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LEAK DETECTION IN MEDIUM DENSITY POLYETHYLENE PIPE USING ENSEMBLE EMPIRICAL MODE DECOMPOSITION METHOD

MAKEEN BIN MOHD AMIN

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Master of Engineering (Mechanical)

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ABSTRAK

Tesis ini memberi tumpuan kepada pengesanan ciri-ciri dalam rangkaian saluran paip menggunakan Penggabungan Empirikal Kaedah Penguraian (EEMD). Pada masa kini, terdapat banyak pendekatan dalam kaedah untuk pengesanan ciri saluran paip itu sama ada dari luar atau dalaman. Satu-satunya hujah adalah kaedah yang akan menyampaikan hasil yang paling berkesan dan dengan kelebihan penjimatan masa dan mesra kepada manusia. Tujuan projek ini adalah untuk mengkaji dan menganalisis data dengan menggunakan kaedah EEMD untuk mengesan kebocoran dalam sistem saluran paip dan membandingkan kedudukan kebocoran antara jarak yang diukur dengan jarak yang dianalisis. Oleh itu, rig ujian dibina dengan menggunakan 56 m panjang paip polyethylene dengan menjadikan kebocoran sebagai ciri utama. Penggunaan injap solenoid adalah untuk menghasilkan fenomena air mengetuk. Fenomena mengetuk air akan menghasilkan gelombang fana di dalam paip supaya ciri-ciri paip tersebut boleh ditentukan. Data yang dikumpul menggunakan DASYLab dan akan dianalisis menggunakan perisian MATLAB. Kedudukan kebocoran dan laluan air keluar ditentukan dengan menjalani intrinsik analisis fungsi mod (IMF) dan kemudian dianalisis menggunakan analisis kekerapan frekuensi (IF) menggunakan kaedah EEMD. Eksperimen dijalankan dalam dua keadaan, pertama dengan menutup injap kebocoran dan satu lagi dengan membuka injap kebocoran. Keputusan analisis menunjukkan bahawa kedudukan laluan keluar adalah hampir sama dengan jarak yang diukur dengan 0.55% dan 6% dalam ralat peratusan. Lokasi kebocoran yang dianalisis juga ditentukan dan dibandingkan dengan jarak yang diukur. Ia menunjukkan hanya 3.21% daripada kesilapan antara jarak diukur dan jarak dianalisis. Kesimpulannya, kaedah EEMD adalah salah satu kaedah yang terbaik sebagai pendekatan untuk mengesan kebocoran sama ada untuk sistem paip bawah tanah atau atas tanah. Di samping itu, kaedah ini boleh dikatakan berkos rendah untuk kos pemasangannya dan lebih menjimatkan tenaga kerja.

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ABSTRACT

Nowadays, there are many approaches to the methods for detecting pipeline's feature either from external or internal. The only argument is which method will deliver the most effective result with the advantage of time-saving and human-friendly. The results were influenced by the surrounding noise either from inner or the outer pipeline networks. This thesis mainly focuses on the detection features in pipeline network using Ensemble Empirical Mode Decomposition Method (EEMD). The objectives of this thesis are to study and analyse data by using EEMD method for leakage detection in the pipeline system and identify and compare the leakage position between the measured distance and analysed distance. Therefore, the test rig was built by using 56m polyethene pipe with the leak as the main feature. Solenoid valve is used to create water hammering phenomenon. The water hammering phenomenon will generate a transient wave inside the pipe. The data was collected using DASYLab software and analysed using MATLAB software. The leakage and outlet position were determined by undergoing intrinsic mode function analysis (IMF) and later analysed by their respective instantaneous frequency analysis (IF) using EEMD method. The experiment was runs in two situations, firstly by closing the leakage valve and the other one by opening the valve to create leakage. The analysed results show that the position of the outlet is almost similar to the measured distance with 0.55% and 6% of percentage error. The analysed leakage location is also determined and compared to the measured distance. It indicates that only 3.21% of error between the measured distance and analysed distance and analysed distance. It can be concluded that the EEMD analysis is one of the best methods to be the approach in leak detection of either underground or above ground piping system. In addition, this method can be said as low in cost and energy saving.

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LIST OF SYMBOLS

σ	Variance
$Z\infty$	I-Kaz coefficient
s	Standard deviation
x	Mean
X_i	The value of data point
K	Kurtosis
r.m.s	Root mean square
f_{max}	Maximum frequency span
LF	Low frequency
HF	High frequency
VF	Very high frequency

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LIST OF ABBREVIATIONS

AWWA	American Water Work Association
CWT	Continuous Wavelet Transform
DQ	Direct Quadrature
DWT	Discrete Wavelet Transform
ECG	Electrocardiogram
EMD	Empirical Mode Decomposition
EEMD	Ensemble Empirical Mode Decomposition
FT	Fourier Transform
GA	Genetic Algorithm
GPR	Ground Penetrating Radar
GUI	Graphical User Interface
HS	Hilbert Spectrum
HT	Hilbert Transform
HHT	Hilbert Huang Transform
IF	Instantaneous Frequency
IWA	International Water Association
I-Kaz	Integrated Kurtosis Algorithm for Z-Filter Technique
MI	Merit Index
MIR	Mutual Information Ratio
NHT	Normalized Hilbert Transform
NRW	Non-Revenue Water
PVC	Polyvinyl Chloride
PPA	Pressure Point Analysis
SNR	Signal to Noise Ratio
TSA	Time Synchronous Average Algorithm
TEO	Teager Energy Operator

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Water is one of essential elements for the human beings and natures to survive and stay alive. In Malaysia, water resources are rich and accessible throughout the year. They are expected at 580 km^3/year (average 1977-2001), corresponding to more than p3,000 cubic meters per capita and year. In 1995, the overall water extraction was expected at 12.5 km^3 or less than 3 percent of resources available. In nature, 76 percent of water was used for agriculture, 11 percent for municipal water supply and 13 percent for industries. Thus, only less than 1 percent of available water resources are used for drinking water supply (2005) Report by State of Water Resources Management in ASEAN.

Water is one of essential elements on earth to all human being and to be a scarce supply in most parts of the world. In the world scenario nowadays, water is a global issue. The World Water Vision Report in the year 2000 has acknowledged that there is a global water crisis. The crisis is not about having too little water to satisfy our needs, but it is a crisis of water management so badly for billions of people in the world and in other words, "suffer badly". The lack of water services is one of the most important physical signs of extreme poverty as estimated in Global Water Supply and Sanitation Assessment (2000) Report by World Health Organisation (WHO) and United Nations Children' Fund (UNICEF). 780 million people had no access to improved water supply and 2.5 billion were without access to improved sanitation. If this current trend continues, these numbers will remain unacceptably high in 2015, where 605 million people will be without an

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improved drinking water source and 2.4 billion people will lack access to improved sanitation facilities.

Water loss is a common problem that occurs in all water supply system. For management, the water reducing is a special concern of every water supply company. Most urban areas throughout the world are losing 30 to 50% of their water supply due to leakage. An investment in repairing leaks, the company purchased new pipes and maintaining existing and new pipe structures would pay for itself in conserved water in a few years. Mexico City's water system loses 1.9 billion cubic meters of water every year due to leakage (R. L. R.Frauendorfer, 2010).

A large water utility may experience 300 cases or more water main breaks a year. Each such main failure causes disruptions to the water supply and may require emergency repairs. Millions of dollars of damage may be the result if a large diameter of main pipe fails. Even without a large main failure, the total cost of small diameter water main breaks represents a significant portion of the annual operating budget of most water utilities (K. A. Porter, 2016). Continuous water movement inside the pipe can cause corrosion. Corrosion is one of the most complicated and costly problems facing drinking water utilities. A large number of parameters affect pipe corrosion, including water quality and composition, flow conditions, biological activity, and corrosion inhibitors. This work synthesizes nearly 100 years of corrosion studies in an attempt to provide the water industry with an updated understanding of factors that influence pipe corrosion (L.S. McNeil, M. Edwards, 2013).

The method using transient waves have been researched by various methods as this is a better way of detecting leakage in the pipeline with a lower cost to operate and it could benefit in real life application. A group of university researchers from Sheffield University have proven that by using cross-correlation method, cepstrum analysis, and using various types of wavelet transform analysis (M. F. Ghazali, 2012).

1.2 Problem Statement

In this research, there are some significant problems that might need to be appraised to run this project smoothly. The sensor is one of the main instruments that is used in completing the experiment. Sensor is a transducer whose function to sense or to detect some characteristic of its surroundings. It senses occasions or changes in quantities

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and be responsible for a corresponding signal output, generally as an electrical or optical signal. Pressure sensor that was used throughout the experiment provides the detection of transient pressure created by water hammer from the solenoid valve.

However, the process of gathering data from the pressure sensor is not only specific for transient signal but also influenced by the surrounding noise either from inner or the outer pipeline networks. This noise can also come from the vibration created by the water flowing in the pipeline and also by work done by the pump. So, the filtering or reduction process of noise need to be handled in order to gather the accurate data of transient pressure.

Water hammer created by solenoid valve causes the pressure surges throughout the pipeline system, which caused the flow of transient signal along the medium density polyethylene (MDPE) pipe (B. B. S. Meniconi, M. Ferrante, 2012). However, MDPE pipe was basically built with the chemical and mechanical properties that caused the high level of water dispersion. The dispersion in MDPE pipe can easily reduce the transient signal created from water hammering phenomenon. It is better to use the pipe that can maintain the transient signal created along the pipeline network so that the detection by the pressure sensor is only specifically for the transient signal.

The large stream of pipe distribution that buried underground need to be analysed. It is difficult to just put the sensor and do the experiment. Before any in field experiment to be done, the small scale of complete test rig have to be develop In order to complete the experiment. The design and sketching of the test rig with straight pipe length, the position of hydrant, pressure transient sensor, water hammering device, data collection, the point of leaks any location in a pipeline is using solidwork. The data collection from pressure sensor detect the water behaviour (water hammering) and internal method (pressure transient) data will be analysed.

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1.3 Objectives

The focus will be:

i) To develop workable single pipeline system that pinpoint leaks working prototype.

ii) To analyse design functionality by using pressure transient for leakage detection and location in the single pipeline system.

iii) To detect leaks using advanced signal analysis Ensemble Emperical Mode Decomposition (EEMD) method.

1.4 Scopes

Scope of research:

i) 60mm medium density of polyethylene pipe within 60-70 meter total length, fixed with 3 mm hole diameter on 19.7 meter away indicates as leak.

ii) Water pressure of 2 bar.

iii) The acquired signal is pressure transient

iv) Fire hydrant act as a point access pipeline network and acquire data.

v) The pressure transient signal analysed using instantaneous frequency.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Malaysia is rich in water resources, but there was a high demand for clean water that increased over the years. The water crisis is faced by most residents in the central region of the country since 1998. Due to the increasing demand for water, an efficient water distribution network is the key to prevent the repetition of such water crisis.

Water distribution systems are networks of pipes. Supply of water from the clear water tank at the treatment plant to various service reservoir is by gravity. Water transmission be necessary to distribute water from a water treatment plant to a service reservoir. Treated water is pumped directly or by gravity to various reservoirs to a main balancing reservoir. For direct supply, tapping points is at different elevation and pressure is required in the network. Water loss can be a high influencer in the distribution of water around the piping systems (World Health Organization WHO, 2014).

Hazardous chemicals can be released from materials and equipment by leaching due to contact with pipe distribution or by corrosion. Leaching can be reduced by selecting materials and fittings that suitable for contact with pipe distribution. Stagnation tends to increases concentrations of hazardous chemicals in water by reducing the impacts of dilution associated with water flow (Sorg, Schock & Lyte, 1999; Lyte & Schock, 2000).

The corrosion can be lead to leaks in pipeline networks. To detect the leaks it has internal and external method. Internal method is the traditional way and can be handle by

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the expert workers or experience to do the investigation. Internal method is the method that lately using by a lot of researchers and big company.

2.2 Water Distribution System

There were three type of feeders in water distribution system. First is the primary feeder, where it is a large pipe. It was usually coming with diameters ranging between 12 to 36 inches based on the size of the population. Primary feeders delivered the water from the water treatment plant to corporation line of the community and/or to major water storage locations within the community.

The secondary feeders is the type of feeders that connected to the primary feeders in order to transport the water into the pipe distribution system in underground along the major streets of the community. Secondary feeders need to be placed to supply a water to all commercial property, public buildings, and private sector buildings that have a needed water flow over 1,000 gpm. Secondary feeders typically are 10 to 16 inches in diameter (World Health Organization and UNICEF, 2005).

The third type is called distributor mains, distributor mains which are used to transport water from the secondary feeders to individual streets in the areas of the community that have small businesses like convenience stores and gas stations but, more importantly, along with residential streets. According to Unicef, 2005, The minimum pipe size should be 6 inches and, based on the system design, a possible dead-end pipe may need to be 8 or even 10 inches. A structure for water supply system from water treatment plant can be illustrated as in figure 2.1.

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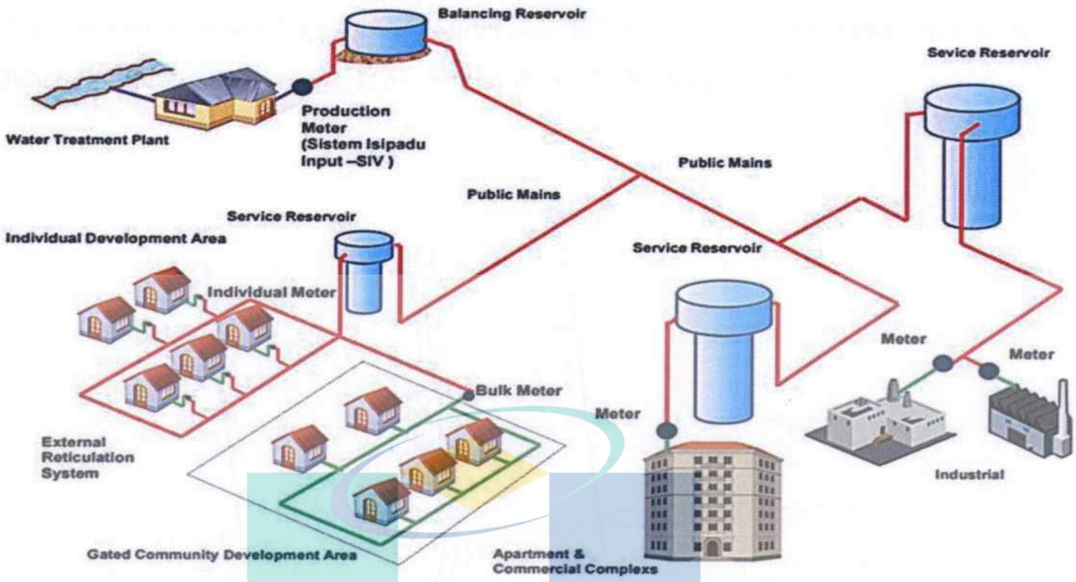

Figure 2.1 Example of the Water Supply System

Source: M. Farley et al., (2008)

The sizes of pipe associated with the three classifications of pipe in a typical water system are in approximations. The classification is primary feeders, secondary feeders and distribution mains. The needed pipe size throughout the built-upon areas of a community is based on the hydraulic gradient of the community, consumer consumption profiles through the community, needed fire flow at representative locations throughout the community, and, quite importantly, the two methods for laying and connecting pipe throughout the community. The traditional pipe system design is referred to as a Single-Point Feed System. This is illustrated in Figure 2.2.

Based on Figure 2.2, water is delivered from the treatment plant to the community corporation line with a single primary feeder. The primary feed, in turn, supplies the secondary feeders along the main streets of the community, and the distributor mains supply the block frontage along the residential streets. Note that any demand point on the system for either consumer consumption or fire flow through a fire hydrant is fed from one direction only. In the single-point feed system, the pipe sizes need to meet the maximum daily consumption demand plus the needed fire flow. This results in a larger pipe needed than under normal daily usage without any fires. The second major weakness of this type of system is that there may be a lot of dead-end mains in the residential areas and at the end of secondary mains. This leads to the stagnation of water, which rapidly reduces the quality of water (H. M. Salleh & N. A. Malek, 2010).

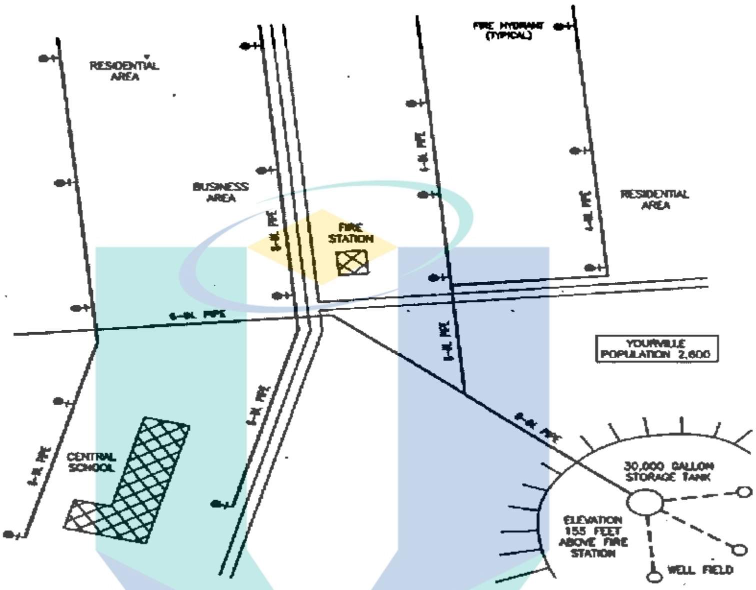

Figure 2.2 Water Supply for Small Community Water Distribution System

Souce: H. E. Hickey (2008)

More modern approach to water system design is to loop all the water mains or cross-tie the mains so that at any demand point, the water is supplied from two directions (M. Farley et al., 2008). A basic Pipe Looped water system is depicted in Figure 2.3. This allows the designing engineer to develop a hydraulic model of the system and to determine mathematically the proper size of a pipe according to flow paths to meet the consumer and the needed fire flow demand points. It is important to note that many older water systems have been updated. By laying a primary feeder around the perimeter of the community to tie in all of the dead-end mains to improve both flow distribution and water pressures through the community.

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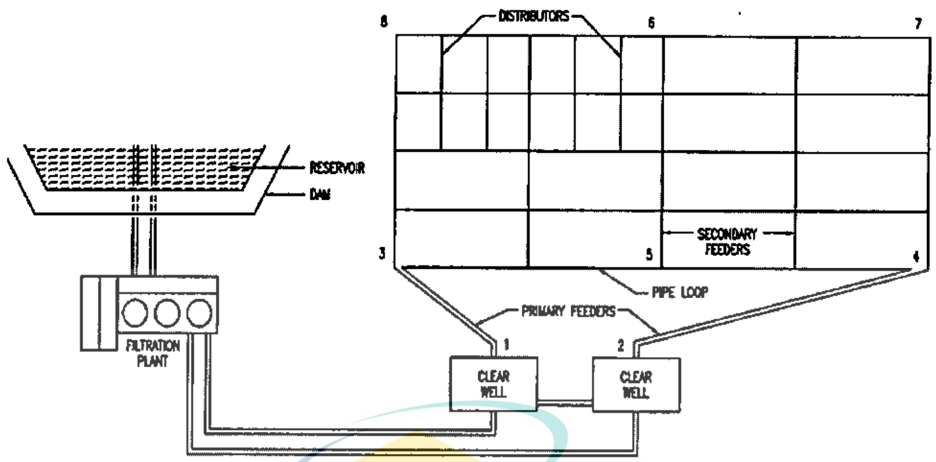

Figure 2.3 Layout of a Typical Looped Water Distribution System

Souce: M. Farley et al., (2008)

2.3 Failure Mechanisms of a Pipe

Continuous water movement inside the pipe can cause corrosion. The corrosion may fail the pipe and expose them to burst and leak at that location (R. Li et al., 2015).

Corrosion will grow with time and ultimately lead to a pipe breaking or leaking. But then, plastic pipe material also may suffer from chemical degradation. In water distribution systems, the failure can be split into two categories, pipe failure and fitting failure. Pipe breakage types have been classified by the previous researcher (D. O'day, 1982). There's many type of failure will pipe cracks or fail, below will explain some of type of failure facing to water pipe that buried underground.

2.3.1 Circumferential Cracking

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Circumferential cracking is shown in Figure 2.4, where normally it is caused by the bending forces applied to the pipe. Bending stress is often the result of soil movement, thermal contraction or third-party interference. Circumferential cracking is the most common failure mode for smaller diameter cast iron pipes. In statistics of asbestos cement water main breaks from the city of Regina in Canada were presented. Circumferential breaks were shown to be the predominant failure mode comprising 90.9% of all pipe failures. It was also demonstrated that the failure rate was decreasing with increasing pipe diameter.

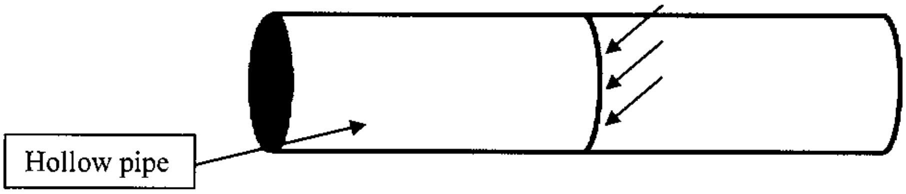

Figure 2.4 Circumferential Cracking

Souce: H. E. Hickey, (2008)

2.3.2 Longitudinal Cracking

Longitudinal cracking as shown in Figure 2.5 is more common in large diameter pipes. A number of different types of loading can be the main reason that caused longitudinal cracking, like the interior pressure of water and ring stress formed by the soil cover burden, outer load or thermal fluctuations. Longitudinal failure can expand along the length of the pipeline due to an initial small crack. When two cracks on opposed sides of the pipe introduced it results in a widespread detachment of the sector of the pipe that may be along the pipe sections itself.

