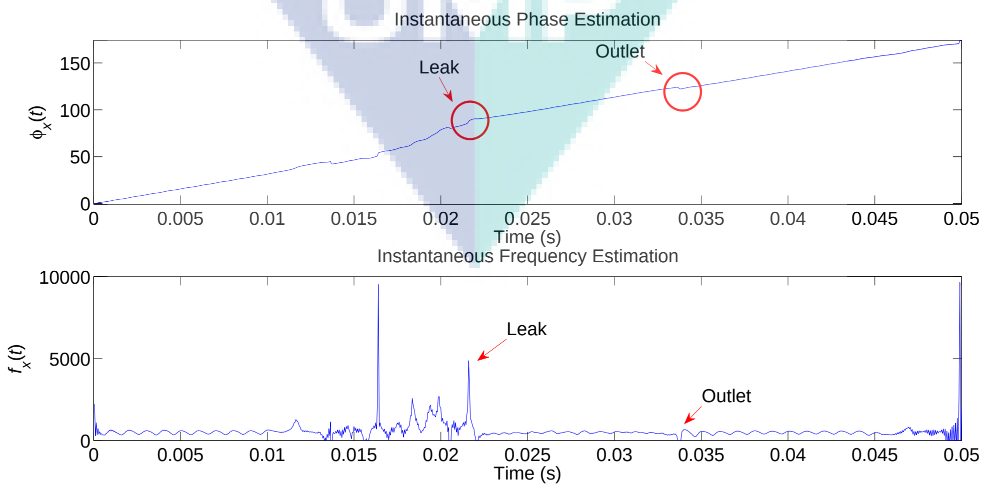


Figure 4.24: Instantaneous phase and instantaneous frequency with leak for GI pipeline

Even though there exists unknown spikes in Figure 4.24 previously, Hilbert spectrum still displayed the good results after selection of IMF. In Figure 4.25, the first spike for both condition was determined as the sound stop being injected. For the Figure 4.25 (a), the outlet is determined at 0.034 s (5.898 m). The leak occurs when the sound propagates in pipeline, and with existence of hole, the sound wave reflected and yield a leak at 0.023 s (4.014 m) as show in Figure 4.25 (b). The leak location error is 0.338 %. This is differed with Figure 4.25 (a) when there is no sound wave reflection. On the other hand, there is another reflection at 0.034 s (5.933 m), to show the outlet.

