Investigation on Unhealthy Control Valve Characteristic using Acoustic Emission Technique

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ELECTRICAL ELECTRONIC ENGINEERING

UNIVERSITI TEKNOLOGY PETRONAS

JANUARY 2013

Investigation on Unhealthy Control Valve Characteristic using Acoustic Emission Technique

By

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Dissertation submitted in partial fulfilment of

The requirements for the

Bachelor of Engineering (Hons)

(Electrical & Electronics Engineering)

SEPTEMBER 2012

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CERTIFICATION OF APPROVAL

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Approved by,

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(Dr. Rosdiazli Bin Ibrahim)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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DO THAI HA

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ABSTRACT

Control valve, commonly known as final control element, is the vital element of any process plant and its performance must be monitored regularly to detect any problem occurring in advance. The detection of defects in control valve at early stages is crucial for plant operator to prevent unexpected shutdown. Thus, an effective maintenance plan could be set up to minimize the costly downtime. This project concentrates on investigating the unhealthy control valves characteristics based on the Acoustic Emission (AE) signal emitted from the fault. From that, the description about the AE characteristic of unhealthy control valve is made and it can be applied for further application in online monitoring system.

The project is divided into three stages. The first stage concentrates on preliminary research on the AE signal characteristics and its application on fault monitoring system. The second stage continues with the data saving process, where an experiment test rig is improved to serve the purpose of experiment activities and AE signal capturing. The experiment foundation basically includes a simple prototype of a process control loop accompany with a signal processing system where an AE sensor is implemented. At the end, the final stage of this project concentrates on processing the recorded AE signal by performing the signal analysis in frequency domain, using Fast Fourier Transform (FFT) and statistical analysis methods. Eventually, conclusions will be made up to summarize the AE signal characteristic of the unhealthy valve.

ACKNOWLEDGEMENT

This research project would not have been possible without the support of many people. The author wishes to express his gratitude to his supervisor, Dr. Rosdiazli Bin Ibrahim, who was abundantly helpful and offered invaluable assistance, support and guidance, for leading the project to the correct path.

Deepest gratitude are also due to the author’s research partner, Ms. Najiha Shukri, without whose knowledge and assistance this study would not have been successful.

Special thanks also to Encik Azhar, the technician of Process Instrument Control Lab, for giving precious guidance and enthusiastic assistance.

Not forgetting to his course mates who always been there. The author would also like to convey thanks to the Electrical and Electronics Engineering Technicians for providing the equipment and laboratory facilities. The author wishes to express his love and gratitude to his beloved families; for their understanding & endless love, throughout the duration of this project.

CHAPTER 1: PROJECT BACKGROUND

1.1 Background of study

Control valve is the fundamental element of the process plant. A healthy control valve contributes a high percentage to the successful operation and desired product quality. Therefore, the operation status of the valve needs to be monitored from time to time to ensure that the valve's health status does not exceed the certain tolerance to prevent the process plant from interruption. Nowadays, the failure mechanism of the process plant, such as cavitation and flashing, occurs more frequently and the location of damaged device is normally unknown. Up to the point when unhealthy valve status is determined, the industrial plan may have to unexpectedly shut down leading to costly operation downtime with expensive maintenance works. Therefore the quality assurance and quality control engineers are facing an obstacle in making a reliable system that can be able to monitoring the working condition, as well as detecting fault that occurs on control valve at early stages.

Some methods of monitoring the valve system, for instance, hydrostatic or pneumatic test which may require partly or totally plant shutdown, were already applied. They are not very convenient in term of implementation in industry plant. Since those systems only indicate the abnormal conditions of the plant but fail to observe the exact location of the faulty source. As a result the operation still needs to be interrupt and devices are disassemble to be able to determine the fault. By applying Acoustic Emission technique, a non-destructive testing system can monitor and capture the unhealthy phenomenon of control valve in an early stage. Then proper action can be implemented to prevent further damage.