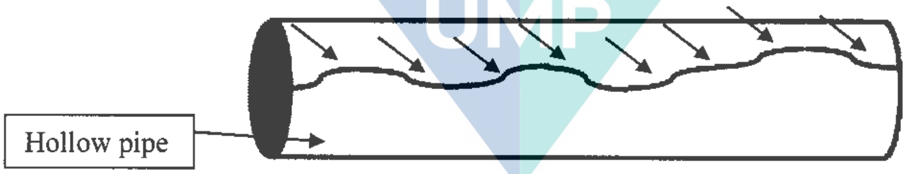

Figure 2.5 Longitudinal Cracking

Souce: H. E. Hickey, (2008)

2.3.3 Bell Splitting

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Bell splitting in Figure 2.6 is most ordinary in a smaller diameter of pipes. The main reason for this type of failure mechanism to happen is the sealing of the intersections. Basically, lead was used to wrap the joints. In the 1930s and 1940s, the lead was switched to leadite. As a non-metallic compound, leadite has a dissimilar thermal expansion coefficient than lead. It causes the occurrence of bell splitting at the low level of temperature.

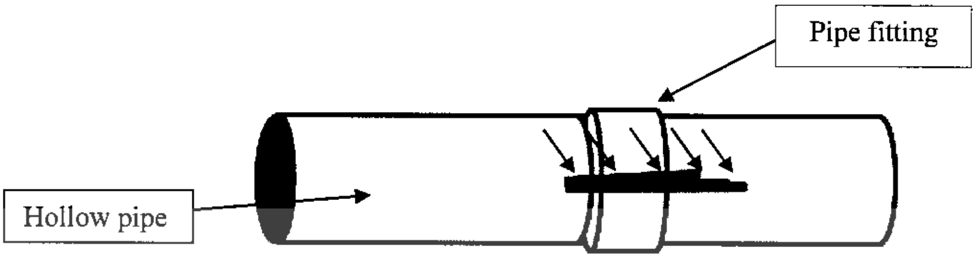

Figure 2.6 Bell Splitting

Souce: H. E. Hickey, (2008)

2.3.4 Corrosion Pitting and Blow-Out Hole

Corrosion is an important factor that plays a major role in the pipe failure process that is widely accepted. Corrosion potholes in Figure 2.7 (a) cause the reduction in the mechanical resistance and thickness of wall for a certain pipe. As the result from the thinned of pipe, pipe deterioration, failure and management in water supply system, pressure blows out a hole at the wall of the pipe as shown in Figure 2.7 (b). The size of the hole is influenced by the distribution of corrosion and the pressure in the pipe. The blow-out hole can be fairly large in some cases (X.Y. Zhang et al., 2013).

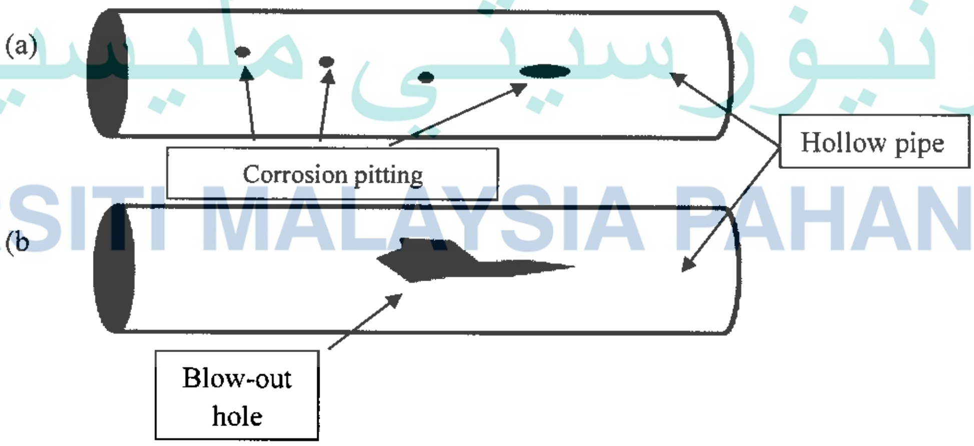

Figure 2.7 (a) Corrosion pitting and (b) Blow-out hole

Source: A. A. Hashem, (2010)

2.3.5 Bell Shearing

Large diameter pipes are not likely to be affected from a circumferential catastrophe. However, large size cast iron pipes may fail by having a sector of a bell shearing failure as shown in Figure 2.8. Longitudinal crack that propagates along the length of the pipeline occurs due to the simple compressive loading from the pressure underground (A. A. Hashem, 2010). The occurrence of bell shearing, however, often results from the bending of the pipelines structures.

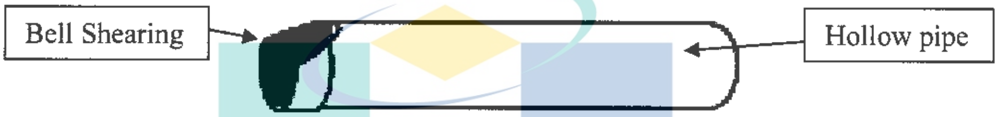

Figure 2.8 Bell Shearing

Source: A. A. Hashem, (2010)

2.3.6 Spiral Cracking

Spiral cracking as shown in Figure 2.9 is a quite unique failure mechanism mode that on occasion happens in smaller pipe's diameter. The originally circumferential crack spreads throughout the pipe in a spiral way. This kind of failure is linked to pressure surges, but it can also be interrelated to an arrangement of pipe that causes bending force and internal pressure (R. Farmania et al., 2017).

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Figure 2.9 Spiral Cracking

Source: A. A. Hashem, (2010)

All the failure mechanism can happen in any pipeline systems either underground piping and also above ground piping. All the failure mechanism can prompt big lost to water supply industries either in water loss and also maintenance services. Pressure surges can create a big disaster for a pipe that already ageing. With the corrosion happen along the pipelines, these become a big primer to pipe failure. These will not only affect the pipelines but also the infrastructure that is located around the pipeline network.

2.4 Failure in Pipeline System

A large water utility may experience 300 or more water main breaks a year. Each such main failure causes disruptions to water supply and may require emergency repairs. If a large diameter main fails, millions of dollars of damage may result. Even without a large main failure, the total cost of small diameter water main breaks represents a significant portion of the annual operating budget of most water utilities (H. E. Hickey, 2008). In addition to corrosion, manufacturing defects, human error and unexpected levels of pipe loading play a role in the large number of pipe failures that occur each year. Corrosion will grow with time and ultimately lead to a pipe breaking or leaking. But then, plastic pipe material also may suffer from chemical degradation (R. Farmania et al., 2017). In water distribution systems, the failure can be split into two categories, pipe failure and fitting failure. The table below in figure 2.10 depicts these types of failure. Pipe breakage type describes the actual manner in which the pipe breaks. The failure mechanism varies depending on the material and the diameter of a pipe.

Figure 2.10 (a) shows the removal of a piece of the pipe wall. This form of failure is brittle in nature. Size can vary depending on pipe material but generally is greater than 100 cm^2. Figure 2.10 (b) shows the small holes usually less than 10 mm^2 in sewer pipes internal erosion from grit can result in perforation of Cement Mortar Lined (CML) steel pipes.

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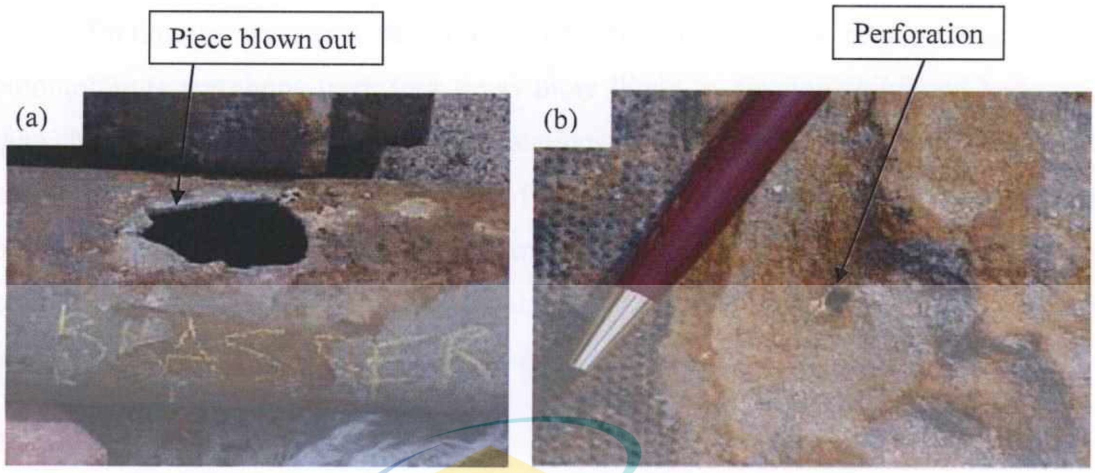

Figure 2.10 Type of Pipe Failure (a) Piece Blown Out and (b) Perforation

Source: R. Farmania et al., (2008)

2.5 Public Health & Environment

Leaking underground pipes are one of the most serious threats to our nation's drinking water supplies source by Water Safety in Distribution System, WHO. Leaking underground storage tank can hold substances such as fuel (e.g. gasoline or diesel), used oil and other toxic substances. Leaking tanks can contain dozens of dangerous chemicals that can contaminate groundwater, seep into homes and pose a risk of explosion (J. M. Makar et al., 2001). Gasoline is a complex blend of several hundred of compounds. Once the tanks leak, many of these contaminants can move rapidly through the surrounding soil, quickly contaminating large quantities of groundwater and seep into the surface water, such as lakes and rivers, and some will seep into pipe leaks (Osama Hunaidi, 2000).

Fifty percent of the nation's population and 100 percent in virtually all rural areas rely on groundwater for drinking water (M. W. LeChevallier, R.W.Gullick, 2010). About 680,000 federally-regulated storage tanks are buried in urban and rural areas across our nation. Underground storage tanks hold toxic material, such as gasoline and waste oil, which contain dangerous substances that can cause cancer and harm developing children (H. Rezaeia et al., 2015). Chemicals in storage tank can quickly move through soil and pollute groundwater. Leaking storage tank has contaminated drinking water supplies for schools and threatened drinking water supplies for the elderly.

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Preliminary research has found that children who live near gas stations or automobile repair shops were four times more likely to develop childhood leukaemia than children who did not live near such stations establishments. Gas stations often have a storage tank that holds gasoline (M. Pal, N. Dixon, J. Flint. 2010). Gas contains benzene, which is known to cause leukaemia. Gasoline and other dangerous substances can silently leak from storage tank contaminating groundwater and migrating under nearby properties, including yards and playgrounds (V. Raman. 1993).

2.6 Non-Revenue Water (NRW)

The global volume of non-revenue water (NRW) or water losses is staggering. Each year, more than $32x10^9$ m^3 of treated water are lost through leakage from the distribution networks (R. Mckenzie, Z. N. Siqalaba, W. A. Wegelin, 2012). An additional of $16x10^9$ m^3 per year are delivered to the customers but not invoiced because of theft, poor metering, or corruption.

As referred in Figure 2.11, we can see the overview of NRW for all states in Malaysia. There is an abundant amount of NRW that are being accumulated, the average nationwide of NRW is 36.63% with the highest percentage of NRW is accounted in each state surpassed a total of 40% of revenue water lost due to numerous surroundings (H. M. Salleh, N.A. Malek, 2007). More than $4.27x10^9$ litres of treated water that is enough to fill more than 1,700 Olympic-sized swimming pools or keep Perlis going for 53 days are leaking out of the country's ageing pipe system every day.

Experts warn that more water will be wasted unless drastic measures are taken. If saved, that amount of water could ease the stressed water supplies in Klang Valley, as fears of a shortage and rationing loom dangerously. According to the National Water Services Commission (SPAN), non-revenue water (NRW) is accounted for 36.6% of all water pumped out of treatment plants in 2013, or about 5.69 billion litres a day (H. M. Salleh, N.A. Malek, 2007). This was higher than 2012, which saw a 36.4% NRW. From this amount, at least 75% was due to problems like leaky asbestos-cement pipes and other infrastructure problems.

Association of Water and Energy Research (AWER), president S. Piarapakaran said that unless the pipes were fixed, more water would be lost even if the state

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governments rushing to build treatment plants to meet a growing local demand (The Star, 27 May 2015). While a number of states have seen their NRW levels fall in 2013, others such as Selangor saw more water lost as shown in Figure 2.11.

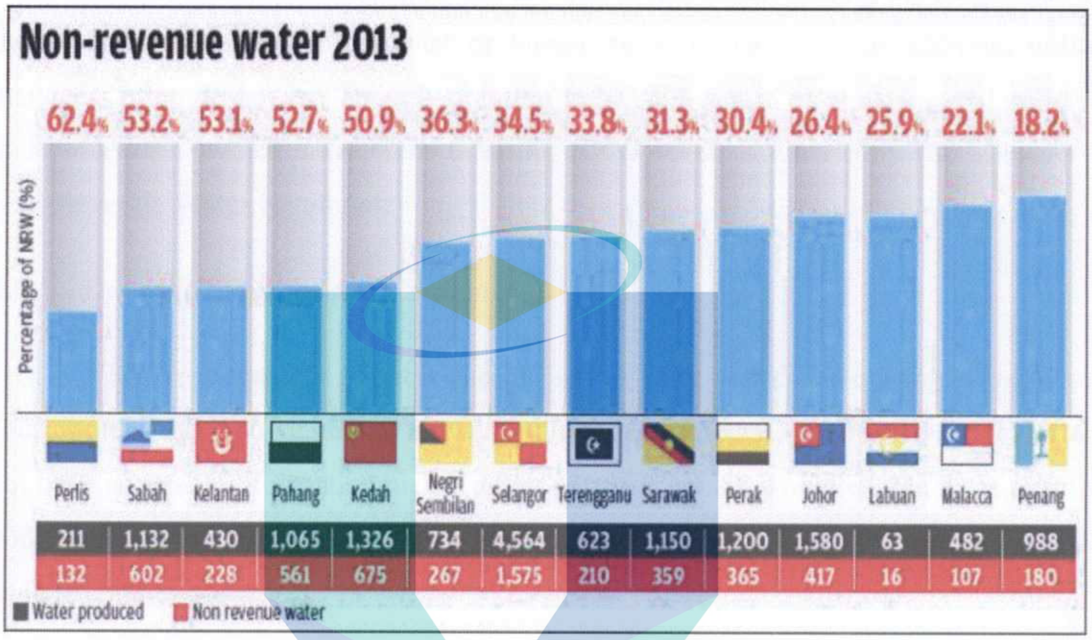

Figure 2.11 Non-revenue water (NRW) 2013 in Malaysia.

Source: The Star, 27 May (2015)

There are areas of plentiful water across Asia, just as there are water-scarce areas, as a result of both regional geography and a country's ability to pay for water. Although reducing NRW cannot solve such global contrasts, it can help to improve the quantity and quality of water available in water-scarce areas (B. Kingdom, R. Liemberger, P. Marin, 2006). Not all countries or regions-particularly those in parts of Asia have the infrastructure and established operational procedures to begin tackling the NRW.

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Many are struggling to ensure that customers receive a reasonable water supply to sustain health and life. Water utility managers in Asia will invariably face greater challenges including the following rapid urbanization, diminishing water supply, environmental pollution, outdated infrastructure, poor operations and maintenance policy, including ineffective record-keeping systems, inadequate technical skills and technology, greater financial constraints, including an unsuitable tariff structure and/or revenue collection policy, political, cultural, and social influences, and a higher incidence of commercial losses, particularly illegal connections (C. H. Lai, N. W. Chan, R.Roy, 2017).

The reasons NRW strategies fail are due to not understanding the magnitude of the problem to a lack of financial or human resource capacity. In addition, utility managers often do not pay enough attention to NRW because of weak internal policies and procedures, which contributes to rising NRW levels source from The Manager's Non-Revenue Water Handbook.

2.7 Leakage Solution and Control

NRW management is not a one-off activity, but one that requiring a long-term commitment and involvement of all water utility departments. Many utility managers do not have access to information on the entire network, which would enable them to fully understand the nature of NRW and its impact on utility operations, its financial health, and customer satisfaction.

Underestimating NRW's complexity, and the potential benefits of reducing NRW, often lead to reduction programmes' failure. Successful NRW reduction is not about solving an isolated technical problem but instead is tied to overall asset management, operations, customer support, financial allocations, and other factors as shown in Figure 2.12.

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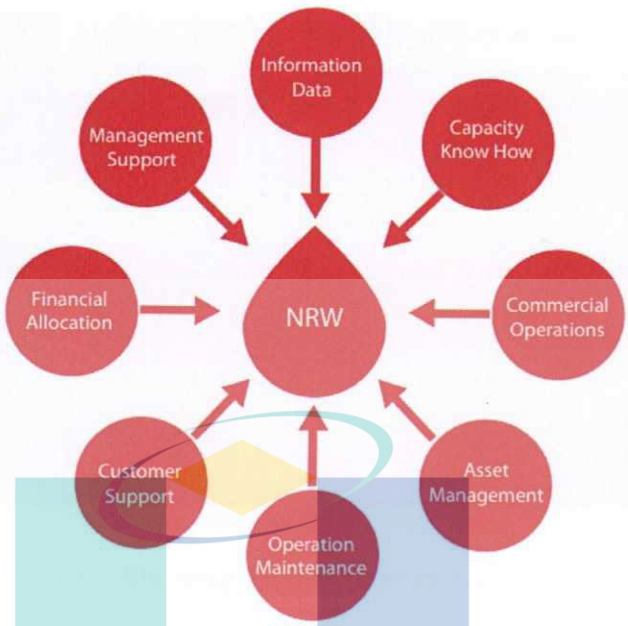

Figure 2.12 Reducing NRW is Everyone's Responsibility

Souce: M. Farley et al., (2008)

Poor governance also affects NRW reduction. Utility managers often lack the autonomy, accountability, and technical and managerial skills necessary to provide reliable service. The utility's management should also tackle organisational challenges, such as policy barriers, inadequate technical capacity, and ageing infrastructure. Finally, poor project design hinders the efforts to reduce NRW, particularly underestimating the required budget. The International Water Association (IWA) has developed a standard international water balance structure and terminology that has been adopted by the national associations in many countries across the world as shown in Figure 2.13.

System Input Volume is the annual volume input of the water supply system. Authorised Consumption is the annual volume of metered and non-metered water taken by registered customers, the water supplier, and others who are implicitly or explicitly authorised to do so (e.g. water used in government offices or fire hydrants). It includes exported water and the leaks and overflows after the point of customer metering. Water Losses is the difference between System Input Volume and Authorised Consumption. It consists of Commercial Losses and Physical Losses.

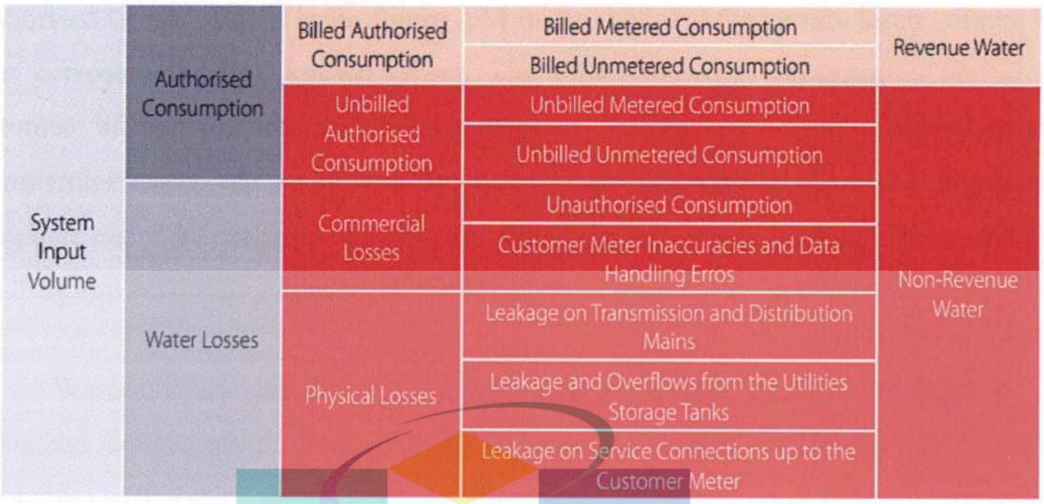

Figure 2.13 Water Balance Showing NRW Components

Souce: M. Farley et al., (2008)

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Figure 2.14 Four Pillars of Commercial Losses

Souce: M. Farley et al., (2008)

Non-revenue water (NRW) is equal to the total amount of water flowing into the water supply network from a water treatment plant ('System Input Volume') minus the total amount of water that industrial and domestic consumers are authorised to use ('Authorised Consumption'). NRW is equal to System Input Volume deducted by Billed

Authorised Consumption. From figure 2.14 it assumed that the system input volume has been corrected for any known errors. The billed metered consumption period for customer billing records are consistent with the System Input Volume period. Commercial losses can be broken down into four fundamental elements, which are: Customer meter inaccuracy, unauthorised consumption, meter reading errors, and data handling and accounting errors (M. Farley et al., 2008).