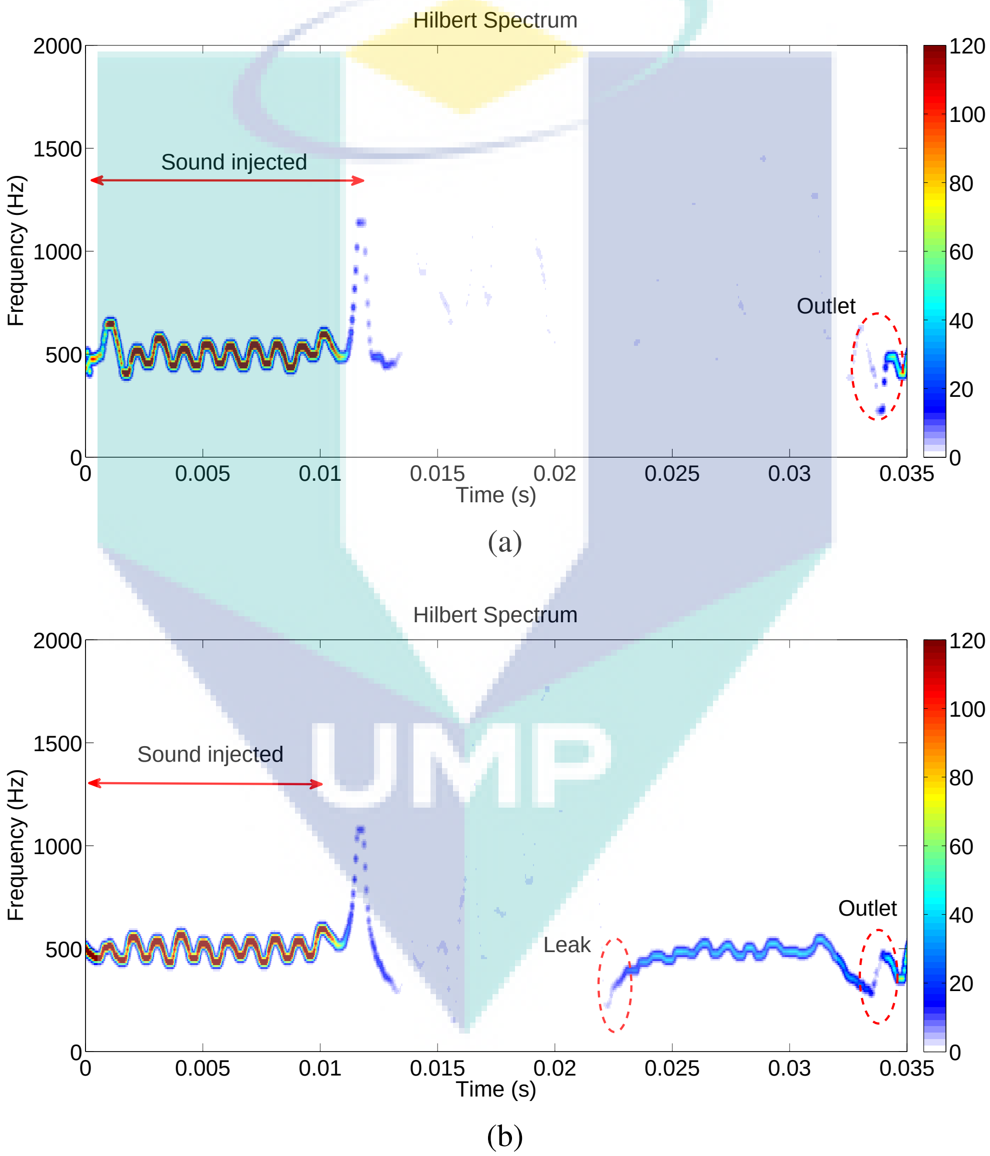


Figure 4.25: Hilbert spectrum of IMF4-IMF7 result for (a) without leak and (b) with leak for GI pipeline

Table 4.4 summarises the results of all of the tests. The lowest percentage error for leak is 0.700 % while 0.362 % for outlet location error and the highest is only 1.275 % for leak and 0.586 % for outlet. In general, the experimental results confirmed that HHT can provide simple and clear results, which indicate that this analysis technique can locate leaks in simple pipe system with acceptable errors.

Table 4.4
Results of the tests with and without leak condition in GI pipe using HHT

Test	Analysed Distance (m)		Measured Distance (m)		Error (%)	
	Leak	Outlet	Leak	Outlet	Leak	Outlet
1	4.010	6.084			1.125	0.431
2	4.005	6.075	4.000	6.000	0.700	0.586
3	4.013	6.074			1.275	0.362

4.4 Junction in Pipeline

The experiment is continued with addition of a feature (see Figure 4.26). In this case, an L-bend is used as the feature in the pipeline system. The objective of adding the L-bend is to validate the results and observe the time-frequency analysis results. The total length of pipeline is 6.8 m, the L-bend location is at 5.8 m while the leak is at 4 m. PVC is chosen as the material to be experimented on since result are easily obtained using this material as in previous experiments. In addition, PVC is easy to assemble and the absorption rate is medium compared to MDPE and GI.

Figure 4.26: L-bend feature

4.4.1 EEMD Analysis

EEMD analysis was done for the L-bend pipeline as shown in Figure 4.27 below. This benchmark results is compared to the one with a leak as in Figure 4.28. The decomposition running from high frequency to low frequency. The different can be easily find at IMF4 in Figure 4.28 compared to Figure 4.27. However, no indicator to show that the existence of L-bend.

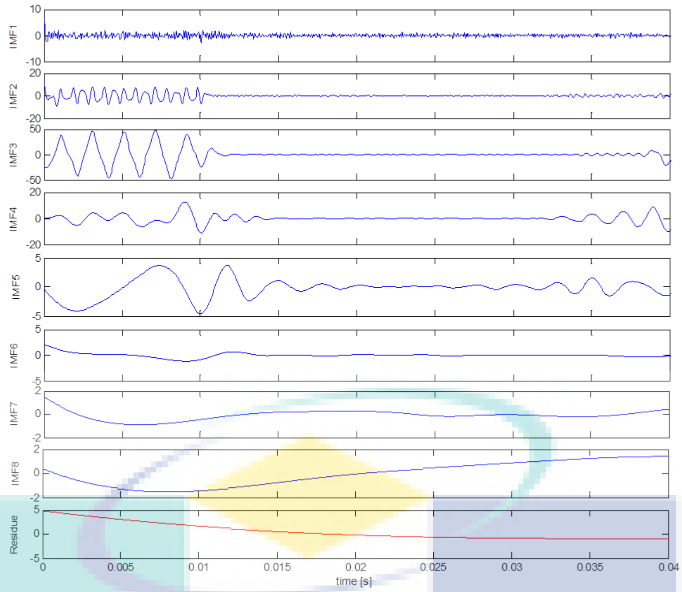


Figure 4.27: IMF1-IMF8 and residue for EEMD analysis (without leak)

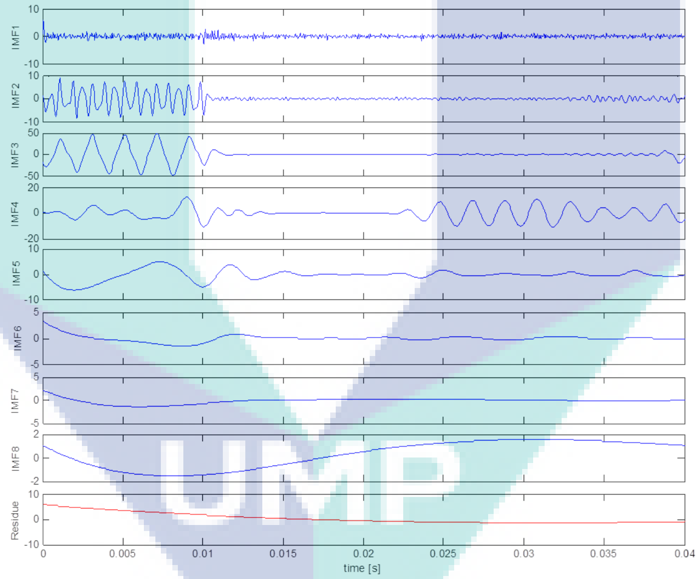


Figure 4.28: IMF1-IMF8 and residue for EEMD analysis (with leak)