1.2 Problem statement

In this project, the three major problems are determined below:

- At the moment, there is no official document and procedure guiding how the fault in control valve is created. The fault is simulated quantitatively by trial error method which demanding lots of time and accuracy.
- Currently, there is no online monitoring system that can be used effectively to determine the status of the control valve. Only after the process is interrupted, the inspection could be implemented to determine the valve status. Therefore, there is no reference when designing the experiment test rig.
- There is no early detection system which is capable to detect the fault in control valve in the first stages. Throughout quality control and maintenance timetable. The control valve is inspected separately and the leak test is implemented in the lab. Therefore, only after the fault has occurred up to some certain level in control valve, the leak test result could indicate its damaged status.

1.3 Project objectives

The main aim of this project is to investigate the behaviour of unhealthy valve based on its AE signal characteristic. In order to observe the aim of the project, three objectives have been outlined below.

- To perform experiments on unhealthy control valve with different sizes of simulated.
- To analyse the captured AE signal of unhealthy control valve in terms of frequency spectrum response.
- To distinguish between different stages of damage on control valve based on their AE signal’s characteristics.

1.4. The scope of the project

In order to observe the objectives of the project, many sets of AE signal data of defect control valve are prepared to study the characteristics. During the experiment, the typical faults which occur in industrial control valve is simulated representing control valve leakage. The fault will be created stage by stage following the increase of leakage rate from early fault, middle fault and damage. Due to the technical specification of the control valve in the lab, the maximum allowable leakage rate is 34ml/min (classified as class IV of damage status).

The major part of this project involves in AE signal processing. The sensor is attached at different locations on control valve: middle body, inlet flange or outlet flange, in order to locate the best AE source. By using Signal processing software, the AE representation in time domain are recorded and processed in frequency domain using specific equipment. The maximum amplitude of AE signals in frequency domain at different valve opening will be analysed and compared with other stages' signals to determine the unhealthy status of the control valve.

Besides, the control process uses water as the medium of operation. Once, the fault in the valve has simulated, the water leakage will produce AE signal.

1.5. Project Relevancy

In this project, the main target of relevancy is the application of AE technique in fault detection which occurred in control valve in a process plant. The project helps to evaluate the potential of AE application in building an online signal monitoring system which indicates the status of the valve without interrupting the process. Based on that, the result can also be related to apply in an early detection system which indicates the stage of the valve fault during the process plant operation.

Furthermore, the project could contribute to develop an enhanced quality control system from a momentive maintenance to a predictive maintenance system that help saving money and time for the operator.

1.6. Project Feasibility

The project is expected to accomplish in two semesters and this creates a chance for author to work on the three major elements of the system. For the first semester, the author will focus more on studying the AE signal characteristic and application on fault monitoring. During this period, it is required to build the test rig to serve the experiment purpose. The main equipment are taken from the Instrumentation lab including control valve, pressure transmitter, pressure gauge, etc. For the signal processing system, the equipment are borrowed from the Communication lab. The second semester is spent to conduct the experiments on unhealthy control valve and apply an analysis method to investigate the captured AE signal.

CHAPTER II: LITERATURE REVIEW

2.1 Introduction to control valve in process control system

Control valves are devices which being automatically controlled by the controllers through the actuators. The actuator's function is to convert the electric signal into pneumatic signal. By adjusting the opening of control valve, each controller can perform the control action to the process in order to obtain the control objectives. Control valve is referred to final control element in the closed control loop shown in figure 1. It is placed at the last position in front of the process that directly implement the control actions to the process.