Water utilities should aim for commercial losses that are not more than 4-6% of authorised consumption. Reducing the commercial losses requires a low level of investment with a short payback period, but it needs sustained management commitment, political will, and community support. Physical losses, sometimes called 'real losses' or 'leakage', includes the total volume of water losses minus commercial losses (The Managers's Non Revenue Water Handbook, 2011). However, the water balance process indicates that commercial losses are estimated and therefore, the resulting leakage volume may be incorrect.

2.8 Leak Detection Methods

Leakage control becomes the high precedence for water supply services due to the numerous complaints from people. This becomes the highest priorities in order to satisfy human will to get continuous water supply to their household. The leakage either big or small in pipeline system can become a big problem to water supplier due to the difficulty to trace where these leaks are. A small leak can be said as a minor problem as an individual, but if it was taken for a long period of time, this can become a remarkable loss for a water resource and revenue for water supplier services with a good management system. Leak detection methods can be done either through external method or internal method. Leak detection basically can detect even for a small leakage point, however, this concern needs to be taken as fact that pipelines are located six feet under the ground and thus reduces the chances to detect the small leakage (K. L. Doney, 2007).

Historically, leak detection technique was by listening, which has been used since 1850s. Listening rods or also known as aqua phones was introduced as the first method for leakage detection. This method is invented in order to detect the sound of water flowing through the leakage point. It was done by letting the listening road directly contact with the piping system or paraphernalia. The non-destructive assessment method

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known as acoustic leak detection was implemented and widely used by water service industries to overcome the water loss problem. Listening rods are a simple sound transmitter, which distinguishes the sound induced by leakage from pressurized pipes. This method can be said to be similar to an application of a doctor listening to a heartbeat through a stethoscope. However, this method can be a time-consuming process because leakage inspector wasted their time searching for leakage position in the wrong place.

The second era of leak detection method was using the ground microphones in order to detect the sound of leakage directly above the pressurized pipe. This method gives some hope for leakage detection in the piping system, however, this method can somewhat well-founded for a large leakage through the piping systems (K. L. Doney, 2007). As the function of microphones is to detect the direct sound from surrounding, the process of leak detection become more complicated due to the sound mixing created by background noise, soil quality, and pipeline location.

In the late 1970s, leak location detection method has improved with the development of the leak noise "correlator". By using a magnetic sensor that was placed on either side of suspected leakage point, the sensors detect a noise and transmit the signal through the amplifier and followed by correlator, which later determines the respective position of the leak from each sensor used through the pipeline systems (K. L. Doney, 2007). For long underground pipelines, there may be no access to pipelines for a comprehensive distance and this technique obliges sensors to be located within at least 152.4 metres of each other. This routine of leak detection is only appropriate for metal pipelines and is a method that is being outdated as many pipelines installed nowadays are manufactured using plastic.

From time to time, many approach of leak detection methods had been establish including ground penetrating radar or infrared spectroscopy, transmission and reflection of pressure waves and widely known as time domain reflectometry (V. J. Misiunas D., Olsson G., Simpson A., Lambert M., 2005), tracer compound, nonlinear fluid model of finite dimension (V. C., 2004), sequential statistical analysis (B. S. G. a. N. G., 2004), frequency response methods (G. S. L. Mpesha W., & Chaudhry M.H., 2001), and transient damping methods (L. M. F. Wang X. et al., 2002).

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A new method of leakage detection by detecting the magnitude of leaks in pipeline structures was developed in 2004 by a researcher (K. E. Abhulimen, A. A. Susu, 2004). Basically, this method is based on the sequential statistical analyses with high-resolution measurements taken at a single point location of the pipeline, which will detect the unsteady leakage rates and generates the maximum and the minimum rates. However, this method does not detect the location of the leakage, it only generates the magnitude of the leak and this lead to the determination of which part of the section in the pipeline networks is in the critical condition.

The method of monitoring the leak detection was introduced in the late 1980s and its needed a division of sector known as District Meter Area (DMA) (R. Pilcher et al., 2007). The flow at each district is monitored from time to time at an important point along the pipelines networks. The leakage is neglected if the difference between the night flow and legitimate usage flow is close to zero (M. F. Ghazali, 2012). The weird water flows during the monitoring process can also be detected. An experienced operator can easily determine leak that is new or not directly from the distorted water flow. Commonly, any real-world leak detection method ought to work with nominal interference during the standard task procedures and be reasonably priced to organize (A. N. Tafuri, 2000).

Leak detection techniques can be classified into two main categories namely, external method and internal method. Both of this method are well-known for all pipelines operators that mainly focusing on finding or detecting the leakage or blocking along the pipeline network distribution. Leak detection method is based on the pressure changes inside the pipe and becomes an utmost topic mainly, industry that is influenced by the loss due to failure mechanism along the pipeline system.

Transient-based method is included under the internal method category due to the basic fundamental of detecting leakage by utilising the pressure change in the pipe due to water hammering phenomenon. Even though there were too many methods existed, none of the methods can be verified to be a successful and reliable technique to be applied in the real application because some of them can be said as poor (M. F. Ghazali, 2012). Many methods existed generally imprecise and time-consuming work and can only be used for specified pipeline networks.

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2.8.1 Internal Method

Internal based leak detection method is the one that normally employed by industrial unit because of the system works as the internal based monitor's leaks through the use of instrumentation devices. There are a few advantages to the internally based method including that it is easier and cheaper to acquire and install as it still makes use of the recent technology. The internal method is based on the observing of pipeline parameters such as pressure, flow and temperature inner pipe with the use of gadgets to measure internal hydraulic circumstances (H. A. Warda, et al., 2004). Examples of this method are pressure point analysis, mass/volume balance, hydrostatic testing, negative pressure wave, statistical analysis and frequency analysis. They are sometimes referred to as computational leak detection methods.

The transient based method system used a low cost and non-intrusive nature; this technique has the potential to locate leaks at a greater distance from a measurement point that is currently possible. However, when there is strong noise present in the pressure measurement records or when a leak is too small or too slow, it can obfuscate the leak reflection signals. A perusal number of a hydraulic transient based technique for leak detection for reduced noise presence: inverse transient analysis, transient damping methods (X. J. Wang, 2002), frequency domain response analysis (W. Mpesha, 1999), direct transient (R. A. Silva et al., 1996), impulse response analysis (C. P. Liou, 1998; J. P. Vitkovsky, A.R. Simpson, and M.F. Lambert, 2000) and wavelet analysis (I. Al-Shidhani et al., 2003).

The transient flow of incompressible fluids in ducts with the constant area is one of the issues that are very important to be discussed in most of engineering fields, especially in engineering research. Transient refers to the phenomena of short-lived burst of energy, where the system is caused by a sudden change of state. The antecedent of transient energy is from internal event or nearby event. The energy is then coupled to another part of the system, at that moment the energy typically appearing as a short burst of oscillation (T. Wang et al., 2012).

By exploiting the hydraulic behaviour of the pipeline system for determining leak position, the phenomena will locate the leak at a specific place, thus it is not surprising that its presence can be detected hydraulically and the transient pressure wave is an ideal

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vehicle used to probe its presence and wave character (M. F. Ghazali, 2012). The changes in physical or propagation of pipe structure or system such as junction, elbow, reducer, valve, blockage or leak will impose a wave reflection to an incoming fluid transient signal.

With the construction of test rig and pressure transient theory or discernible at other location in the pipelines network and characterization have the potential to reveal the useful information about the nature of pressure transient singularity. The pressure transient signature reflected different signal for not leak pipeline network and leak pipeline network. The signals are analysed using the computational software. The leak and not leak data is plotted in the same graph, then the overlapped amplitude shows the pipe feature, then the single higher amplitude shows the leak. The graph plotted is amplitude versus time, therefore to locate and position the leak, the time taken for amplitude is the multiplication with speed of sound in water through MDPE pipe (M. Taghvaei et al., 2006).

2.9 Signal Processing

2.9.1 Empirical Mode Decomposition (EMD)

The EMD method is very self-adaptive to decompose any non-linear and non-stationary signal into a set of intrinsic mode functions (IMF) from high frequency to low frequency (A. F. Colombo et al., 2009; M. F. Ghazali, 2012), which the formula is written in Eq. 2.1:

$$x\,(t) = \sum_{i=0}^{N} c_i\,(\mathrm{t}) + r_N(\mathrm{t}), \qquad 2.1$$

Where, $c_i\,(t)$ is the ith IMF, $r_N\,(t)$ is the residual of the signal. Since this method does not have a priori defined basis, which is much different from the aspect of Fourier transform and Wavelet transform, thus it could be easily adapted in non-linear and non-stationary signal data. The theory of this method is that any data set essentially non-compromises of the super imposition of a finite number of different IMF.

These IMF have a few restrictions. One of the restrictions is the number of extrema and the number of zero-crossings must either be equal or different at most by one. At any point, the mean value of the envelope defined by the local maxima and the

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envelope defined by the local minima is zero. With these concepts are in place, to extract the IMF from a given data set, the process is implemented as follows:

Identify all the extrema of x (t).

i. Connect all of the local maxima by cubic spline line as the upper envelope, and repeat the procedure for the local minima to produce the lower envelope.
ii. With the upper and lower envelope are obtained, then their local mean is designated as m (t) is calculated.
iii. As the mean is designated, extract the detail of h (t), in which it is an IMF from the difference between the data of m (t) and x (t). E.g.:

$$x(t) - m(t) = h(t) \tag{2.2}$$

iv. Then, with the details that have been extracted, let the h (t) becomes the extracted IMF and continue on iterating the residual m (t).

From the equation above, ideally h (t) should be the IMF and for the next construction of $h_1(t)$ is shown below:

$$h(t) - m_1(t) = h_1(t) \tag{2.3}$$

Where, $m_1(t)$ is the mean of the upper and lower envelopes of h (t), which in terms that the process is to be iterated by up to k times, $h_k(t)$ which was given by the equation below:

$$h_{(k-1)}(t) - m_k(t) = h_k(t) \tag{2.4}$$

With the iteration process is done with each step, it must be checked on either the number of zero crossings equal to the numbers of extrema, which in turn resulting the time series is the first IMF, that designates as $c(t)=h_k(t)$. The data that contains the highest oscillation frequencies in the original data is subtracted with the original data that is denoted in the equation below:

$$x(t) - c(t) = r(t) \tag{2.5}$$

The residue that is left in the data is denoted as $r(t)$ and it is used for the next iteration process as to find more intrinsic modes $c(t)$ until the last iteration of the intrinsic mode is acquired as the last residue mode will be a monotonic function, the equation of the iteration are summarised in the equation below:

$$x(t) = \sum_{i=1}^{L} c_i \text{ (t)} + r_L \text{ (t)} \qquad L=1, 2, 3\ldots n \qquad 2.6$$

2.9.2 Ensemble Empirical Mode Decomposition (EEMD)

Ensemble Empirical Mode Decomposition (EEMD) has more suitability in extracting a broad range of signals for a rich data of non-linear signal and non-stationary systems. The methods implement the method of Empirical Mode Decomposition (EMD) but have been alleviating the problems of the mode mixing, by introducing a noise-assisted method.

The single Intrinsic Mode Function (IMF) that is acquired, either having signals of widely disparate scales or a signal with the same scale reading in different IMF components. The mode mixing could result in a serious data aliasing with the time-frequency distribution and also cause each of the IMF data to be severed and unclear. Before reviewing the methods of the EEMD, a list of method is list down upon the details and properties of the EMD that have been discussed earlier (M. Zhao, D. A. Mclnnis, D. H. Axworthy, 2005). EMD is a method that adept the data analysis based on the local properties of the data and acquires the non-linear and non-stationary oscillation signals effectively.

The method is a dyadic filter bank for any white noise or fractional Gaussian noise-only series. As the data is intermittent, the dyadic characteristics are often compromised in the original EMD. By implementing the noise in the data signal, it could provide a uniformly distributed reference scale, which enables EMD to fix the compromised dyadic characteristics. The IMF of different series of noise has no correlation with each other. Therefore, the means of the corresponding IMFs of different white noise will likely to cancel out each other (M. Ferrante, B. Brunone, S. Meniconi, 2007).

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From the properties of the EMD, it is proposed by the method of noise-assisted, where data analysis was proposed by them. The white noise series is added to the targeted data (the original signal). Then, the signal is decomposed with added white noise into the IMFs using EMD method. By repeating the steps of i. and ii, series of different white noise series for the targeted data are included each time. The means of a corresponding IMFs component of the decompositions are obtained (B. Brunone, M. Ferrante, 2002). The means of ensemble corresponding to the IMFs of the decomposition are retrieved as the final result. The means of ensemble corresponding to the residue components of the decompositions are retrieved as the final result.

In other word, it can be summarised in the form of equations stated as below:

$$x_m(t) = x(t) + w_m(t), \qquad m=1,2,3\ldots n \tag{2.7}$$

$$x_m(t) = \sum_{i=1}^{L} c_{m,i} + r_{m,L}(t), \qquad m=1,2,3\ldots n. \tag{2.8}$$

$$x(t) = \frac{1}{N}\sum_{i=1}^{L}\sum_{m=1}^{n} c_{m,i}(t) + \frac{1}{N}\sum_{m=1}^{n} r_{m,L}(t) \tag{2.9}$$

Where $x(t)$ is the original signal, $w_m(t)$ is the m^{th} term added white noise, $x_m(t)$ is the noisy signal of the m^{th} trial, L is the number of IMFs from the EMD method, and N is the ensemble number of the EEMD method.

2.9.3 Hilbert Transform (HT)

According to the method of EEMD, the obtained IMFs could use Hilbert-Huang Transform by applying the Hilbert transform to each of the IMF components with the equation below (B. Wang, R. Chen 2008):

$$H[c(t)] = \int_{-\infty}^{+\infty} \frac{c(\tau)}{t-\tau} dr \tag{2.10}$$

As $c(\tau)$ and $H[c(t)]$ forming a complex conjugate pair, which in turn defines an analytical signal $z(t)$ in the form of the equation below:

$$z(t) = c(t) + jH[c(t)] \tag{2.11}$$

That could be expressed as:

$$z(t) = a(t)e^{[i\omega(t)]} \qquad 2.12$$

With amplitude $a\ (t)$ and phase $\theta\ (t)$ defined by the expressions

$$a(t) = \sqrt{c^2(t) + H^2[c(t)]} \qquad 2.13$$

$$\theta(t) = \tan^{-1}\left(\frac{H[c(t)]}{c(t)}\right) \qquad 2.14$$

Therefore, the instantaneous frequency $\omega\ (t)$ can be given by

$$\omega(t) = \frac{d\theta(t)}{dt} \qquad 2.15$$

Thus, the original data can be expressed in the following form

$$x(t) = Re\sum_{i=1}^{n} a(t)e^{j\int \omega t\, dt} \qquad 2.16$$

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2.10 Effect of a Leak on a Pressure Wave

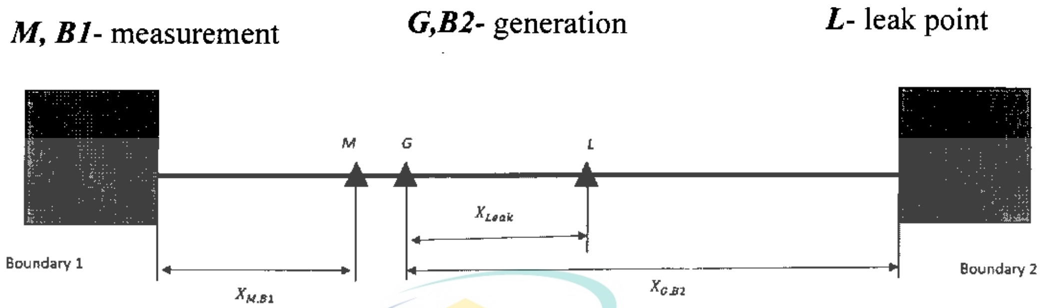

Figure 2.15 Pipeline with a leaking point and two boundaries

Source: Misiunas, (2005)

A pipeline running between two boundaries is considered as an example. In some cases, the transient generating and measuring device might have to be installed separately, or close to each other, but somewhere in the middle of the pipelines as shown in

Figure 2.15. As suggested, the leak detection procedure should not interrupt the operation of the pipeline. The generated transient response and the pressure measurement point are located at point G and M, respectively.

$X_{M,B1}$ = point position from boundary 1 to measurement point

X_{Leak} = point position from generation point to the leak point

$X_{G,B2}$ = point position from generation point to boundary 2

As the transient generation point is located along the pipeline, two waves will be generated (upstream positive and downstream negative), which will propagate in opposite directions towards boundary 1 and 2. Consequently, as shown in

Figure 2.15, the leak, L is simulated at a distance X and leak from the generation point in the direction of boundary 2. The procedure of transient wave propagation and its reflection in pipelines are summarized in sequential steps as displayed in Figure 2.16. It is assumed that the transient generation, G and pressure measurement, *M* to be located at the same point, which is the same as the experiment works in this research.

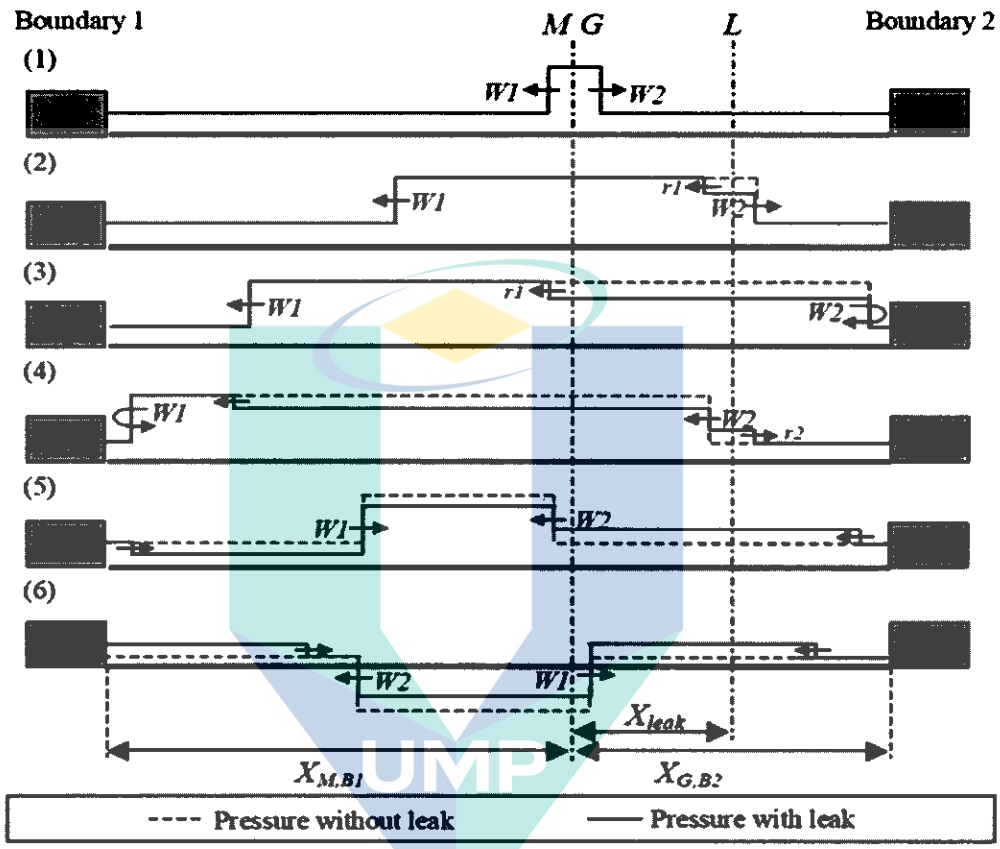

Figure 2.16 Transient Wave Propagation and Its Reflections from Leak and Pipelines Boundaries

Source: Misiunas, (2005)

The generation and measurement points should be located as close to each other as possible. If the leak occurs in between the measurement and generation points, the location of it becomes more complicated. The generated transient wave is reflected from the leak before it reaches the measurement point. As a result, the reflection of a generated wave from the leak is no longer detected in the measured trace. The pipeline system from Figure 2.15 is considered, where the leak will be positioned at *L*.

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2.10.1 Wave Characteristic

Figure 2.17 shows and explains the wave flow throughout the pipe will partially reflect back, partially transmitted forward and some of it will be absorbed when there are discontinuities by leaks and feature of pipe along the pipeline's system (K. Asamene & M. Sundaresan, 2012). Different in leak size and distance will affect the disturbance of discontinuities. A feature of the pipe on pipelines system are elbowed, T-joint, pump, valve and reducer.