4.4.2 HT Analysis

Instantaneous Phase and Frequency Analysis

In Figure 4.29, a clear spike indicates the feature in the pipeline without leak. At t = 0.012 s (2.015 m), the first spike was determined as sound injected stop, that is the reason the spike is higher. The L-bend was determined at t = 0.032 s, and converted to distance give 5.540 m, with location error of 4.476 %. The outlet can be seen at t = 0.039 s which is equivalent to 6.718 m and the location error is 1.202 %. On the other hands,

Figure 4.30 shows the result for instantaneous phase and frequency of leak with additional of L-bend in pipeline. The sound injection stops at t = 0.016 s (2.705 m) which is a little bit forefront from what was given, 0.010 s. The leak found at t = 0.026 s is corresponding to the leak at 4.520 m while the L-bend was found at t = 0.032 s equals to 5.619 m. On the other hand, the last spike at t = 0.036 s which equals to 6.352 m indicates the outlet. As compared to the real features in pipeline, the location error for leak is 12.988 %, L-bend is 2.663 % and outlet is 6.591 %. Even though the location error is quite high, the analysis is continued with EEMD to de-noise unwanted signal so the analysis is more accurate (Ghazali et al., 2012).

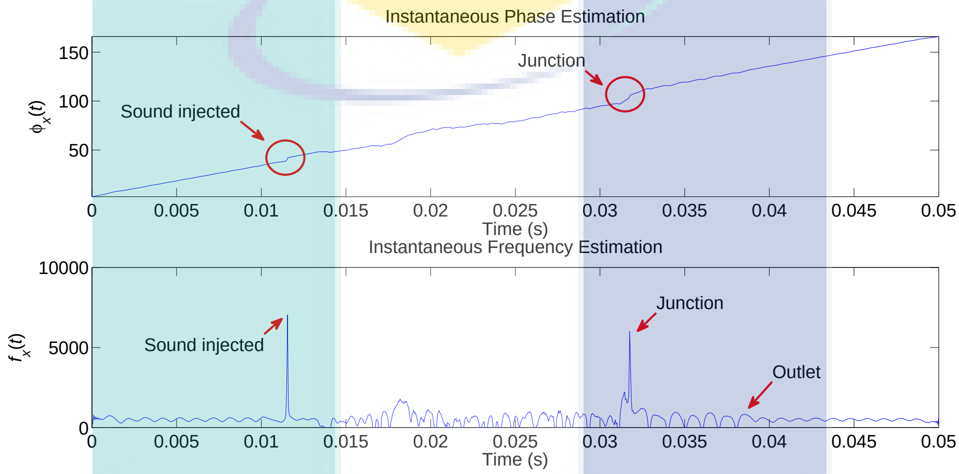


Figure 4.29: Instantaneous phase and instantaneous frequency without leak in PVC with addition of L-bend

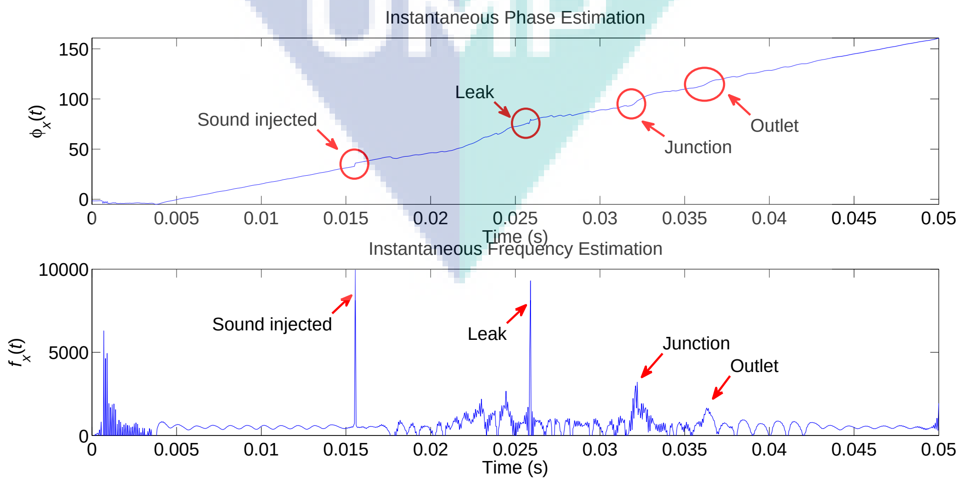
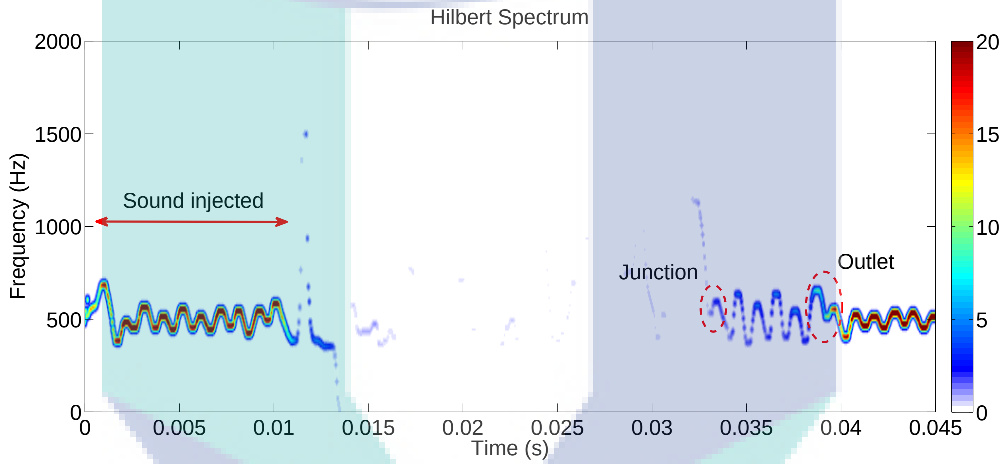


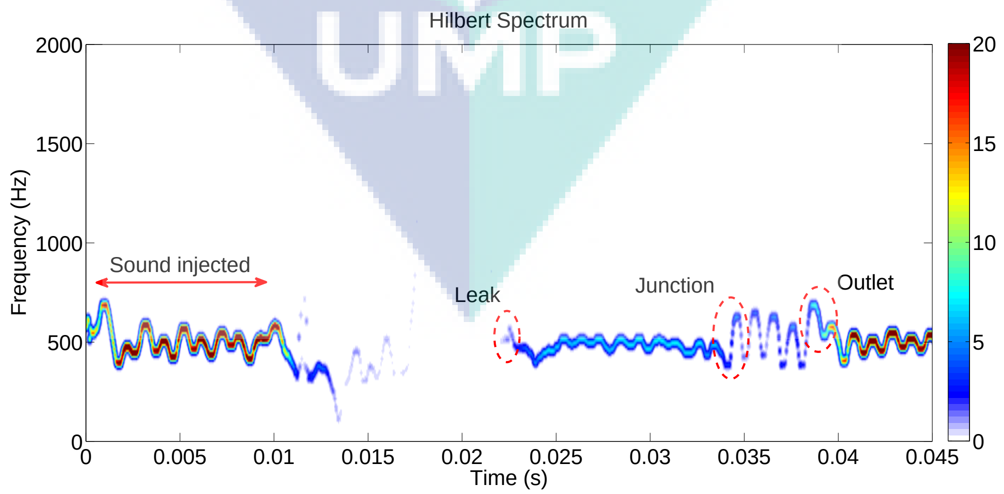
Figure 4.30: Instantaneous phase and instantaneous frequency with leak in PVC with addition of L-bend

Hilbert Spectrum

HHT results are shown in Figure 4.31. In the actual pipeline, the leak occurs at 4 m and the L-bend signal starts at 5.8 m while the outlet is at 6.8 m. The HHT results for without leak condition (see Figure 4.31 (a)) shows the presence of L-bend at 0.033 s and outlet at 0.039 s. Using 349 m/s speed of sound give 5.692 m of L-bend location and 6.854 m of outlet location. The location error was calculated with 1.859 % for leak and 0.799 % for outlet. For the leak condition (see Figure 4.31 (b)), the leak occurs at 0.023 s, L-bend at 0.034 s and outlet 0.039 s. When converted into distance, the leak occurs at 3.935 m (1.625 % location error), L-bend at 5.998 m (3.406 % location error) and outlet at 6.749 m (0.740 % location error).



(a)



(b)

Figure 4.31: Hilbert spectrum of IMF4-IMF7 result without leak (a) and with leak (b) for L-bend pipeline

Table 4.5 summarises the results of all the tests with addition of L-bend based on HHT analysis. In general, the results confirmed that HHT can provide good and satisfactory result to indicate the leak and L-bend in pipeline system with acceptable errors.

Table 4.5
Result of leak location and error for leak and L-bend condition for PVC pipe

Test	Analysed Distance (m)			Measured Distance (m)			Error (%)		
	Leak	Junction	Outlet	Leak	Junction	Outlet	Leak	Junction	Outlet
1	3.935	5.998	6.749				1.625	3.406	0.740
2	4.007	5.760	6.792	4.0	5.8	6.8	0.175	0.690	0.118
3	3.927	5.920	6.884				1.825	2.069	1.235

4.4.3 Discussion

Leak detection is crucial in gas pipeline area for preventing any accident to the surrounding environment. To improve the detection method, acoustic method is proposed in this study. This method includes the analysis of the data using HHT as signal processing in time-frequency analysis. Kim and Lee (2009) have concluded that time-frequency technique is the better analysis method compared to power spectral density (PSD). In the study, the time-frequency method was used to explain some of the features of wave propagation measurements made in gas pipes. In addition, time-frequency method can identify the cut-off frequencies for acoustic modes in a circular duct. In this study, three types of materials were used for straight pipeline and L-bend feature.

According to Huang et al. (1998), HHT is a robust method to analyze the non-stationary signal. This transformation is especially suited for analyzing non-linear and non-stationary data. HHT consists of two major components which are EMD and HT. However, the limitation in EMD such as the existence of unwanted ripple and mode-mixing problem leads to development of EEMD, which consequently resulting to the addition of noise signal to solve the problem (Flandrin and Goncalves, 2004; Wu and Huang, 2009). The synthetic signal that is performed in sub chapter 3.6 seeks to observe the difference of EMD and EEMD. The result is shown in Figure 3.13 an 3.15 shows a better resolution in EEMD compared to EMD. The unwanted ripple can be eliminated successfully. Mode mixing not only can cause serious aliasing in subsequent IMFs, but also cause individual IMFs to be devoid of physical meaning (Huang and Wu, 2008; Wu and Huang, 2009). The less meaningful IMFs also can be extinguished as presented in Chapter 4. The result shows that the obtained IMF1 to IMF3, and IMF8 did not have any meaningful fact.