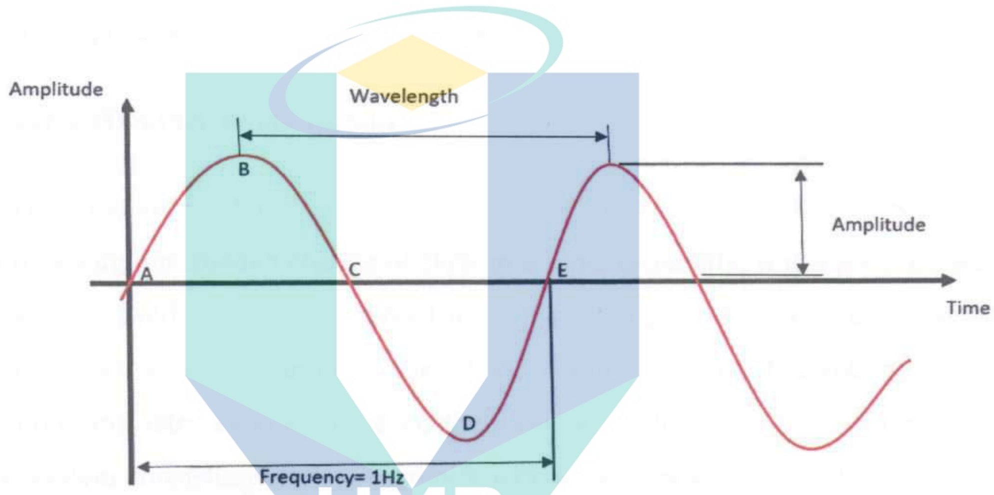

Figure 2.17 Wave Characteristic

Source: L. D. Misiunas, (2006)

2.10.2 Wave Propagation Speed

One of the important issues in the research when we conducted leakage detection is the speed of wave propagation. That is one of the main challenges to the worker to find it because to successfully analyse the signal of leakage, the value is needed to be measured. Most parameter that affects the speed of wave propagation are such as pipe diameter, pipe stiffness, pipe material and type of (T. J. Pedley, 1997; T.Zhanga et al., 2014). Theoretically, the speed of wave propagate in the pipeline is shown in Eq. 2.17.

$$C = \frac{1}{\rho(\frac{1}{k}+\frac{D}{eE}\theta)} \qquad 2.17$$

Where C = wave propagation speed (m/s), ρ = density of the fluid flow in the pipeline (Kg/m^3), K=Bulk modulus of the fluid (N/m^2), E = Young Modulus of the pipe material (N/m^2), Ø = restraint factor dependent on the Poisson's ratio of the wall material

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and how well the pipe is supported, D = diameter of the pipe and e = wall thickness of the pipe.

In actual water distribution networks, the actual wave speed may differ from the theoretical value because several factors affecting their wave propagation such as uncertainty in the assets information of pipes buried many years ago, the occurrence and recording or otherwise of rehabilitation work, such as relining, assets deterioration, such as the formation of mineral deposits lining the pipe wall, decreasing the actual pipe diameter from those asset records and presence of stretches.

2.11 Water Hammer Phenomenon

Water hammer refers to the transient conditions in a hydraulic system that prevails following the sudden change of flow in a pipe. Generally, it is a pressure wave resulted when a fluid in motion is forced to stop or change and there is a momentum change in it. Let us first examine some of the common things that accompany the phenomenon, and later explore more on the associated attributes. Consider a simple hydraulic system consisting of two reservoirs with a valve positioned at the mid-length point of a straight pipe carrying fluid between two reservoirs. The two pipe sections upstream and downstream of the valve are identical in all respects. When a valve is suddenly closed, it causes the nearest fluid to the valve to be compressed and then brought to rest (K. Asamene & M. Sundaresan, 2012).

Due to the pipe walls, this compression cannot cause a change in volume, and hence, the pressure rises. The increase in pressure at the valve results in the wave being propagated upstream, bringing the fluid to rest as it passes, compressing it. As a result, the compressed liquid will now start to release liquid in the pipe back to the source and return to the static pressure of the source (T. Zhanga et al., 2014). As the wave arrives at the upstream end of the pipe, the mass of fluid will be at rest but under great pressure. This creates an unbalanced condition at the upstream (reservoir) end at the instant the pressure waves arrive since the reservoir pressure remains unchanged and all kinetic energy has been converted into elastic energy (A. R. D. Thorley, 2004).

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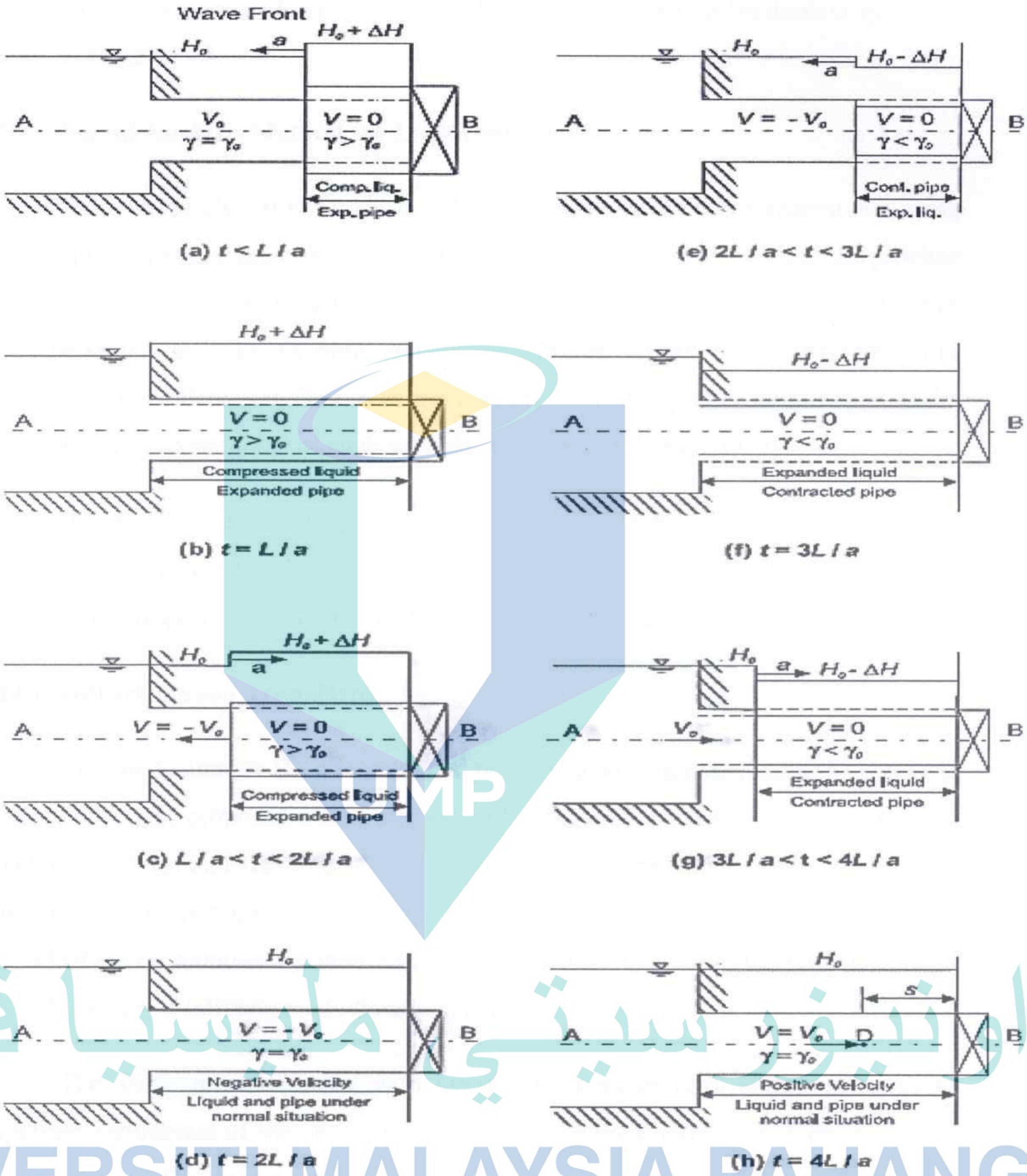

Figure 2.18 Valve Closure in a Frictionless System

Source: M. W. Thomas M. et al., (2003)

This process of conservation travels downstream towards the valve at the speed of sound in the pipe, which depends on the properties of the fluid and the pipe material. Similarly, on the downstream side of the valve, the retardation of flow results in a reduction in pressure at the valve, with the result that a negative pressure wave is propagated along the downstream pipe, in turn, retards the fluid flow (M. W. Thomas et

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al., 2003). The sequence of events after sudden valve closure in a frictionless system is shown in Figure 2.18.

2.12 Signal Analysis Method for Leak Detection

Many researcher studies about leaks detection showed that transient test using water hammer create a pressure wave that ultimately propagates throughout the pipeline network. Portions of this are reflected back from various pipeline features. Irregularities in a pipe system provoke discontinuities in this pressure signals so that the problem of leak and features detection is akin to the investigation of signal discontinuities as the pressure wave is constituted of such irregularities (M. F. Ghazali, 2012).

By using the advanced signal processing techniques, this should make it possible to identify and locate these discontinuities through the analysis of the corresponding pressure time response signal; obtained through a single sensing device.

2.12.1 Hilbert-Huang Transform

In order to analyse the nonlinear and non-stationary signals, Huang (B. Huang & A. Kunoth, 2013) proposed a new method called the Hilbert Huang transform (HHT), which is based on empirical mode decomposition (EMD). The HHT consists of two parts: The EMD and Hilbert transform. The proposed technique decomposes any given signal as a set of nearly mono-component signals with each component of the set is termed as a simpler mode or intrinsic mode functions (IMFs).

The IMFs are associated with energy at different time scales and enclose important parameters of the data. They are actually unique intrinsic oscillating modes within the data. The decomposition of the signal also can be viewed as an expansion of the data in terms of the IMFs. Then, these IMFs, based in and derived from the data, can serve as the basis of that expansion, which can be linear or non-linear (depending on the data) and is complete, almost orthogonal and most importantly, adaptive. Expressed in IMFs, they have well-behaved Hilbert transforms, from which the local energy and instantaneous frequency can be calculated, thus, providing a full energy-frequency-time distribution of data, and such representation is known as the Hilbert spectrum. Furthermore, the adaptive nature behaviour of EMD would be ideal for nonlinear and non-stationary data analysis; hence the HHT is potentially viable for analysing nonlinear and non-stationary signals.

2.12.1.1 Hilbert Transforms (HT)

To get a well-defined and physically meaningful instantaneous frequency, the signal must be analytic and it must be within a narrow band by means of Hilbert transform (HT). Considering the expression of the analytical signal in Eq. 2.18, where the instantaneous frequency, $\omega(t)$ of the analytical signal is expressed as the time derivative of (t) :

$$\omega(t) = \frac{d\phi(t)}{dt} \text{ and } f(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt} \quad 2.18$$

Since the instantaneous frequency is a derivative, it is local and can, therefore, describe intra-wave variations within the signal. As explained by Boashah (B. Boashash, 1992) , the Hilbert transform produces a more physically meaningful result for monocomponent or nearly monocomponent (i.e. narrow band) functions. Since engineering data do not show these necessary characteristics, sometimes the conventional Hilbert transform makes little physical sense in practical applications. As a result, the effectiveness of EMD decomposition is particularly necessary for the evaluation of instantaneous frequency by the subsequent Hilbert transform.

To demonstrate the calculation of instantaneous frequency (IF) for a monocomponent signal, one can gain intuitive appreciation by examining a linear chirp signal. A chirp can be considered as a signal in which the frequency increases or decreases. It is shown that when Eq. 2.18 is used, the frequency properties of the chirp signal can be revealed. A plot of linear chirp with its instantaneous frequency is shown in Figure 2.19.

As we can see from this figure, the instantaneous frequency calculation using HT is able to show that the frequency of the chirp increases linearly with time. However, as expected, HT experiences the Gibbs' phenomenon induced by the discontinuity at the two signal ends due to a final length and its polar representation. The Gibbs' phenomenon is an overshoot (or ringing) of Fourier series and other eigenfunction series occurring at

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simple discontinuities. To reduce Gibbs' phenomenon in the Hilbert transform, Huang proposed to add the two ends characteristics waves to smooth it at the edges. Alternatively, it is a very simple and efficient method, where the signal can be oversampled so that the propagation of end effects is outside of the required window.

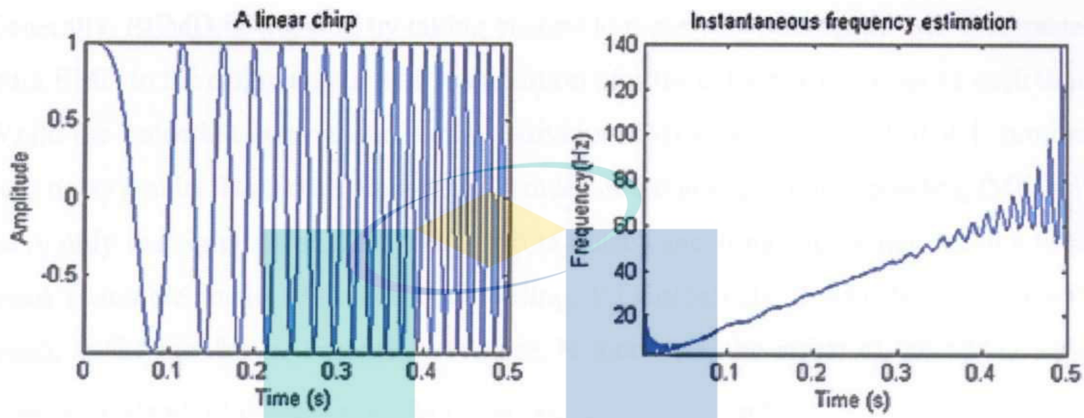

Figure 2.19 The Instantaneous Frequency Estimation a Linear Chirp Signal

Source: M. W. Thomas et al., (2003)

2.12.1.2 Ensemble Empirical Mode Decomposition (EEMD)

One of the major drawbacks of the original EMD is the mode mixing, which is defined as a single IMF either consisting of signals of widely disparate scales or a signal of a similar scale residing in different IMF components. As a result, it renders the EMD algorithm to unstable (M. W. Thomas et al., 2003). In order to alleviate these problems, a masking approach in order to prevent any lower frequency signal to be included in the IMF and appropriately extracted, the intermittent components had been proposed (P.Flandrin, G. Riling, P.GonÌ§alveÌs, 2004). Masking adds a component with a known frequency higher than the frequency of the component that is to be extracted and later subtracts it out to restore the actual result returned by EMD.

The advantage of this method is prevented by the presence of the higher frequency signal, which will be extracted before a lower frequency oscillation mode occurs from the data. However, it is difficult to select the appropriate masking signal that is going to be used in the analysis, hence this strategy requires a priori knowledge of the temporal signature of components, which is seldom available to the analyst. Another solution to the problem with mode mixing and also working to reduce the end effect,

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Ensemble Empirical Mode Decomposition (EEMD) was proposed. EEMD is a noise-assisted data analysis method that introduces finite white noise to the signal.

The idea is to corrupt the data with known noise, where in this case the white noise and subject to the EMD to achieve a split of the signal into various frequency bands. Generally, EEMD is working by taking ensemble mean of a number of IMF's extracted from EMD to the original data with the addition of different white noise series each time. While the noise has been added to the individual IMFs for every trial, it will produce very noisy results. However, the ensemble mean of a number of corresponding IMFs will leave only the signal as a collection of white noise cancelling each other out in a time-space ensemble mean (P.Flandrin, G. Riling, P.GonÌ§alveÌs, 2004). By an ensemble mean, as the number of ensemble member, N increases, the effect of the added white noise with standard deviation, ε, the noise decreases as given by:

$$\varepsilon_n = \frac{\varepsilon}{\sqrt{N}} \qquad 2.19$$

where, ε_n is defined as the different between standard deviation of the original data and the sum of corresponding IMFs. The proposed EEMD method can be given as follows;

i) Add white noise series to the data.
ii) Decompose the data with added white noise into IMFs.
iii) Repeat step (i) and (ii) again and again but with different white noise series each time.
iv) Calculate the ensemble means of the decomposition for each IMF as the final result.

EMD method will be a truly dyadic filter bank when applied to the white noise. Therefore, the principle of EEMD is relatively straightforward since it utilizes the scale separation principle of the EMD (Huang, N. E., et al. 1998).

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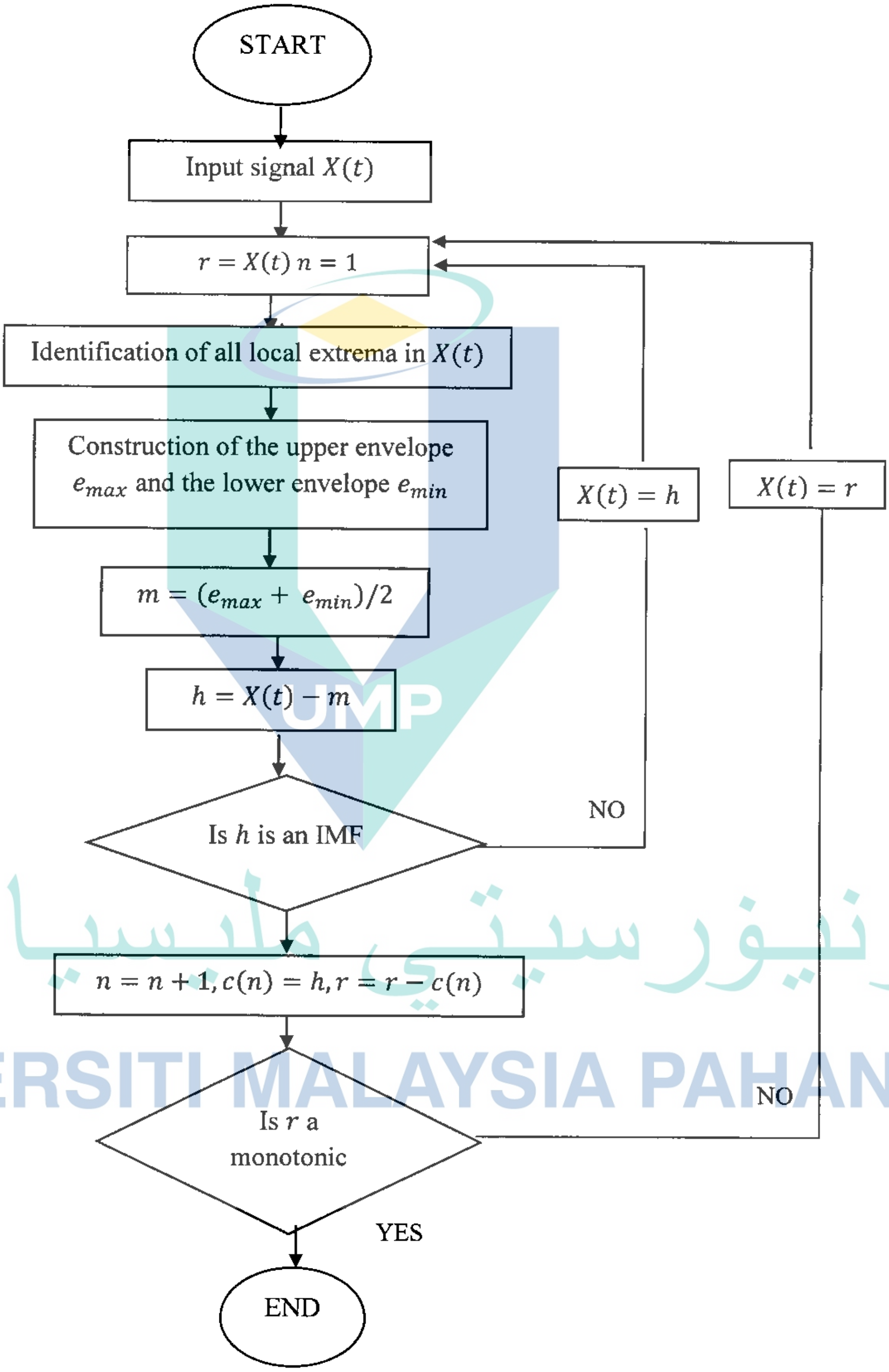

Figure 2.2 Flowchart of EEMD process

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2.13 Chapter Summary

In this chapter, it describes how the water move continuously inside the pipe can cause corrosion and what type of pipe normally breaks or type of leak happened. It also leads to the unwanted change in water quality as water being distributed to people. Non-revenue water (NRW) leads to this investigation and also has been described in this chapter. The methods for leak detection and location in pipelines network have been described. In this investigation, it uses the internal method and one of the methods used to detect leaks is empirical mode decomposition (EEMD) method that is described from the beginning of its history, the internal method been used, where most researchers choose the method due to cost-effective of this method.

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CHAPTER 3

METHODOLOGY

3.1 Introduction

The method using transient waves have been used by various methods as it is a better way of detecting leakage in the pipeline with a lower cost to operate and it could benefit in real life application. A group of university researchers from Sheffield University have proven that by using cross-correlation method, cepstrum analysis, and using various types of wavelet transform analysis.

Utilizing a method of water hammer in the pipeline is one of the methods that were used for this experiment. The system uses the method of closing and opening for a specific time which in turn causes the water to propagate in transient waves. The pressure wave of this method propagates along the pipeline such that whenever it encounters any certain types of features (e.g. T-junction, Closed valve, Leak, est.), it will be acquired along the movement of the wave as the pressure waves are being reflected, absorbed by the pipe or friction, loss due to mechanical resistance, and others.

The pressure wave that is reflected back is detected through the transducer as it contains vast information along the pipeline. If the method of processing the data was correct, it could be used to acquire the characteristics that the pressure wave had encountered along the pipeline as well as the type of feature that being used, the distance of the pipeline leakage, and what are the pressure difference through the pipeline. These methods have been proven to be reliable and easy to construct without much relative application errors during the experimentation, it also has a very low cost to be conducted as it only needed a few transducers and need to be a good skill in terms of operating the equipment for detecting the pipeline leakage.

3.2 Designing the Pipeline Network System

The idea of fabricating the experiment setup consisting of various types of the pipeline network are massive in variation and can be constructed in various method to testing the acquired data. In this experiment, fabrication is in according to real life situation, so it is almost impossible as it requires a huge pipeline test rig with a massive space for it to be constructed. Therefore, most of the researchers are conducting a miniature scale of the actual size of the pipeline to be the scale that is easy to fabricate and easy to be manipulated throughout the test setup.

A simple experiment setup for the pipeline leak detection method with the use of solenoid valve on the transducer on the pipeline proposed that the pipe was connected to a large stream reservoir or a water pump, such it will supply a constant water pressure with a constant flow velocity from the inlet of the pipeline, in which that the head was kept constant to prevent varying pressure difference and to minimized other significant influences.

The pipeline was connected to a series of pipe features such as 90^{o} angle, T-junction, and different types of pipe diameter. The outlet of the pipe is kept connected to a free surface tank such that the water from the pipe ends discharged underwater. This is to prevent the sudden expansion of the pressure waves and the negative pressure of the waves could be minimized as it will have an impact on the data that will be acquired on the transducer.

The method for detecting the leakage in the pipeline was proposed by introducing a number of short pipe series in the pipe network with a leak point on the pipeline and the water flow is being controlled by a solenoid valve, so that it could implement the water hammering method on the pipeline to acquire the transient waves square wave at a frequency of 0.5 Hz and amplitude of 20 V.

The pressure waves that are being created from the water hammering method are being captured by the transducer that is bonded at the pipeline and the transducer is being

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connected to NI-DAQ as to acquire the signal and synchronizing it to the DASYLab software to record the data on the triggered for the test run.

The second step in constructing the test rig is to design the test rig so that the blueprint for the actual setup is shown. In this designing stage, the software for computer design is being used, namely computer-aided-drawing (Solidworks). This software helps in constructing the blueprint of the test rig and can actually approximate on the test rig scale size so it could predict on the actual implementation on the actual pipeline network, either it is suitable to be implemented or not.

3.2.1 Designing Base Part Using Computer Aided Drawing (Solidworks)

To create the water hammer phenomenon, the test rig must have one of the rigid body parts for the whole systems. Normally, open solenoid valve is used to create transient waves in the pipeline. In the system, one section of the base part is created and it contained fire hydrant, pressure sensor, shut off valve, and normally open solenoid valve. Before the system is fabricated, the sketching is made in the Solidworks based on the dimension of fire hydrant and MDPE pipeline system.

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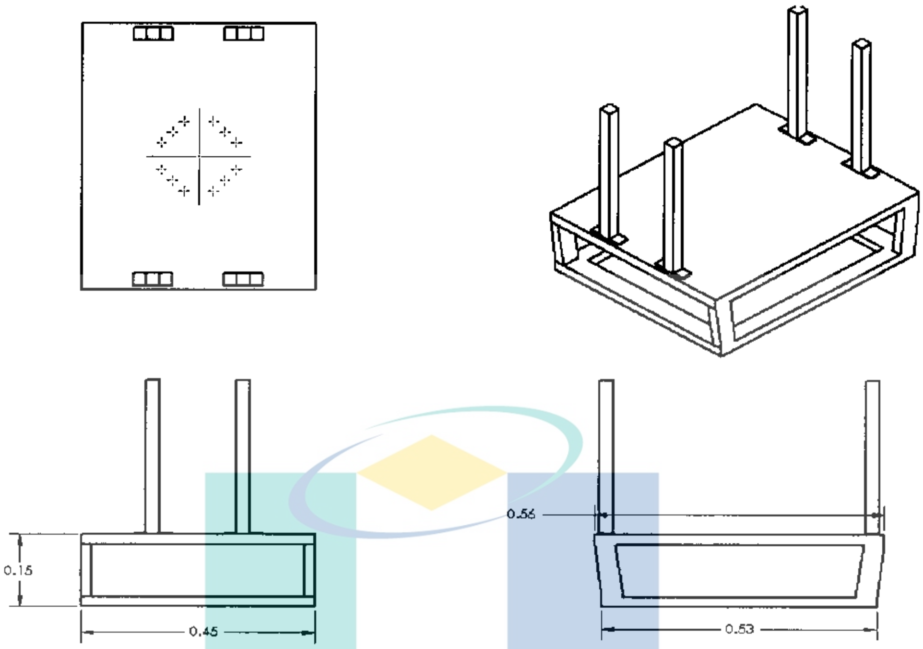

Figure 3.1 Schematic Diagram for Base Part

The material used for fire hydrant is ductile iron, max working pressure is 16 bar and the temperature range is from -10˚C to +70˚C. A critical part of this part is to fit the fire hydrant into the base rig, the seal has to use the bottom of the fire hydrant due to the high pressure in the pipeline.

Table3.1 Data for Underground Fire Hydrant

Physical Properties		
Quantity	**Value**	**Unit**
Max. Working Pressure	16	Bar
Temperature	-10 - +90	°C
Flow Rate	2200	L/min

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Figure 3.2 Fire Hydrant

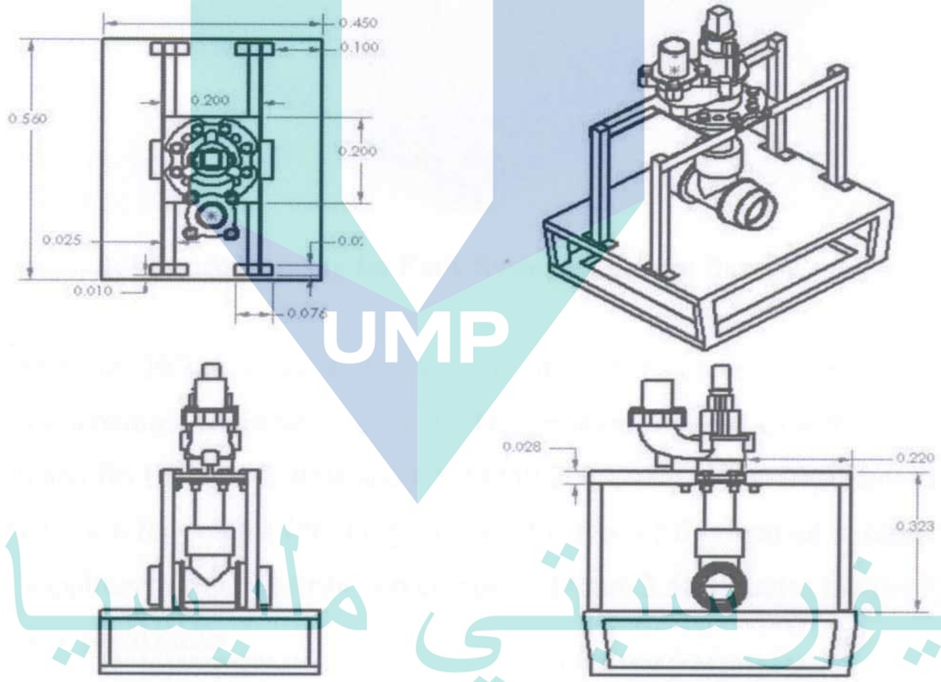

Figure 3.3 Schematic Diagram Full System Leakage Assemble Base

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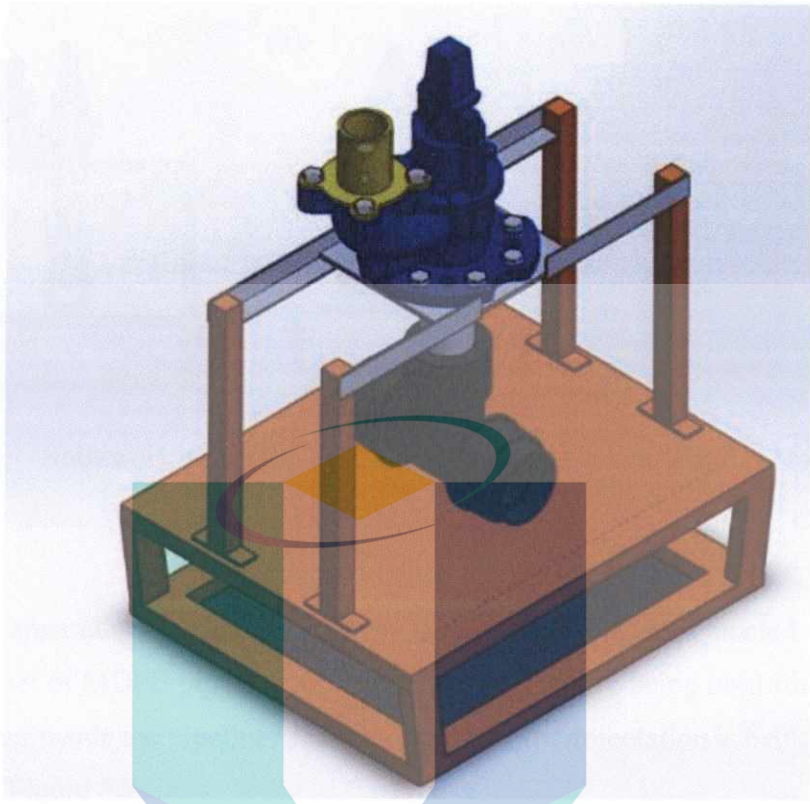

Figure 3.4 Solidwork Drawing for Fully Systems Leakage Base

The Series 29/388 is a squat fire hydrant suitable to be used with water and neutral liquids, to a maximum temperature of 70°C. This series also complies with requirements of BS 750 and BS EN1074-2:2004 and EN 14339:2005, underground hydrants and also to BS EN 1074-6 for potable (drinking) water. This type of fire hydrant is usually used by many suppliers to water distribution company. Figure 3.5 illustrates the fire hydrant assemblies in Solidworks.

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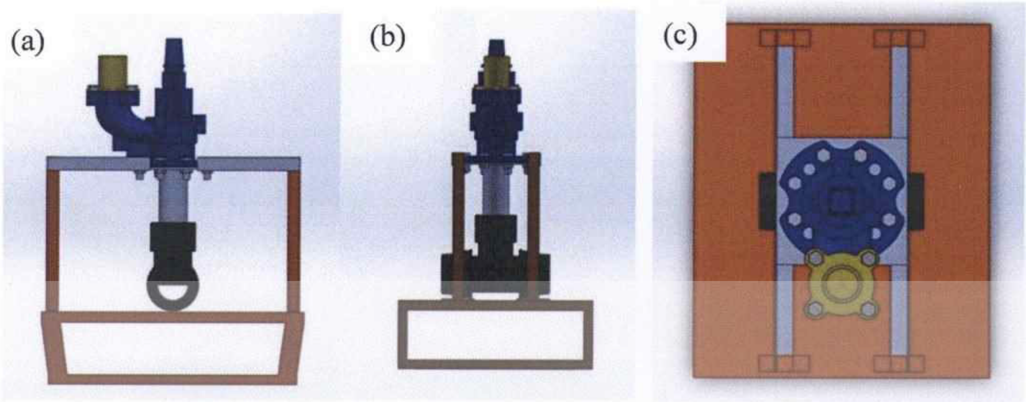

Figure 3.5 Solidwork View from (a) front view, (b) side view and (c) top view.

The apparatus for this experiment is setup for the implemented method that consist of a set of MDPE pipe and a controlled type of valve being used for creating the water hammer inside the pipeline. The set-up of the experimentation is being constructed as shown in Figure 3.7.

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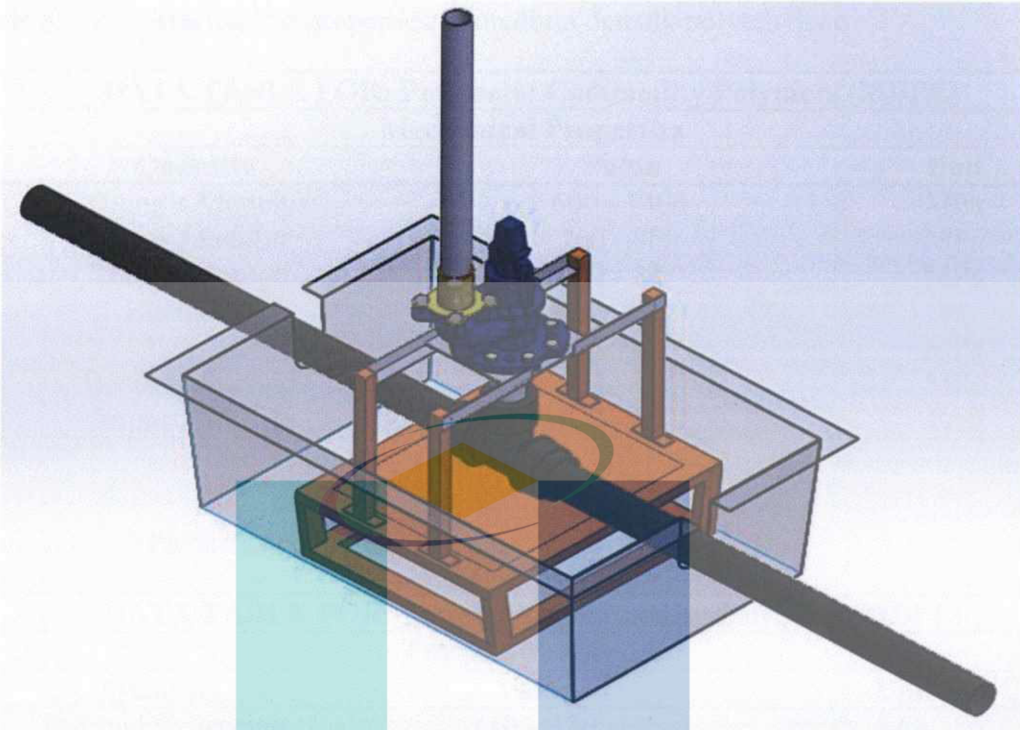

Figure 3.6 Full Assemble Leakage Data Collection Base System

3.3 Material Selection

The materials used for the experimental analysis are high-density polyethylene (MDPE) pipes. This material has been selected because this type of material is the common material used for the piping system in Malaysia.

3.3.1 Medium Density Polyethylene (MDPE)

MDPE can be categorized in the thermoplastic section. It is odourless, tasteless, and nontoxic polymers, which make it become a common material used in the industry. The high-density polyethylene replaces the galvanized iron, which is difficult to join, higher in weight and more expensive. Table 3.2 and the material properties of the materials used in this study listed in Table 3.3.

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Table 3.2 Mechanical properties of medium density polyethylene

DATA TABLE FOR: Polymers: Commodity Polymers (MDPE)		
Mechanical Properties		
Quantity	**Value**	**Unit**
Young's Modulus	600 - 1400	MPa
Shear Modulus	700 - 800	MPa
Tensile Strength	20 - 32	MPa
Elongation	180 - 1000	%
Fatigue	18 - 20	MPa
Bending Strength	20 - 45	MPa
Impact Strength	0.27 - 10.9	J/cm

Table 3.3 Physical properties of medium density polyethylene

DATA TABLE FOR: Polymers: Commodity Polymers (MDPE)		
Physical Properties		
Quantity	**Value**	**Unit**
Thermal Expansion	110 – 130	e-6/k
Thermal Conductivity	0.46 – 0.52	W/m.k
Specific Heat	1800 - 2700	J/kg.K
Melting Temperature	106 - 134	^0C
Glass Temperature	-110 - 110	^0C
Service Temperature	-30 - 85	^0C
Density	940 - 965	kg/m^3
Resistivity	5e+17 - 1e+21	$Ohm.mm^2/m$
Breakdown Potential	17.7 - 19.7	kV/mm
Dielectric Loss Factor	0.0005 – 0.0008	
Friction Coefficient	0.25 - 0.3	
Refraction Index	1.52 – 1.53	
Shrinkage	2 – 4	%
Water Absorption	0.01 – 0.01	%

The table above shows the characteristics and specifications of high-density polyethylene. The advantage of MDPE is that it has a good low temperature, excellent chemical resistant, greater tensile strength, higher in heat distortion temperature and high in viscosity. This type of material is usually applied on the pipe, container in refrigeration, storage vessels and seal caps.

3.3.2 Test Rig Straight-Line Piping Systems

The total length of the MDPE pipe itself is measured to be 57.90m; the length is measured starting from the inlet of the pipeline, from the pump until the outlet of the pipe back into the tank. Throughout the pipeline, there have attached a few pipe features that

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would be influencing the pipeline behaviour and the data that would be received from the transducer.

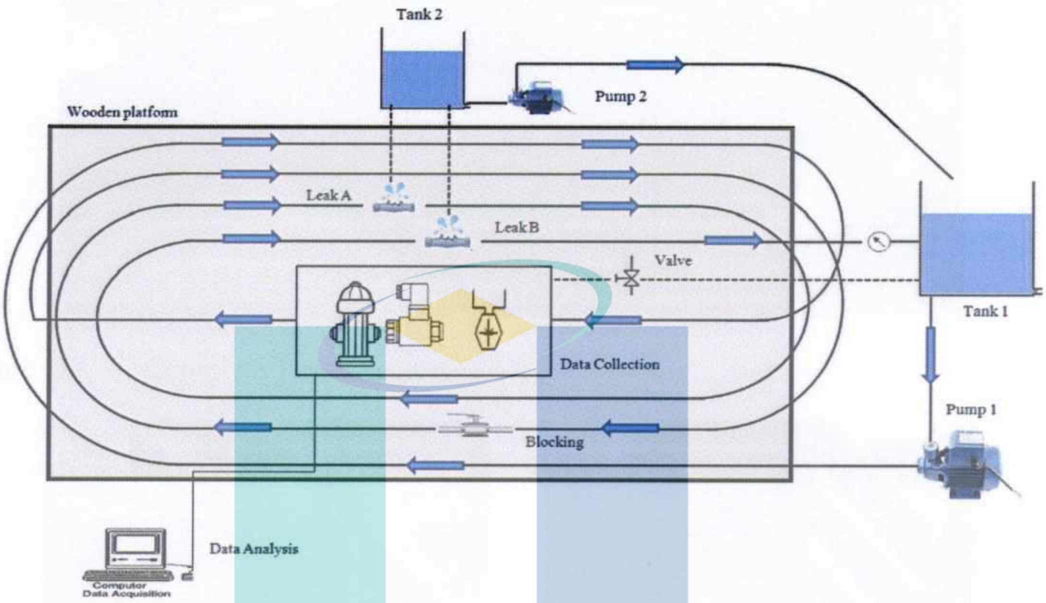

Figure 3.7 Schematic Diagram Straight Line Test Rig using MDPE Pipe

Figure 3.8 Test Rig Development Process (a) no structure (b) with not complete structure

Even though this will influence the resulting analysis of the data, the focus should be on the leakages that are introduced on the pipeline. There are 2 different leakages on the pipeline that are being used for detection. They are Leak A and Leak B as shown in Figure 3.11. The distance of the leakage A is measured to be 21.50m, meanwhile the distance of the leakage B is measured to be 51.20m.

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Figure 3.9 Complete Test Rig

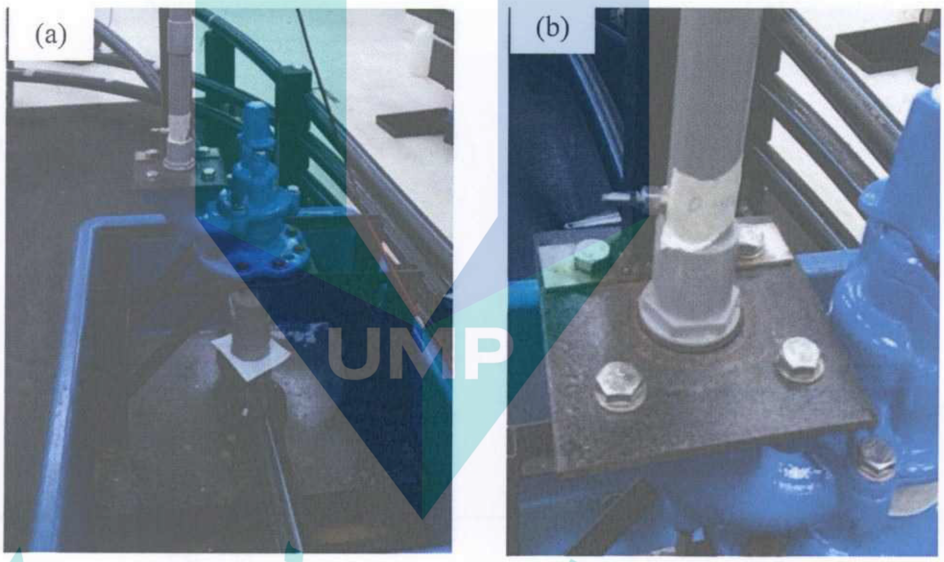

Figure 3.10 (a) Fire hydrant with base and (b) pressure sensor location

Figure 3.11 (a) Leak A and (b) Leak B pinhole leak position

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3.3.3 Piezoelectric Pressure Sensor

Table 3.4 PCB Piezoelectric pressure sensor specifications

Piezoelectric Pressure Sensor Model number: 113B27	
Performance	Value
Measurement range (± 5V output)	689.4 kPa
Sensitivity (± 15 %)	7.25mV/kPa
Max. Pressure	6895 kPa
Resonant frequency	≥ 500 kHz
Low frequency response (-5 %)	0.5 Hz
Environmental	
Acceleration sensitivity	≤ 0.0014 kPa/(m/s^2)
Temperature range (operating)	-73 to +135 °C
Max. vibration	19614 m/s^2 pk
Max. Shock	196140 m/s^2 pk
Electrical	
Output polarity (positive pressure)	Positive
Discharge time constant (room temp.)	≥ 1.0 sec
Excitation voltage	20 to 30 VDC
Output impedance	< 100 Ohm
Output bias voltage	8 to 14 VDC
Physical	
Sensing geometry	Compression
Sensing element	Quartz
Housing material	17-4 Stainless steel
Diaphragm	Invar
Weight (with clam nut)	4.5 g

Figure 3.12 Piezoelectric Sensor

Generally, piezoelectric pressure sensor is an instrument used to measure strain, shock, vibration, pressure and etc. For the study, pressure type of piezoelectric pressure sensor will be used. Piezoelectric pressure sensor usually is used to measure dynamic pressure like turbulence, ballistics and blast. The sensor has a fast and steady response, high stiffness value, and extended ranges. The sensor applies voltage output value

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proportion to compression and tensile strain. Table 3.4 shows the full specification of piezoelectric pressure sensor that was used for the study and experiment.