Polikar (1996) found that FT is not relevant to analyze non-stationary signal as presented in most industrial practice. HT of *x(t)* produces time-domain signal. One of the advantages obtained with the representation of instantaneous frequency is that frequency can be determined at any given time *t*, since frequency can be calculated by differentiating the phase angle with respect to time (Huang and Attoh-Okine, 2005) as explained in Chapter 2. Ghazali (2012) also found that HT is the best transformation to present instantaneous frequency. The proposed method has shown that features and leak points along a pipeline can be determined with only a small error in distance.

Yunus et al. (2008) performed an experimental and simulation of gas pipeline leakage with different features consists of hole, L-bend, T-bend and crack type. Using Finite Difference Time Domain (FDTD), they presented the suitable frequency characteristic of the signal based on the features and successfully estimated leak location. They discovered the suitable frequency of injected sound is in range of 20-600 Hz for both circular leak and crack type. Wang et al. (2009b) have discussed that the experiment should be done either use low frequency or shorter time duration of injection. This is to get the better result and easy implementation during the experiment. The summary of the result is presented in Table 4.1. other than that, Urbanek et al. (2012) concluded that amplitude of echoes is directly proportional with size of hole and decrease with the distance from the hole because of the damping in the medium.

Pressure balance in the pipeline system can be interrupted when something is blocking the flow. Three effects that is occurred due to the incident wave (Burn et al., 1999; Beck and Staszewski, 2004) are reflection, transmission and absorption (Figure 2.8). Dispersion is the phenomenon of speed change in frequency due to structural and geometric size. Meanwhile, absorption is determined by the material used. Different material shows the difficulties during the analysis especially to find instantaneous frequency and phase. However, HHT is capable to perform satisfied result. The result for without leak and leak is presented in Figure 4.11 and Table 4.2 for MDPE, Figure 4.18 and Table 4.3 for PVC while Figure 4.25 and Table 4.4 for GI pipe. All the result is below than 5 % of error **?**.

Tao et al. (2015) studied on simulation wave propagation within network pipeline system for several branch. When an acoustic wave is propagating towards the branch joint in one of the pipes, part of the signal will be reflected at the branch joint. Wang et al. (2009a) used the signal generated by an acoustic pulse generator to inject the input signal into the pipeline. A 800 Hz sound was injected into the pipe with a bend. In conjunction, his study proposed the L-bend using PVC pipe with 6.8 m total length. The leak location error and also L-bend location is presented in Table 4.5 as well. The leak, L-bend and outlet is clearly presented in HHT as shown in Figure 4.31.

The proposed method has successfully present leak and L-bend location via EEMD and HT with lower than 5 % of error. Other than that, instantaneous frequency and phase can perform acceptable spikes to show the leak location. Due to different absorption rate in material, the result also shows the difficulties in analysing the result. However, clear understanding of time-frequency domain is important to define the leak location accurately.

4.5 Summary

The experiment was conducted using three different materials which are MDPE, PVC and GI pipelines. The extended experiment was conducted using PVC pipeline with additional L-bend. Preliminary study was done to choose the suitable frequency of sound injection to run in the experiment. As a result, 500 Hz of sound wave is chosen to inject into the pipeline. The instantaneous phase and frequency using HT helps the analysis and EEMD method is proven as an effective technique to filter the noise by removing the unwanted noise. As shown in previous results, it can be concluded that all of the experiments can removed IMF1-IMF3 and IMF8 before HT is being conducted, including for the L-bend case. The existence of L-bend can be performed by the instantaneous phase and frequency. The results was analysed to be perform in Hilbert spectrum. The percentage error is calculated to measure the accuracy of the leak location. Next chapter will present on the summary of findings, objectives, as well as conclusions for the study. Besides, some recommendations for further studies were also suggested in the same chapter.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Leak detection and location are vital to prevent any losses in term of financial and energy, ensure safety and control environmental problems. Therefore, effective techniques for leak detection are very important in order to improve these problem. The Hilbert Huang Transform (HHT) with Ensemble Empirical Mode Decomposition (EEMD) was developed and its performance testing had been successfully carried out. The observation on EEMD performance had involved experimental analysis. The experiment was conducted using different materials with different features. The results were analysed using HHT that consists of two components which are Hilbert transform (HT) and EEMD and as has been discussed thoroughly in this thesis. This study has found out that HHT can be alternative advance signal processing method for leak detection application. Thus, some recommendations for future studies were suggested in the last part of this section.

5.2 Summary of Findings

The objectives and conclusions of this research are stated below:

1. The experiment conducted using MDPE, PVC and GI pipe. All the materials show different level of difficulties on getting the signal. Using FFT, the leak cannot be detected because of limitation in time domain. However, the decomposition using EEMD shows the ability to decompose the signal while IMF is capable to eliminate the noise. In this case, 8 IMFs are presented in EEMD analysis. IMF1-IM3, and IMF8 is eliminated in order to get a clear signal to be analysed using HT. The unwanted ripple present in low frequency part of the spectrum in EMD also can be eliminated by using EEMD so that the result is more robust.