3.3.4 Solenoid Valve

Solenoid valve is the device used to create pressure transient in the water flow. This will be easier for pressure transducer to capture the signal and compare the flow with and without leakage in pipelines. Solenoid valve is controlled by an electric current through a solenoid. The valve in the flow was switched on or off at high speed.

Figure 3.13 Solenoid Valve

3.4 Conducting an Experiment

There are several ways to make this experiment successful. What will be told in this section is the experiment was carried out in the fluid mechanics laboratory, mechanical engineering faculty, university Malaysia Pahang, is one that successfully implemented. Pipe leaks test rig shall be made desolate area or airtight. This is to avoid noise disturbance that would cause inaccuracy in data reading.

The experiment was conducted at steady state system operating and system flow rate of about and 1.923×10^{-3} m^3/s. In order to create the effect of leakage into the test rig system, control valve with diameter 4 mm has been installed at the leakage area pipeline.

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Single pressure transducer located as close as possible to the solenoid valve in order to show pressure time response once the pressure transient has been created. The measuring instrument for data capture used data acquisition from National Instrument at frequency 1 kHz and 1000 sample size to capture any change in the steady-state operating. Pump must be positioned away from the pressure transient sensor. This is because in order to avoid disturbance, thus ballooning disturb the original data obtained. The main function for pump is to pump the water from the tank to developed high pressure of the normal condition.

The most important step in this experiment is to make sure all equipment is in good working condition. To start the experiment, make sure the water is full in water tank, the computer used should be compatible with the software. Please used windows 10 and above. After water is full in the tank, turn on the pump and open the valve and fill the water in the pipeline. After a few minutes make sure the water pressure inside the pipe is in a stable condition. Set the water pressure at 3 bar by adjust the pump valve. Make sure the water in a tank do not have any rough impurities like sand to avoid the sand into the water pipeline that will cause a reading on the data compromised.

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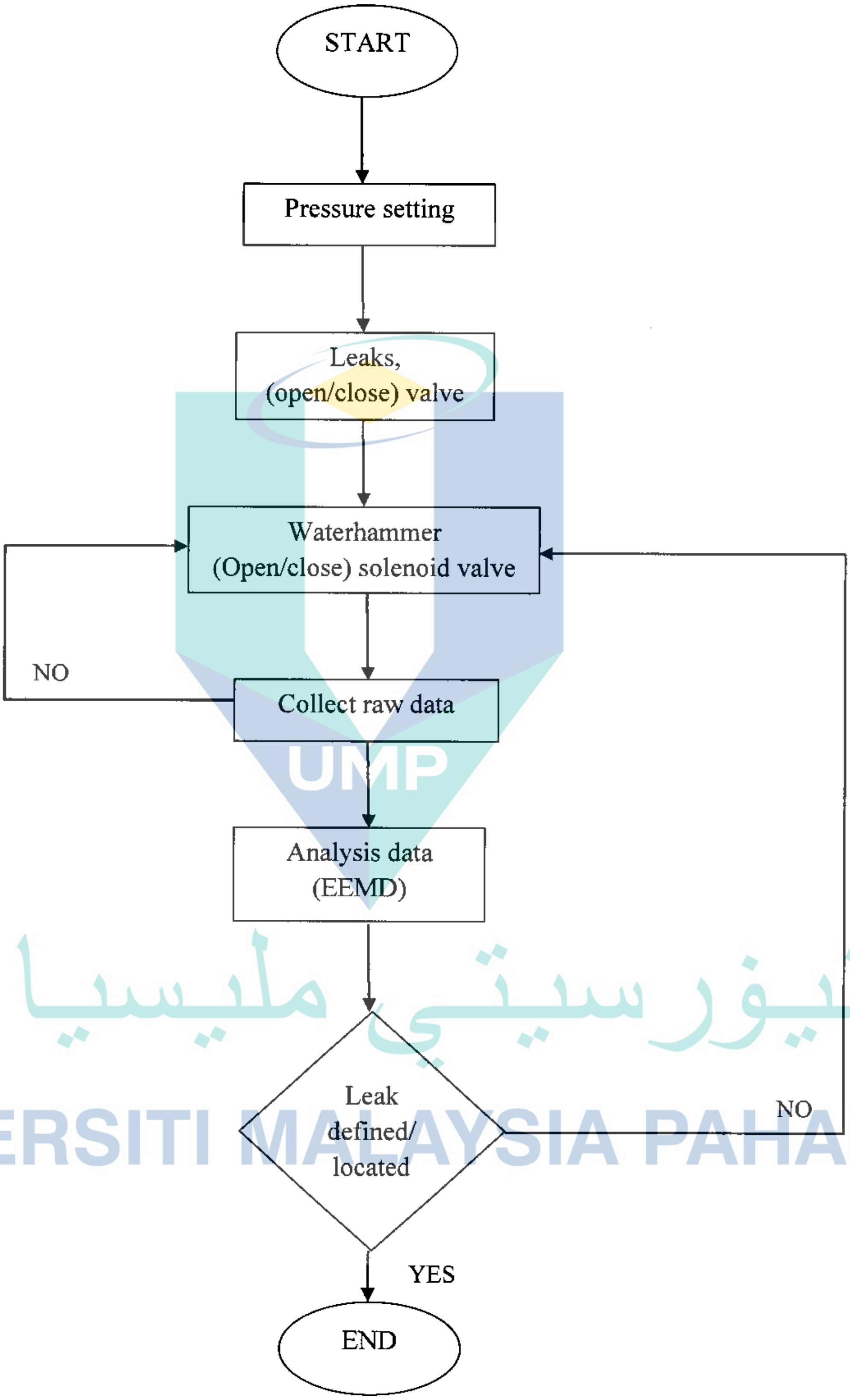

Figure 3.15 Flowchart of Internal Leaks Detection

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Make sure the pressure is on stable reading 3 bar and then open the leak valve and make sure there are no other leaks along the pipeline. After the water pressure in the pipe is in stable condition, press the switch to generate a solenoid valve to create a sudden open/sudden close valve inside the pipe to create a waterhammer. Solenoid valve and pressure sensor are placed on a fire hydrant as in figure 3.11. Data taken at the time of the solenoid valve is turned on within two seconds. Data taken using data acquisition system laboratory (DASYLab) software. The data taken using the specific modules as in figure 3.16. Typically data will be taken according to the situation as much as 10-20 times, data must not exceed 2 seconds.

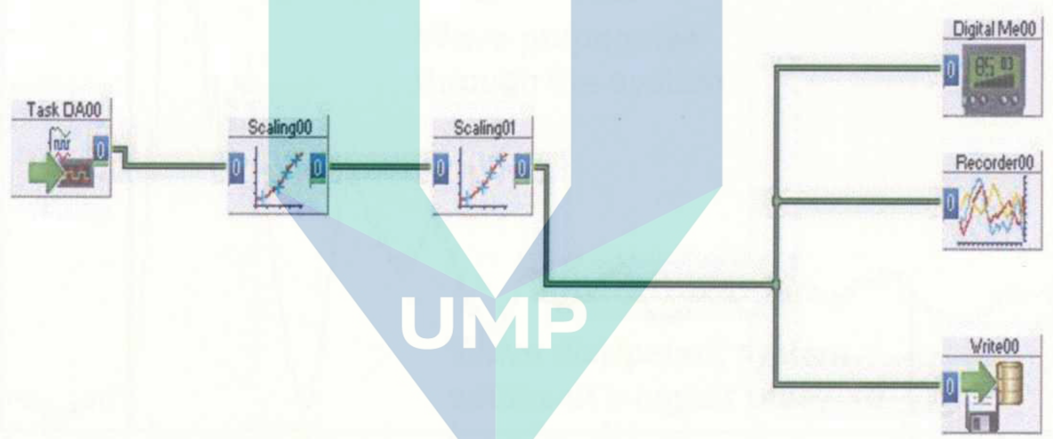

Figure 3.16 DASYLab Modules

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DASYLab includes a wide range of real-time data analysis and control functions for easy developing custom application. There are modules for performing many tasks such as Fast Fourier Transforms (FFT), digital filtering, and logical operations. With the modules, a complex calculation can be set up in seconds. Generally, the DASYLab work by extensive hardware support from national instrument device. It supports measurement computing data acquisition hardware by choosing I/O from analog, digital, counter/timer, IEEE 488, RS232, Modbus and many other devices. Figure 3.16 shows the DASYLab modules used in this study.

DASYLab Software procedure begins by connecting the NI-DAQmx to the computer. The DASYLab is then synchronizing with the NI-DAQmx software so that the reading or anything related to the DASYLab with be the same in the NI-DAQmx software. To display the data, the digital meter and recorder is used. Write modules are used to save the file in excel format. The advantage used DAQ system compared to traditional measurement system, PC based DAQ systems exploit the processing power, productivity, display and connectivity capabilities of industry standard computer providing a more flexible and consistent measurement solution tool to capture signal analysis source from (http://www.ni.com/data-acquisition/what-is/).

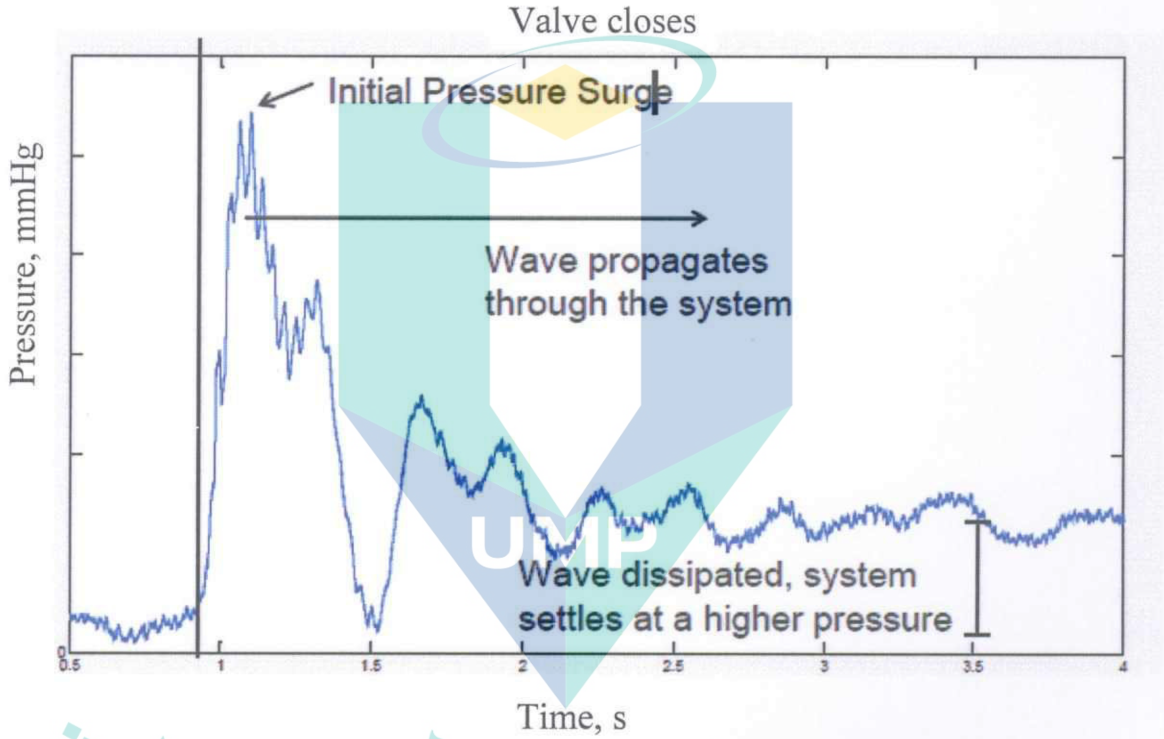

Figure 3.17 Typical pressure transient signal

If the data cannot be taken as too much outside interference/noise, the open/close solenoid valve will be performed again. After the original data for analysis were taken from DASYLab. The data will be analysed by the EEMD method by using MATLAB software and will get the result for pressure transient signal, the example is in figure 3.17. Only 2-3 data can be retrieved from the original data/raw data to be anlyzed using EEMD process. This is because a lot of data taken with too much noise.

After the EEMD analysis performed and the process goes through filtering and leakage data will be identified through data released after the analysis. Leaks data will be identified with the manual calculation and will find out how much error from the real data. If the result is totally out of range the experiment will goes to collect the original data again. And the process will be the same until get the leaks data as shown in experiment process in flowchart figure 3.15.

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CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

Water fit for human consumption is called drinking water or potable water. Water that is not potable may be made potable by filtration or distillation, or by a range of other methods. However, water loss can reduce the main source of living for a human being and other nature. Therefore, in order to prevent this phenomenon, leakage reduction have become the main priorities for water industries and also other industries that are related to the piping networking.

There are numerous factors that highly cause this occasion to occur such as the inevitable pipe ageing that prompt undesirably high leakage levels (M.F. Ghazali et al., 2012). In addition, this process speeds up by some factors that naturally occur inside the pipe, pressure surge inside the pipeline or outside the pipe, deficient design of pipeline, corrosion on the metallic structure of pipe, and also the present of third parties. Water losses due to the outflow seem simple for a normal person but for a specific person that handle the services, they lost resource, money and energy.

This chapter describes the method of Ensemble Empirical Mode Decomposition (EEMD) brings out a solution in preventing or reducing the cost of leakage detection. This method can be said as reasonable in cost and simple to handle. This method only needs monitoring of computational data that detected from the sensor placed to the fire hydrant. The result from the experimental procedure will be shown and discuss precisely based on the data analysed by using matrix laboratory (MATLAB) software.

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The data gathered in Data Acquisition System Laboratory is decomposed into series of signal using the new approach method that is EEMD. The leakage location then can be diagnosed from the series of Instantaneous Frequency (IF) related to their respective Intrinsic Mode Function (IMF).

4.1.1 Original Response

Original response or also known as raw data is a set of data that gathered after the water hammer phenomenon induced by using the solenoid valve throughout the pipeline system. The raw data recorded by DASYLAB software transferred to the MATLAB software for the data analysis process. The original response gathered was taken with surrounding noises that can affect the result.

The water hammer phenomenon was induced many times in order to give the best transient signal to be chosen for the next process. The experiment data that is obtained from the transducer response shows that on how the behaviour of the pipeline does would be and in this signal response, the signal that is recorded also retrieves the characteristic of the whole pipeline network itself.

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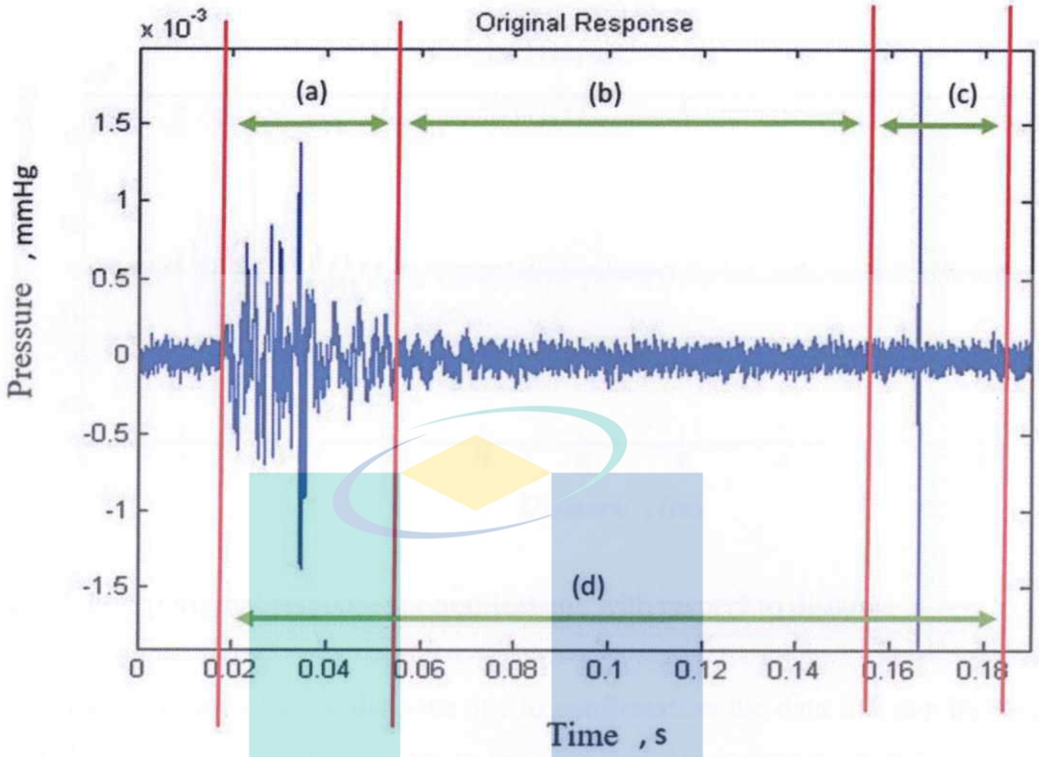

Figure 4.1 Original response vs Time for non-leakage pipeline system

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Figure 4.1 shows the original response for leakage detection MDPE pipe without resistance that is reflection point. The following figures indicate on the original response of the pressure transducer that is being obtained throughout the experimentation with a variation of pressures (P) with data retrieval. As we can see from figure above, the higher amplitude of wave is recorded around 0.02 until 0.06 seconds.

As can be seen in Figure 4.1, the pressure transient can be seen clearly in the beginning time/pressure response and the transient generating is taken along the pipeline from boundaries as stated in line (d) after the waterhammer is creating as stated in line (a) from sudden close valve. The wave in the fluid created acoustic waves and will travelling along the pipeline. Wave propagation in the fluid throughout the pipe and partially reflected back, partially transmitted forward in a some point boundaries in line (b). The wave flow will absorbed when there are discontinuities by leaks and feature of pipe along the pipeline system as in stated in line (c).

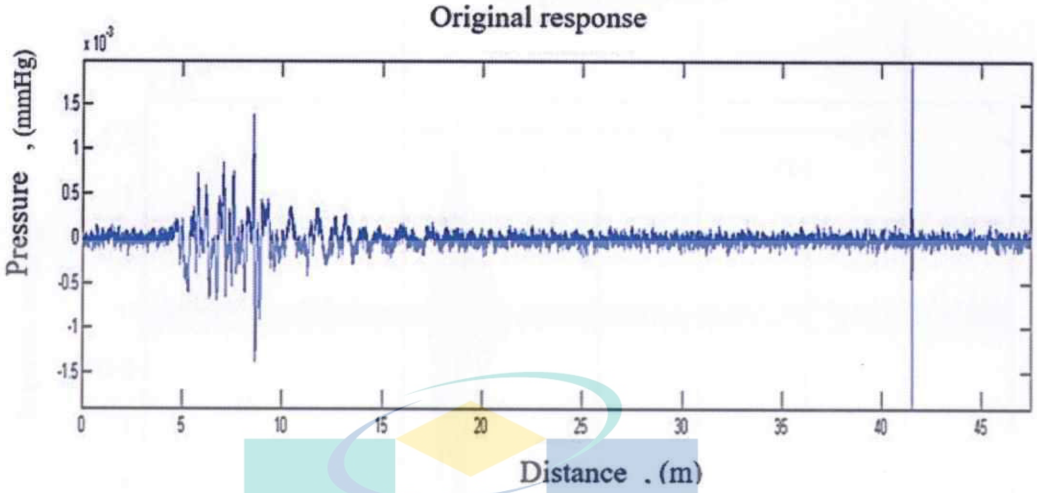

Figure 4.2 Original response for non-leakage with respect to distance

The data converted to distance due to confirmation the data that can be used to analyzed as in figure 4.2. This is due to the pressure surge when the water hammering induced through the system. However, the noises from the surrounding interrupted the data gathering process. In Figure 4.4.3, the original response shows the data when there is leakage present in the system. The water hammering is applied to the system around 0.02 second and 0.053 seconds. The raw data is important to be observed before the analysis process taken. It is hard to recognize any leak present in the pipe network without further analysis using appropriate signal processing.

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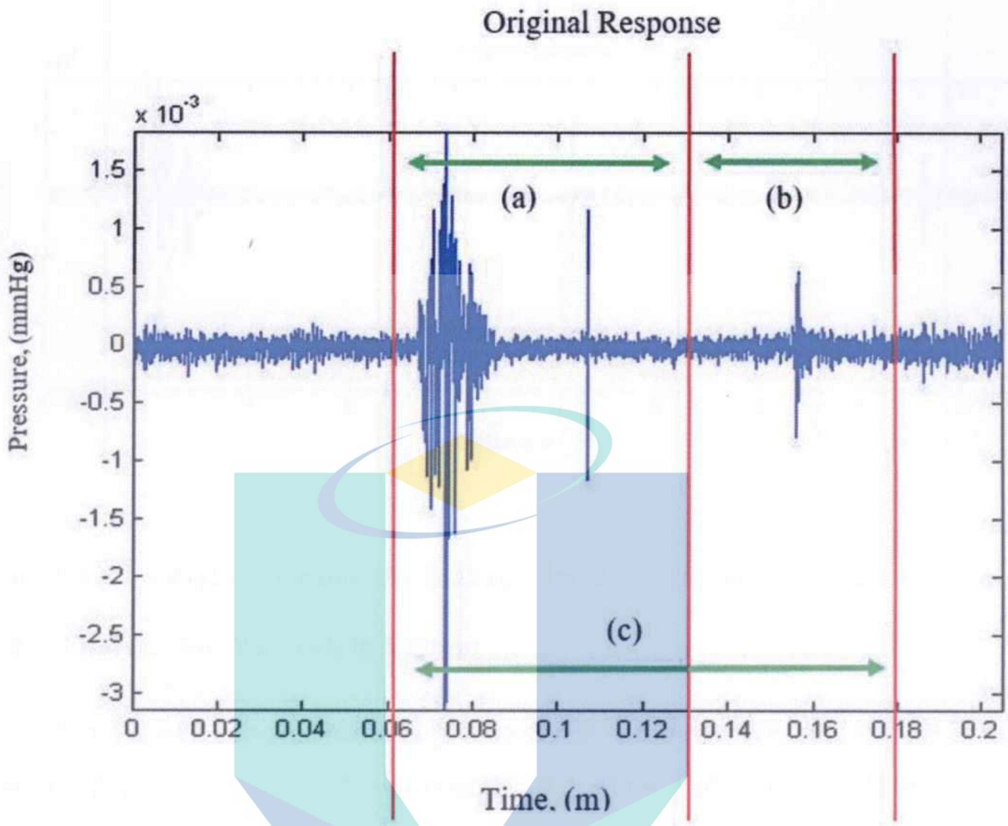

Figure 4.3 Original response with leakage in pipeline system

From Figure 4.3, the data taken is clearly have some disturbance in line (c) in wave reflection. This is due to any leak or any medium that effected the result. This data is analyzed using EEMD method process. Initially in line (a) is the water hammering and (b) section is the discontinous wave presence in this data that can be clarify the final wave. In figure 4.4 the total distance taken is 38.5m.

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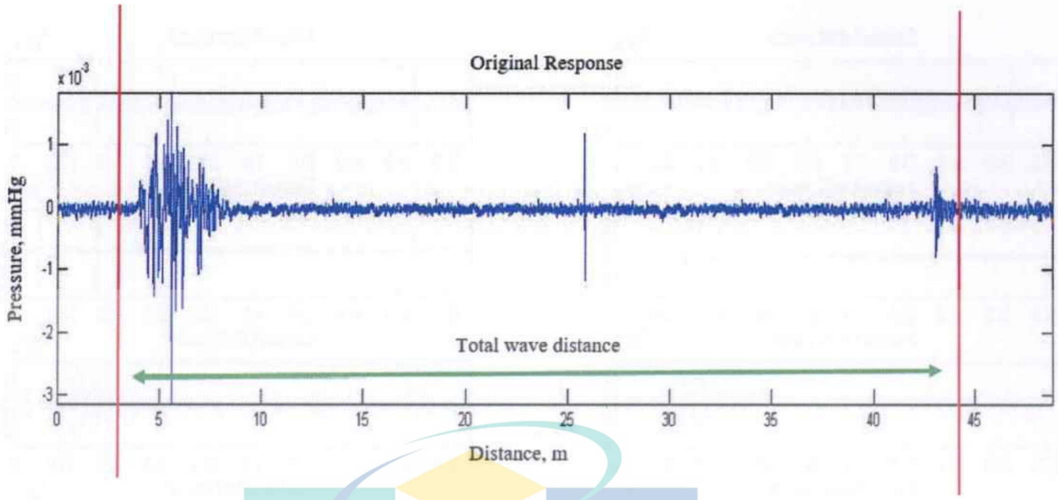

Figure 4.4 Original response for leakage signal with respect to distance

4.1.2 Analysis for No Leak in System

Even a well behaved stationary time series will have problems if there is random noise in addition to the signal. Fortunately, the method of Ensemble Empirical Mode Decomposition (EEMD) is able to counteract the effect of a noisy signal by averaging a large number of trials together.

As the number of trials grows, the signal tends to emerge from the averaged IMF set. The signal is decomposed using EEMD, which yields twelve IMFs from a high to a low frequency. Certain IMFs consist mostly of the noise while others contain the basic response of the signal. Therefore, all of these IMFs have been selected for next data processing. Figure 4.5 shows the result of IMFs obtained from the decomposition using EEMD method.

The EEMD method recovers three main IMFs: the first one is a high amplitude, high-frequency component. secondly, a high amplitude, low-frequency component and lastly, a low frequency, low amplitude component. While the presence of a high-frequency component is clear from the original signal, the spindle shape of this component is not obvious until it is decomposed into an IMF.

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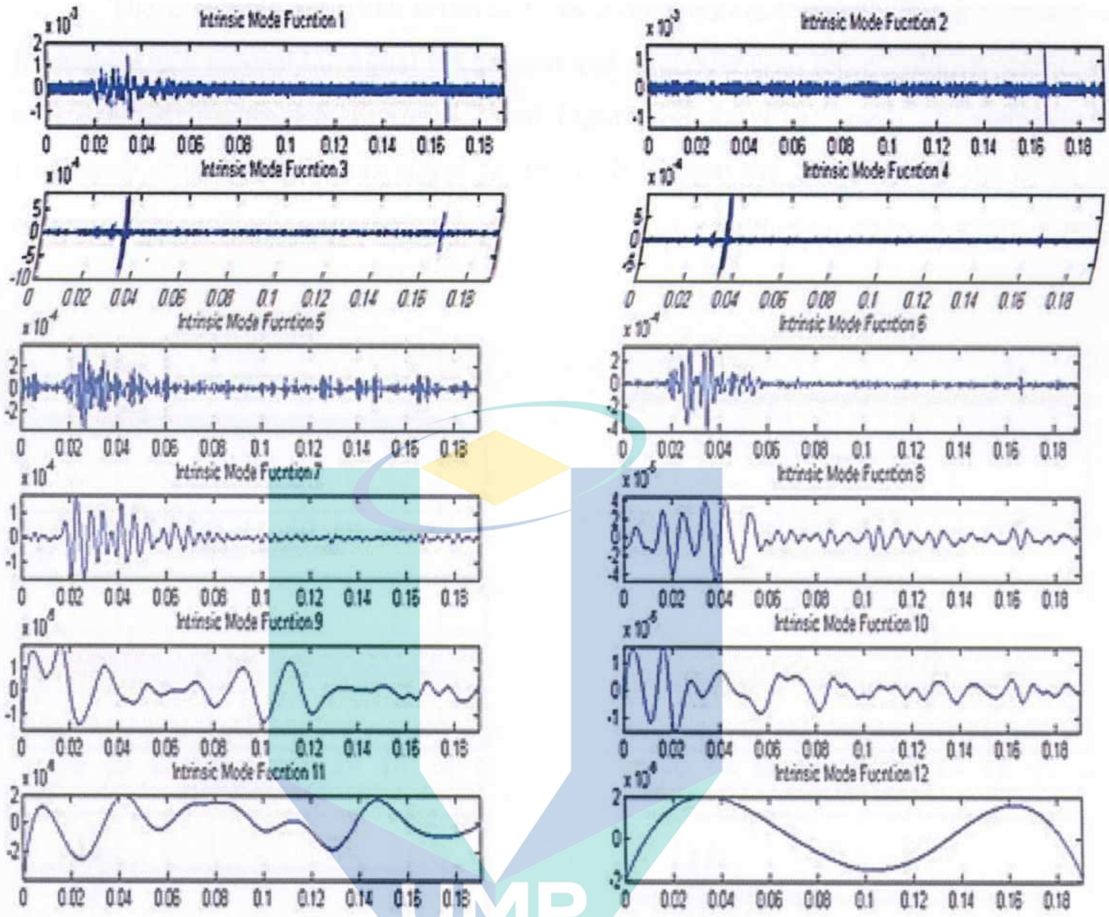

Figure 4.5 Analysis of Intrinsic Mode Functions (IMFs) 1st until 12th using Ensemble Empirical Mode Decomposition (EEMD) method for no leakage signal

Although this could have been discovered by using a bandpass filter, the signal could have been distorted because of the transient nature of the waveform and the fact that this element has frequency modulation. Therefore, the EEMD has already improved potentially valuable statistics on the dissimilar mechanisms of this signal. After the twelve IMFs is observed start from low past frequency IMFs 1 until IMFs 12 high past frequency as in figure 4.6. The data is then converted for their respective Instantaneous Frequency (IF). In this step, all twelve IMFs is converted to their respective IF. In contrast to a Fourier frequency, the instantaneous frequency is, in general, a time-dependent frequency. The importance of the IF concept stems from the fact that in many applications, the signal analyst is confronted with the task of processing signals whose spectral characteristics, in particular, the frequency of the spectral peaks is varying with time.

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These signals are often referred to as a nonstationary signal. The instantaneous frequency of a sinusoidal signal is constant and equivalents to the oscillation frequency as estimated. Figure 4.6, Figure 4.7 and Figure 4.8 show the result of instantaneous frequency analysis of no leak signal for the 1st IMF until the 12th IMF. All the IMFs are separated respectively with their IF.

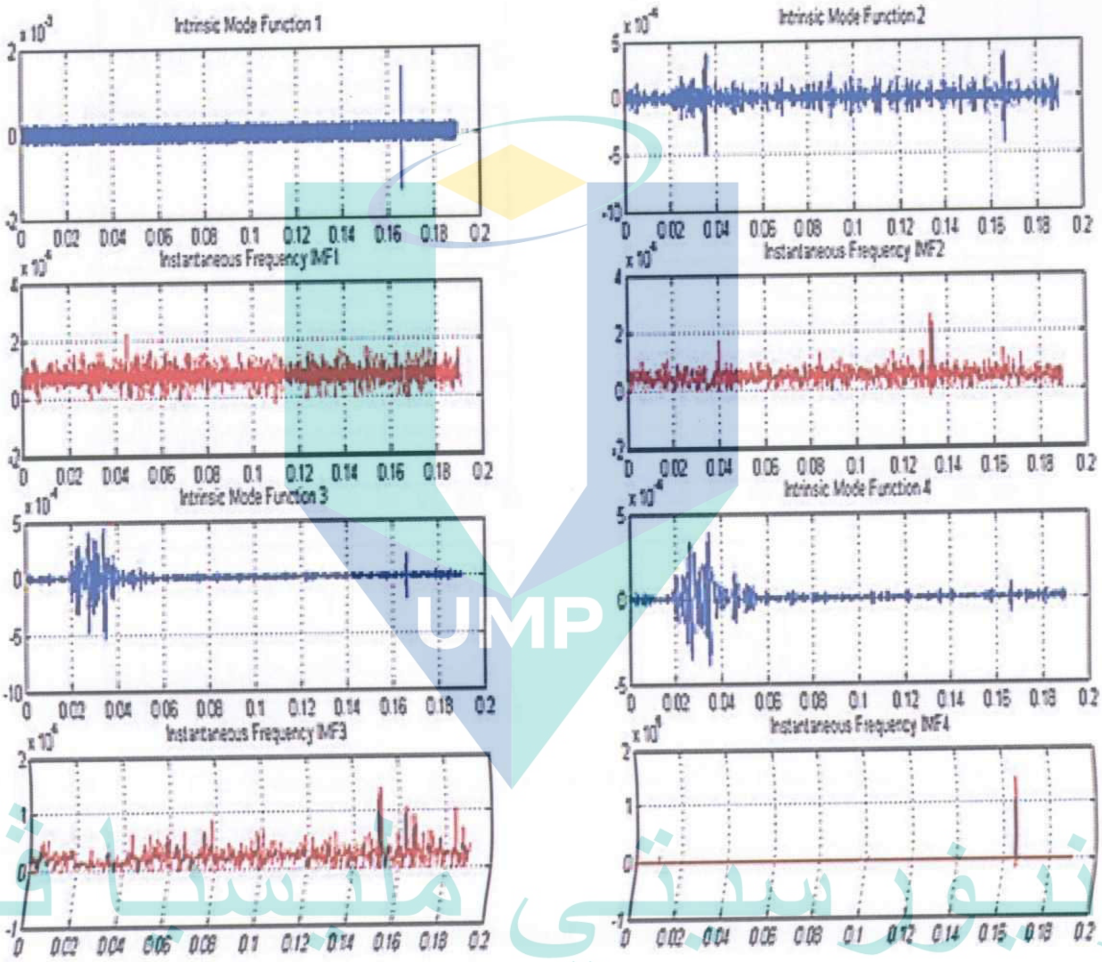

Figure 4.6 The instantaneous frequency analysis of no leak signal for the 1st IMF until the 4th IMF

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The result of the instantaneous analysis shows that IMF1-IMF3 only indicate the presence of noise in the data with the same amplitude continiously either from inside the pipeline or from the surrounding. Sensor that used in the experiment very sensitive to the surrounding noises. So, by using EEMD analysis, the useful signal can be separate with an unwanted signal like noise. Therefore, all the three IMFs will be ignored for the next data analysis. By reducing all three IMFs, the summating of other signal indicates the pressure signal without noise.

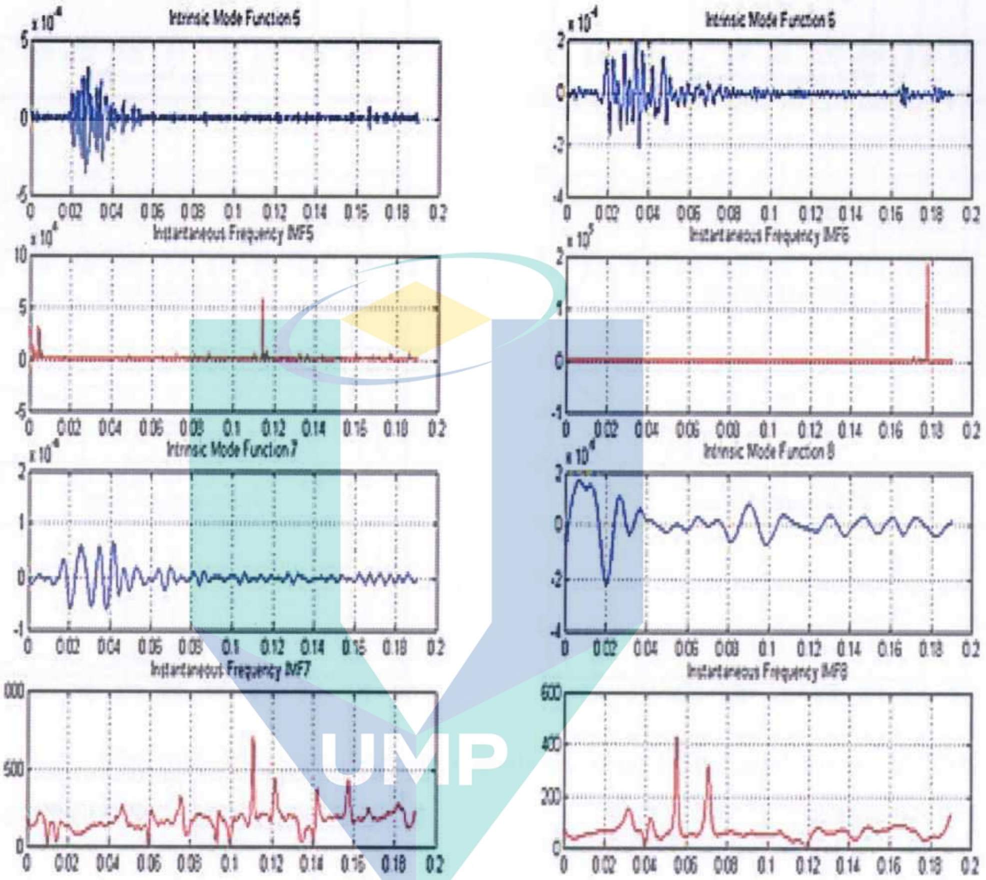

Figure 4.7 The instantaneous frequency analysis of no leak signal for the 5th IMF until the 8th IMF.

All the other remains signal are combine in one single plot that is all instantaneous frequency as shown in Figure 4.9. In the figure of all instantaneous frequency, there are two main peak frequencies observed. The first peak generated around 0.01second through instantaneous frequency analysis shown the time, where water hammering is applied to the pipeline system. The other peak observed in the frequency analysis result is around 0.165second. The time will indicate the location of the feature in the pipeline system after the conversion of time to distance.

From the figure 4.8, IMFs 5 and IMFs 6 likely to have a clearer result other than IMFs 7 and IMFs 8. From this IMFs and IF process the result seems to get the best result to get in final dicision in IF selection.

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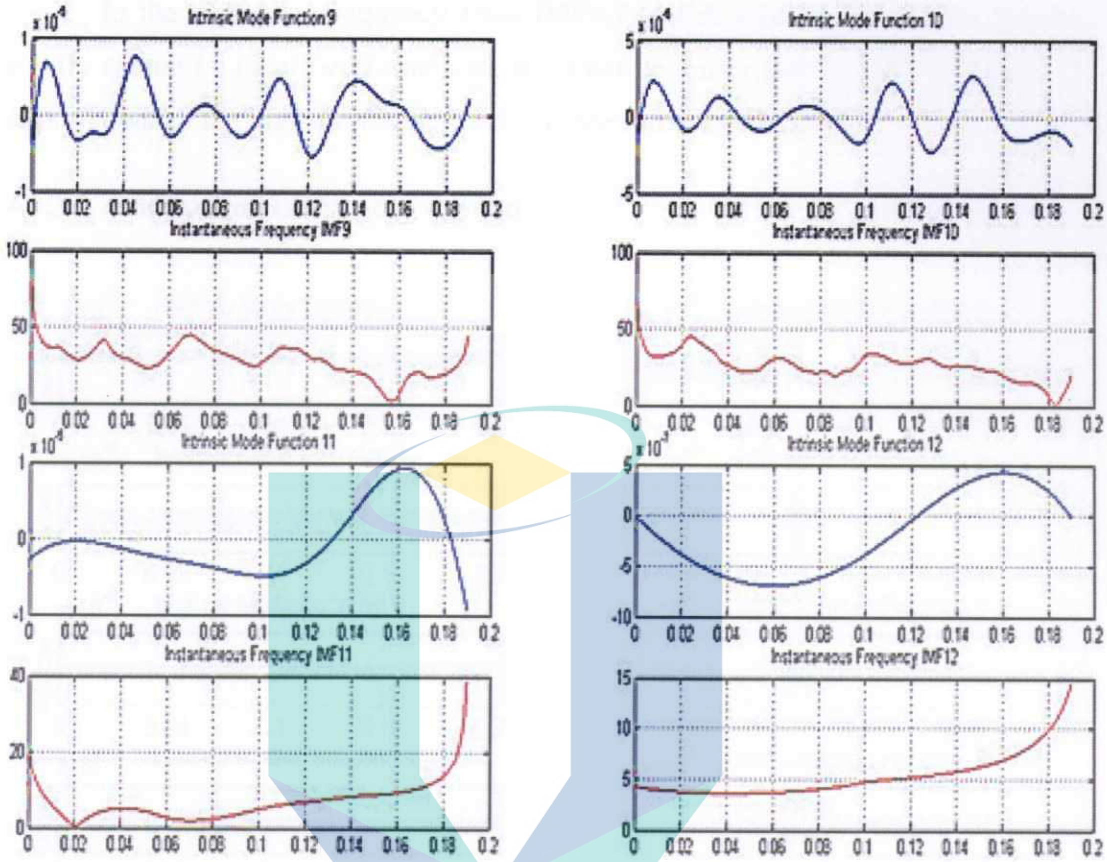

Figure 4.8 The instantaneous frequency analysis of no leak signal for the 9th IMF until the 12th IMF.

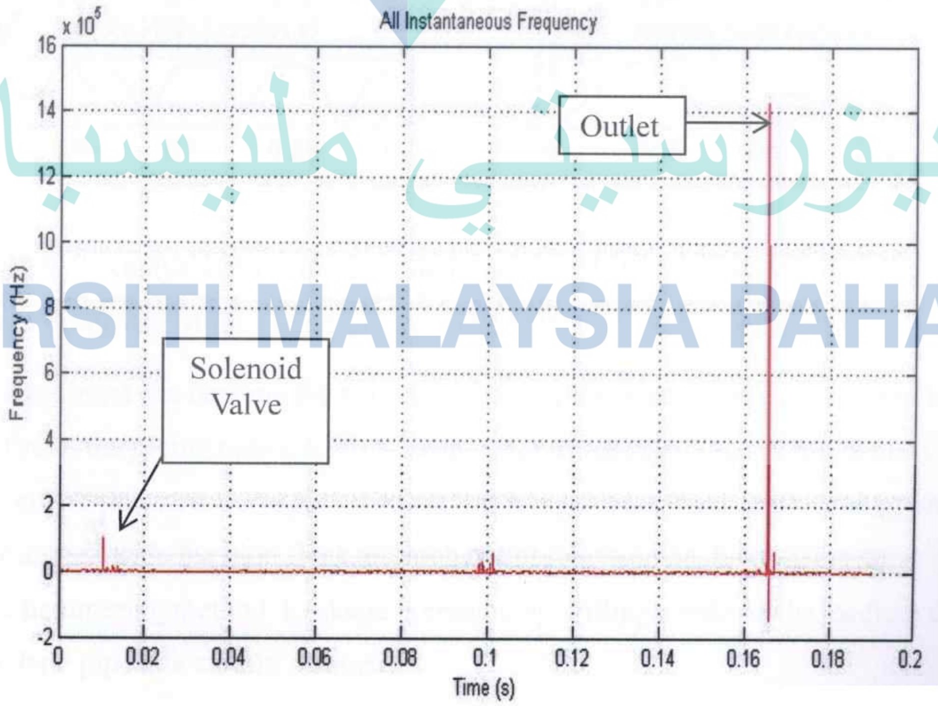

Figure 4.9 Analysis of All Instantaneous Frequencies

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In the high pass frequency from IMFs 9 to IMFs 12 in Figure 4.9. The result clearly cannot be identified to indicate any interruption or leak in the pipeline. In high pass frequency the high amplitude condition are shows on the graph.