2. The non-stationary signal is decomposed by EEMD and then analysed by HT to get instantaneous phase and frequency. From the result, it showed that the HT method can capture most of the features but at the same time produces unnecessarily spikes, especially in the GI pipeline due to the hard type of material. For the soft material as MDPE, has lower sound absorption while PVC pipe which is harder has moderate low sound wave absorption.

3. The leak location and their condition was detected and demonstrated using Hilbert spectrum (HS). The reflection of the injected sound is clearly presented by HS and percentage error is calculated by using 349 m/s speed of sound. All materials can identify leak and outlet location with an acceptable error with 0.125 % to 1.850 % (leak) and 0.917 % to 1.250 % (outlet) for MDPE, 1.375 % to 2.200 % (leak) and 0.362 to 3.196 % (outlet) for PVC while 0.700 % to 1.275 % (leak) and 0.362 % to 0.586 % (outlet) for GI pipe. The highest error is 3.406 % in the L-bend condition. The range is below 5 % for acceptable error as discussed before. A few factors that can lead to inaccurate results including incorrect frequency of sound injection for L-bend and also the L-bend is too close to the outlet. The EEMD method has shown that leak points and features along a pipeline can be determined by analysis of instantaneous frequency, with only a small error in distance.

5.3 Recommendations for Future Works

Supposing this proposed method would be used, some improvements should be made in order to improve the results of the study. Some of the recommendations for future works are:

1. The experiment can be replaced with complicated pipeline arrangement in order to observe the effect of leak on the change in pressure wave in different size of pipe at different complexity.

2. The experiment can be done as field test and as simulation works.

3. Design pipelines with more complex features such as joints and L-bends since different features will produce different results.

4. Design a test rig with different types of leak since different types of leak will also produce different results.

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APPENDIX A

MATERIAL PROPERTIES

Table A.1
Properties of MDPE

Properties	Value
Tensile Strength	12.4-19.3 MPa
Young Modulus	172-379 MPa
Density	0.926-0.940 g/cm^3
Elongation	100-150 %
Specific Heat	1.916 kJ/kg.K

Source: *www.vinidex.com*

Table A.2
Mechanical Properties of PVC

Properties	Value
Ultimate Tensile Strength	52 MPa
Elongation	50-80 %
Shear Modulus	1 GPa
Bulk Modulus	4.7 GPa
Elastic Tensile Modulus	3.0-3.3 GPa
Elastic Flexural Modulus	2.7-3.0 GPa

Source: *www.vinidex.com*

Table A.3
Mechanical Properties of GI

Properties	Value
Tensile Strength	320-460 MPa
Yield Stress	195 MPa %
Young Modulus	165-180 GPa
Density	7.05-7.25 Mg/m^3
Elongation	20 %

Source: *www.vinidex.com*

APPENDIX B

Australian Journal of Basic and Applied Sciences, 8(15) Special 2014, Pages: 356-360

LEAK DETECTION IN MDPE GAS PIPELINE USING DUAL-TREE COMPLEX WAVELET TRANSFORM

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ABSTRACT

The pipeline system plays the important role in the industry and commonly use as media transport in the piping field on the land or on the sea as well. They are buried underground or situated in the wall of the buildings. The maintenance should be done properly to avoid any leakage to the surrounding. Therefore, the detection of the leak detection is the main investigation issue in order to get the fast and reliable leak detection method. Even though the reasons for these leaks are very well known, some of the current method is quite complicated and not precise. In addition, it is all about time consuming and cost of instalment. In this paper, we proposed a leak detection method using acoustic. The chirp signal injected into the pipeline system and the estimation of the leak location from the delay time passing by the reflection in the pipeline if there have a leak. Using Dual Tree Complex Wavelet Transform, the signal filtered and decomposed into five levels. Then, the cepstrum analysis was used to detect the echoes for leak location estimation. When a leak occurred, the new peak shows and identified the presence in the pipeline network. The leak detected at a certain point and the error in this experiment is 0.62 % for leak location and 1.24 % for the outlet, which is nearly accurate to the original leak position. The DTCWT and ceptrum analysis could give acceptable result and possible to identify leaks that are difficult to find by other method.

APPENDIX C

8th MUCET 2014, Date: 10-11 November 2014, Melaka, Malaysia

DETECTING LEAK IN GAS PIPELINE USING CONTINUOUS WAVELET TRANSFORM AND KURTOSIS

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ABSTRACT

The detection of the leak detection is the main investigation issue in order to get the fast and reliable leak detection method. Even thought the reasons for these leaks are very well known, some of the current method is quite complicated and not precise. In addition, it is all about time consuming and cost of installment. In this paper, we proposed a leak detection method using acoustic. The chirp signal injected into the pipeline system and the estimation of the leak detection from the delay time passing by the reflection of pressure wave in the pipeline if there have a leak. Using wavelet as the noise filtering, there can give a useful signal to verify the leak. Wavelet is the tool to de-noise the noise from the original signal and then tuned using maximum values of kurtosis. The main idea is the echoes detection of the pressure wave from the signal given by the original signal. Kurtosis plays the main role as the component to choose the filter parameter because of their nature to measure spikiness. The result shows that the highest value of kurtosis for the pipeline with leak is 6.465 while for the pipe without leak, the highest value for the kurtosis 5.3214.