4.1.3 Analysis for Leakage in System

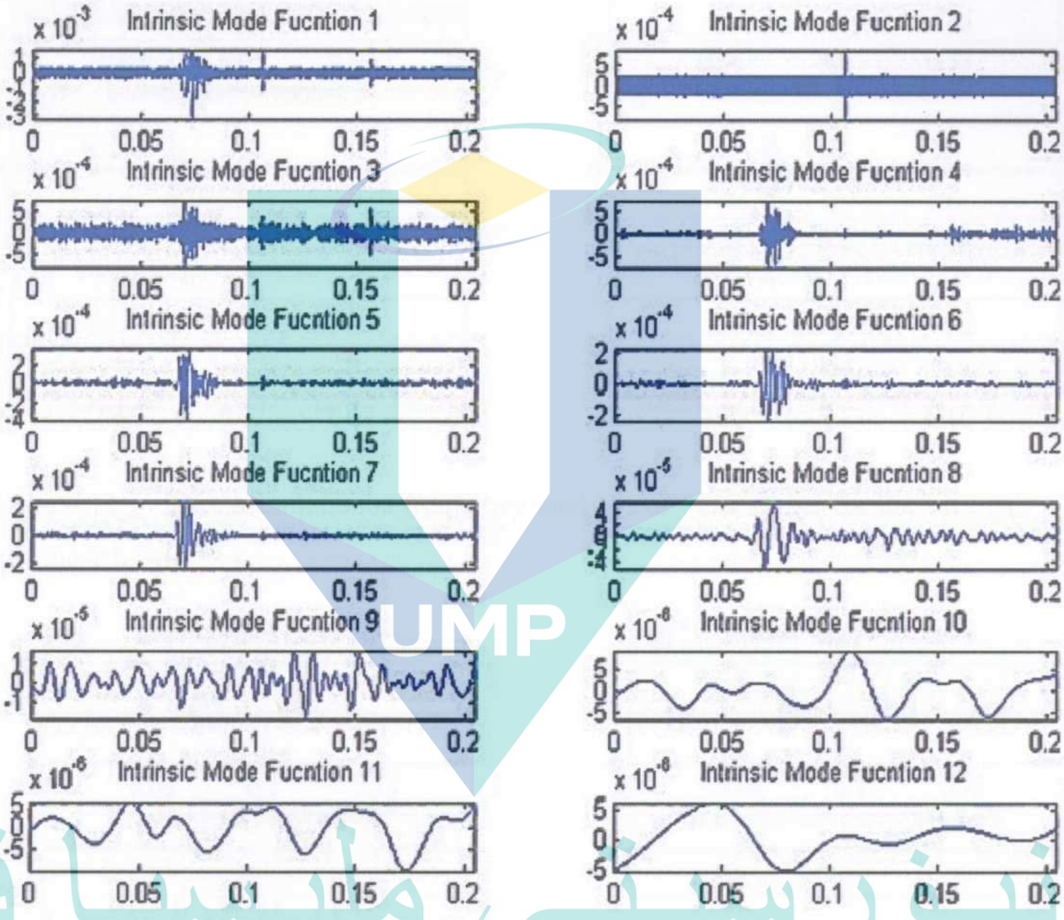

Figure 4.10 Analysis of Intrinsic Mode Functions (IMFs) 1st until 12th using Ensemble Empirical Mode Decomposition (EEMD) method for leakage signal.

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Pipe burst can become the main problem in pipeline failure. Pipe burst or leakage hard to find if the piping network burns deep under the ground. It can happen due to many reasons either pressure that applied around the pipe, corrosion, pipe ageing, and also pressure surge inside the pipe. This research mainly focused on the pressure surge creates by water hammering method. Leakage is created by drilling a hole on the medium density polyethylene pipe at a certain distance.

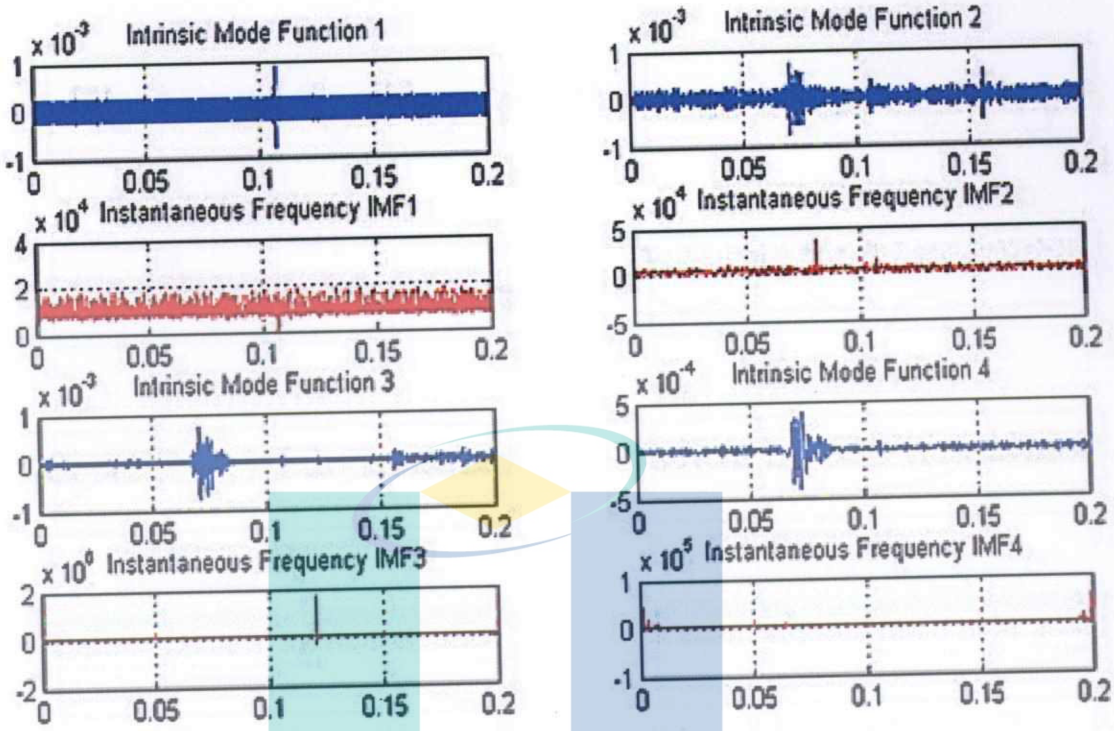

Figure 4.11 The instantaneous frequency analysis of leak signal for the 1st IMF until the 4th IMF

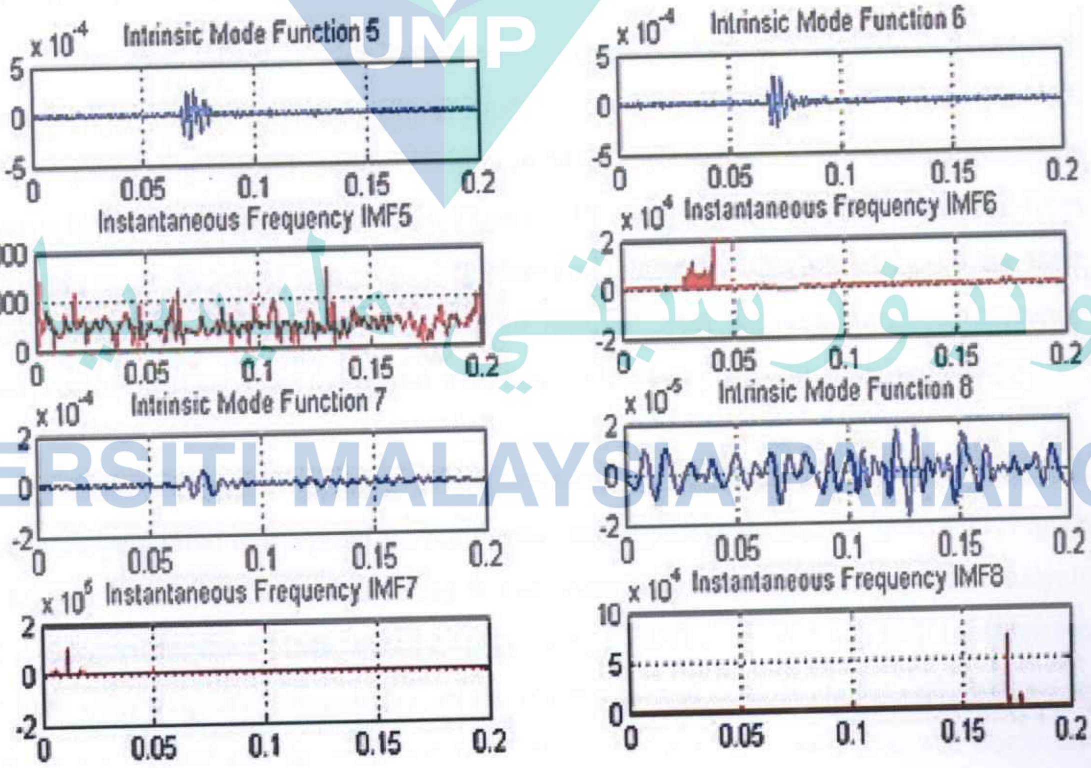

Figure 4.12 The instantaneous frequency analysis of leak signal for the 5th IMF until the 8th IMF

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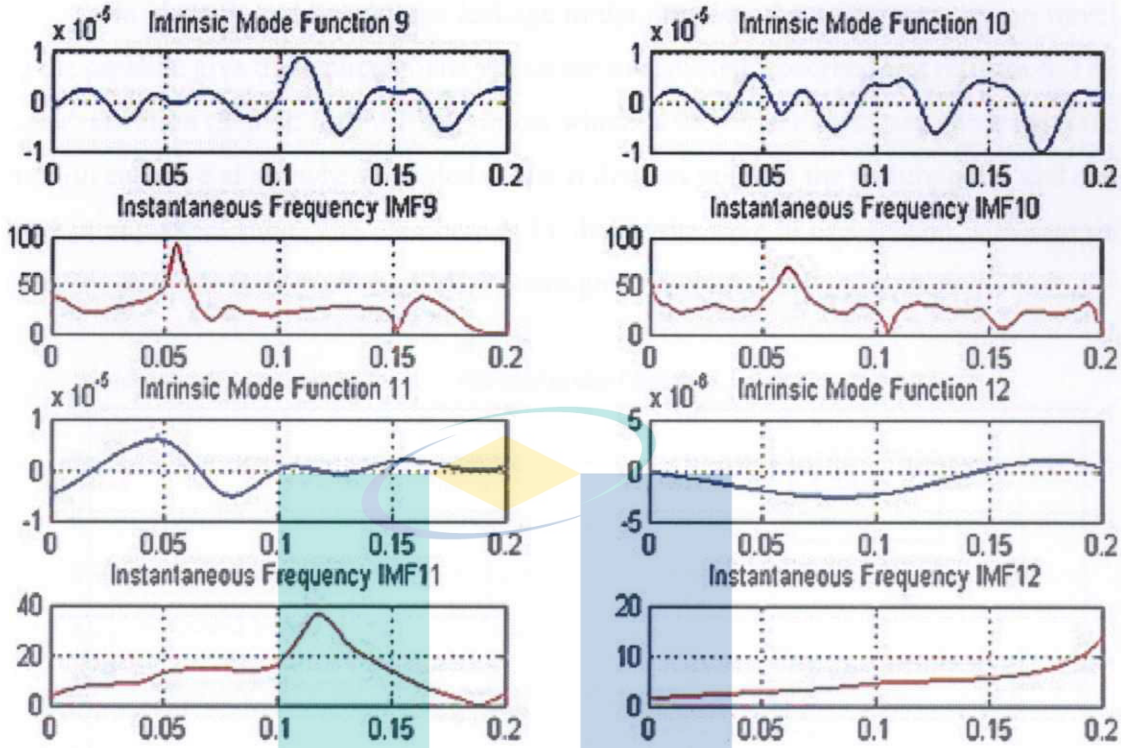

Figure 4.13: The instantaneous frequency analysis of leak appearance signal for the 9th IMF until the 12th IMF

The data collected with the hole in an open condition. This hole or leakage is controlled by a small valve either in opened or closed condition. From the data collected, the analysis using EEMD method is done in MATLAB software. The coding generates twelve IMFs for the signal collected. Figure 4.10 shows the twelve IMFs resulted from intrinsic mode function analysis. IMFs created classified the signal based on their amplitude level. The data will be used to proceed with the instantaneous frequency analysis that will separate the signal with their respective instantaneous frequency.

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Ensemble empirical mode decomposition (EEMD) method will convert each of the IMFs generated in the previous result into the frequency domain. Figure 4.11, Figure 4.12, and Error! Reference source not found. show the instantaneous frequency analysis of leak signal for the 1st IMF until 12th IMF using EEMD method. Each IMF is converted to their own frequency domain. From the observation of each IF, noise that includes in the data collected can be removed for further analysis. IF2 until IF8 will show the pressure signal if they are sum up. Therefore, other IFs will be ignored or remove in later analysis. The removed IFs only show the noises that are included when the data was collected.

To identify and located the leakage in the pipeline, the wave propagation travel in the pipeline give three phenomena which are transmitted, absorbed and reflection. The Leak reflection method for this experiment which is the reflection of wave in transverse motion can give at anywhere located of the reflection point of the feature point and can give in anywhere time. The idea here is by divide the time in one second with sample size, for example the experiment MDPE straight shape used 1000 sample and 1 kHz.

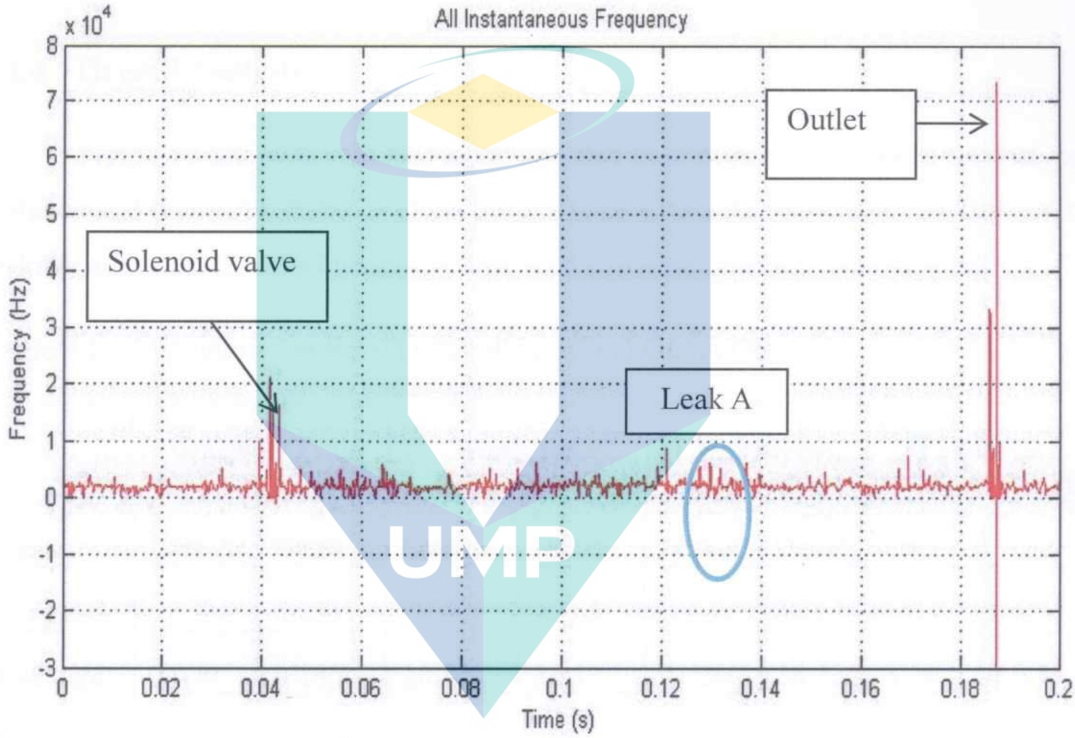

Figure 4.14 Analysis of all instantaneous frequencies

Table 4.15 summarizes the result of all experiment. In general, both experimental and simulated results confirm that EEMD process can provide simple and clear results which indicate that this analysis technique is able to locate leaks and features in simple pipeline system with acceptable errors. The instantaneous frequency for all intrinsic mode function drawn together and the unwanted IF deselected from the plot and remove. The only remain IF is the pressure signal without noise as shown in Figure 4.14. Three main peaks are observed in the all instantaneous frequency plot. The first plot appears at 0.04 second follow by the second peak at 0.12 second and last peak at around 0.19 second.

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The first peak consistant with the position of solenoid valve, where the water hammering creates into the pipeline. The last peak shows the highest frequency follow by the first peak with the frequency of 7.2×10^4 Hz, 2.1×10^4 Hz, and 0.9×10^4 Hz respectively. While the smaller peak in the middle said to be the location of leakage and the last peak illustrate the location of the outlet. All this time of the peak generated used to calculated the analysed distance to be compared with the measured distance that is the actual distance on the test rig.

4.1.4 Overall Analysis

Figure 4.1 shows all the best result and also the comparison between the analysed distance and measured distance. This project is divided into two categories that are no leakage and leakage experiments.

Table 4.1 Summarize Result of Both Leak and Outlet Distance

	Analysed Time (s)		**Analysed Distance (m)**		**Measured Distance (m)**		**Error (%)**	
Test	Leak A	Outlet	Leak A	Outlet	Leak A	Outlet	Leak A	Outlet
No Leak	-	0.155	-	40.63	-	38.33	-	6
Leakage	0.079	0.145	20.81	38.12	21.50	38.33	3.21	0.55

It can be seen clearly that the outlet of the pipeline feature can be identified by using EEMD method. For the test rig with leak valve closed, the outlet is analysed at 0.155 seconds while the setting for leak open, the time is 0.145 seconds, respectively from the measuring point. The distance of the outlet or leakage from the source of transient that is solenoid valve can be calculate simply by multiplying the time different corresponding to the each peak by the calculated speed of sound, V, that is 540m/s in the medium density polyethylene pipe and dividing by two, this value to value the go and forth distance.

Therefore, the analysed outlet distances for without leak and with leak experiment are 40.63 m and 38.12 m, respectively. The real distance or measured distance of the outlet on the test rig was 38.33 m. So, the error of analysed outlet distance compared to measured distance for without leak test is 6% while for the experiment with the leak is 0.55%. The analysed time of leakage in the experiment with leak observed at 0.079s.

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Hence, the analysed distance is 20.81 m. The measured distance is 21.50m from the point of measure. So, this shows the error of 3.21% after comparing both values.

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CHAPTER 5

CONCLUSION

5.1 Introduction

This chapter summarizes the important and significant outcomes from the work carried out in this research. It also embraces some recommendations for future work related to this research.

5.2 Conclusion

Leak detection methods have become one of the most important aspects in handling leakage either in water supply industries or oil and gas field. Water supply companies bear millions of costs in preventing or repairing pipe burst and also water loss. Leak detection and position in pipelines are vital to avert cost and energy losses, warrant safety and reducing environmental harms. So, when managing a pipeline network, the most effective or accurate leak detection method is needed. Nowadays, a number of leak detection methods had been proposed in order to prevent losses. The work designated in the first part of the present study show the new leak detection techniques based on the analysis of a transient pressure wave.

Furthermore, the pipe feature such as T-joint, 90-degree elbow, reducer, and valve are also attached to the test rig. Solenoid valve is used to create the pressure transient and disturbing the wave. The wave propagates by solenoid valve will propagate along the pipeline system then will reflect back if there any disturbance along the pipeline system. The reflected signal or waves are collected using pressure transient signal. The single pipeline system that pinpoint leaks successfully developed and the leaks

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successfully detected using pressure transient signal and analysed using ensemble empirical mode decomposition (EEMD) method until the best result archive.

The vibration from pump in test rig that very close can add noise in wave propagation in pipeline. Flexibility in use single pressure transducer can detect leakage in pipeline and can apply in pipe hydrant by using pressure transient techniques have been shown to offer an entirely new way of pinpointing leaks. The result confirmed that pressure transient analysis can identify leak with the percentage of error for non-leaks is 6% and for leaks 0.55%.

5.3 Recommendation

There are many things that were found to be complicated in this research. Many ways more to make this research more valuable in the future. There is a matter of time to make this thesis complete altogether. Something that been found to be useful for the next researcher that found this research useful and need to be brought forward more.

i. The researcher needs to focused on designing the test rig well because test rig will influence the data that will be analysed.
ii. The equipment of this study is limited in order to design a better experimental procedure. It is recommended that other researcher to precede this experimental procedure in real underground working pipeline system for a better result.
iii. In this study, only one pressure sensor used to detect all features in a pipeline. For better way to gather the data, place a sensor 10meter each along the pipeline path. This allows sensors to detect any change in pressure occur either due to the leakage or other features.
iv. This research can be altering by improving data analysis process. The data analysis using EEMD method is enhanced by adding other method such as spectrum analysis.

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