APPENDIX D

The Engineering Technology International Conference 2015, Applied Mechanics and Materials Vol. 815 (2014) pp. 403-407

LEAK DETECTION IN GAS PIPELINE USING HILBERT-HUANG TRANSFORM

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ABSTRACT

This paper proposes a leak detection method using acoustic. The Hamming chirp signal injected into the pipeline system and the estimation of the leak location from the delay time passing by the reflection in the pipeline if there is a leak. By using Hilbert-Huang Transform (HHT), it can give a useful signal to verify the leak. HHT transforms Empirical Mode Decomposition (EMD) and Hilbert Spectrum analysis to perform time-frequency analysis. The leak location can be detected by multiplying by the speed of sound. This simple method gives accurate leak location and easy to implement.

APPENDIX E

3rd International Conference on Mechanical Engineering Research (ICMER 2015), IOP Conf. Series: Materials Science and Engineering Vol 100(1) pp. 012013

LEAK DETECTION IN GAS PIPELINE BY ACOUSTIC AND SIGNAL PROCESSING - A REVIEW

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ABSTRACT

The pipeline system is the most important part in media transport in order to deliver fluid to another station. The weak maintenance and poor safety will contribute to financial losses in term of fluid waste and environmental impacts. There are many classifications of techniques to make it easier to show their specific method and application. This paper discussion about gas leak detection in pipeline system using acoustic method will be presented in this paper. The wave propagation in the pipeline is a key parameter in acoustic method when the leak occurs and the pressure balance of the pipe will generated by the friction between wall in the pipe. The signal processing is used to decompose the raw signal and show in time-frequency. Findings based on the acoustic method can be used for comparative study in the future. Acoustic signal and HHT is the best method to detect leak in gas pipeline. More experiments and simulation need to be carried out to get the fast result of leaking and estimation of their location.

APPENDIX F

Automatika Journal, ISI (Impact Factor=0.307)

APPLICATION OF ENSEMBLE EMPIRICAL MODE DECOMPOSITION IN GAS PIPELINE LEAKAGE (Submitted)

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ABSTRACT

Hilbert-Huang Transform (HHT) is a powerful signal analysis method which is consist two part: empirical mode decomposition (EMD) and Hilbert transform (HT). The application of EMD in leak detection widely used but the mode mixing problem disturb the overall result especially to detect the leak location. To solve the problem in EMD, a white noise added to data analysis and called ensemble mode decomposition (EEMD). In this paper, the application of EMD compared using data from gas pipeline leakage. As the result, EEMD successful to give realistic leak location based on calculation of leak location error. In addition, the sharp distribution of time-frequency analysis also excel to appear compared to EMD. The selection of IMFs also can be choose constantly in order to filter the noise.

APPENDIX G

G.1 Publications

1. M. M. Amin, M. F. Ghazali, M. A. PiRemli, A. M. A. Hamat and N. F. Adnan, 2015. Leak Detection in Medium Density Polyethylene (MDPE) Pipe using Pressure Transient Method. *IOP Conf. Series: Materials Science and Engineering* **100**(1): 012007.

APPENDIX H

H.1 DEVELOPMENT OF LEAK DETECTION SYSTEM (LeDectSys)

Leak Detection System or short name, *LeDectSys* developed to detect the leak in online monitoring system for the unburied pipeline. This system developed by Advanced Structural Integrity and Vibration Research (ASIVR) in Faculty of Mechanical Engineering, Universiti Malaysia Pahang. MYIPO official patent application no is **PI2015002757**. This section included to proved this theory is able to detect the leak with including the most simple signal processing method which is cepstrum analysis. The early setup can be used for the next development using another powerful signal processing method.

H.1.1 How it Works

LeDectSys built from combination of Matlab and Graphical User Interface (GUI). The easy setup of *LeDectSys* is shows in Figure H.1 and their description of each instruments can be explained in Table H.1. The objective of this system is to detect the defect in the pipeline using online monitoring. Behind the system, cepstrum was used as the signal processing to analyse the signal. Cepstrum is the simple method and easy to use. The coding of cesptrum used together with GUI to handle the system properly. GUI will appear attractively to show the result.

Table H.1
Description of each instrument

Instrument	Description
National Instrument-DAQ	Data acquisition driver
Microphone	Captured the reflection of the injection sound
Pipeline	The part to be tested
Speaker	To spread the sound into the pipeline
Laptop	The online system

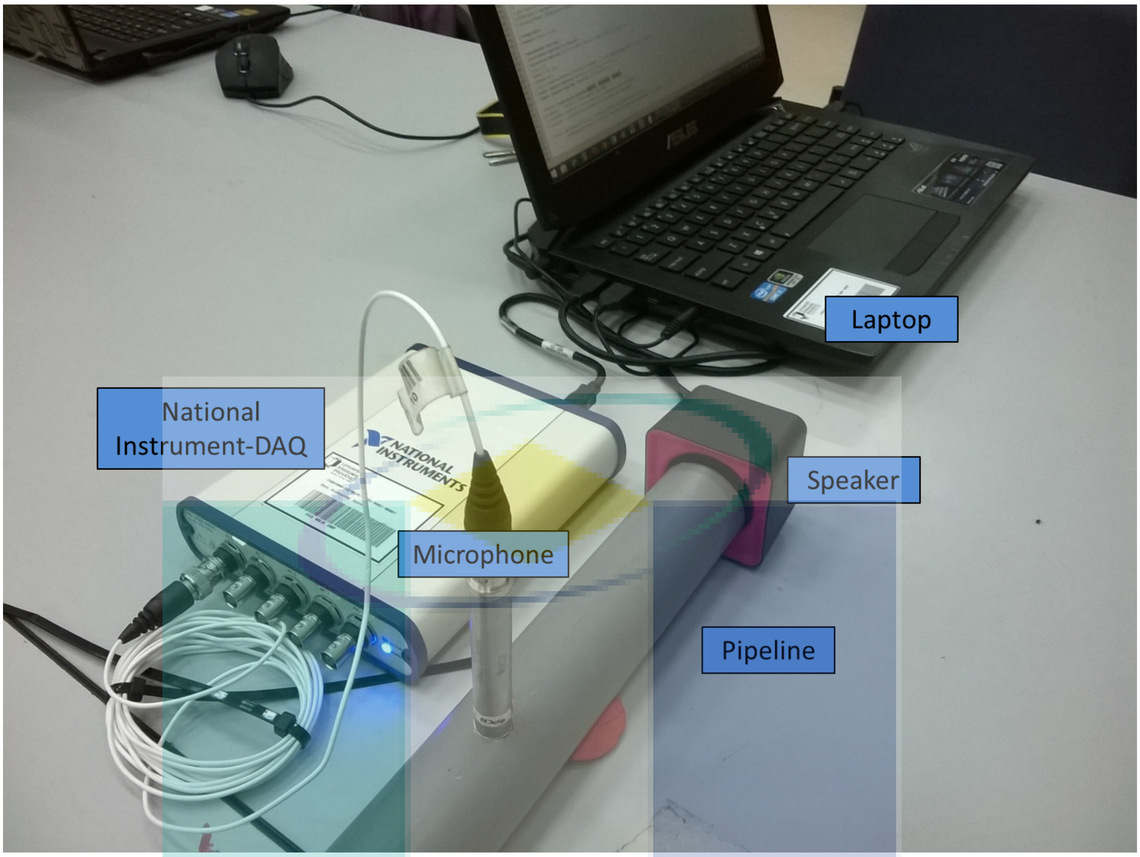

Figure H.1: Example setup

The *LeDectSys* works when the sampling rate, measurement duration, and microphone sensitivity were key in into the column. With suitable amplitude and frequency of sinusoid wave, *LeDectSys* can detect the defect in the pipeline. The leak can be located with the present of the positive spike as shown in Figure H.2.

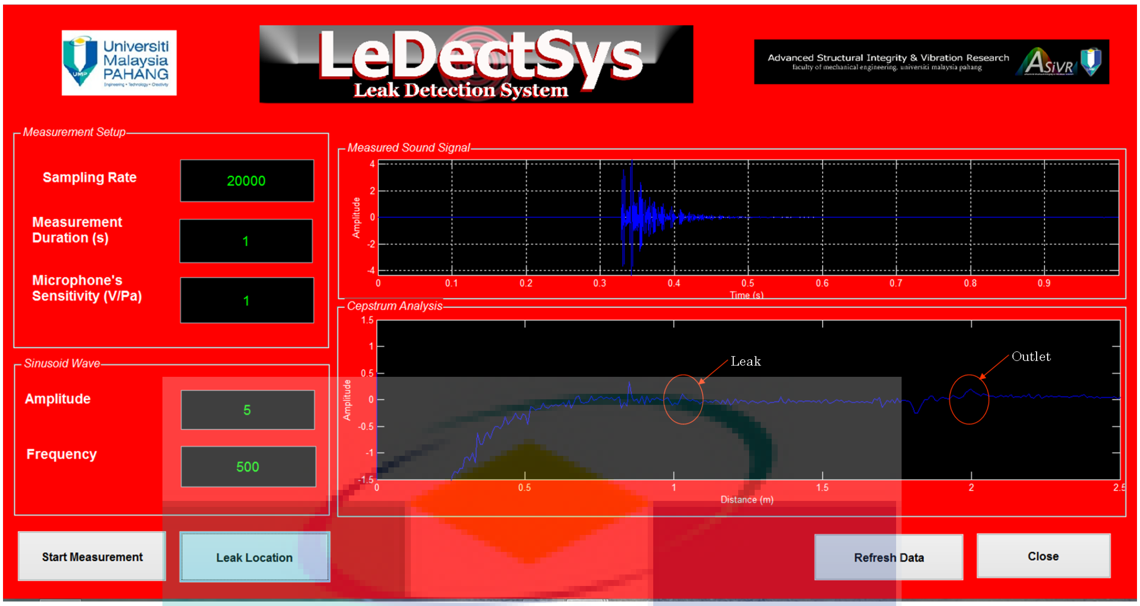

Figure H.2: LeDectSys interface

Table H.2
Description of functional icons during data acquisition process

Feature	**Description**
Sampling rate	Sampling rate of NI-DAQ
Measurement duration	Time for input signal injected into pipeline
Microphone's Sensitivity	Refer the transducer that we used
Amplitude	Sine wave amplitude
Frequency	Sine wave frequency