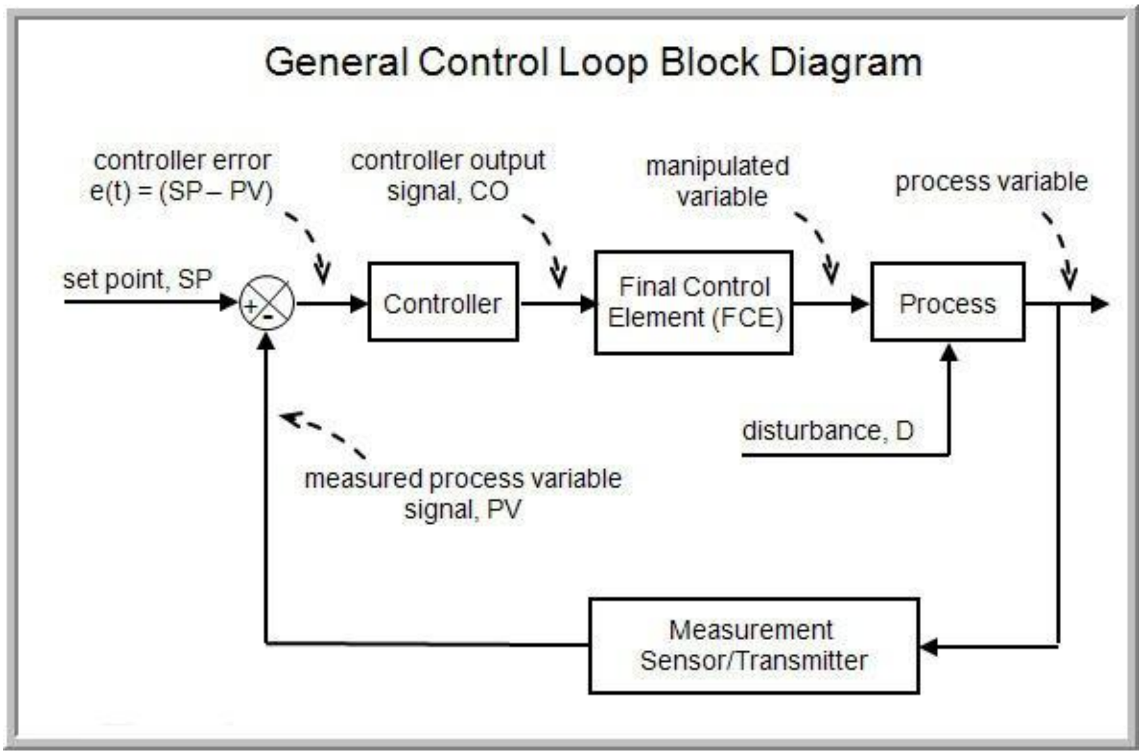


Figure 1: The typical process control loop block diagram

Dale Seborg [9], in his book "Process Dynamic and Control", showed that, in order to manipulate the rates of energy transfer and material flow into and out of a process, some methods are applied such as pump driving, screwing conveyer or blower, etc. However, the most popular way of obtaining this result regarding to fluids dynamic is using a control valve. In petroleum and chemical processes, the flow rate of material, such as solid matter, liquid, and gas, is manipulated by the final control element. Therefore, control valves play vital roles in the process control loops as they are the major elements that directly execute the control action and lay impact on the process. With the significantly importance, control valves contribute considerably to the stability of the process's performance within their capacity to fulfil the control objectives and output requirement for production. Any fault occurs on this final control elements may immediately lead to operation interruption, low quality production as well as huge cost and profit loss for trouble shooting and maintenance.

The operation of the control valves, which is basically the plug's closing or opening movement, is directly manipulated by the valve's actuators through the controller's instruction. In closed-loop control, the controller compares the value of output process variables, which are measured by the sensors, to the predefined values called setpoints. As a result, the controller controls the input variables through the control elements to adjust the output variables to reach the setpoints and eventually eliminate the difference between output process variables and desired setpoints. Generally, the intermediate devices attached to control valve which create force to open and close the valve's plug are electric, hydraulic or pneumatic actuator which receive electricity signal from controller. In industry application, these control signals are calibrated in the range of 4-20mA corresponding to 3-15 psi (0.1-1.0 bar) of applied pressure, following the industry standard (Wikipedia, 2012).

Studying the internal construction of the pneumatic control valve, the globe valve's main components include the valve body, trim, seat and actuator as shown in figure 2. It is an air-operated device which controls the flow through an orifice by positioning appropriately a plug. In other words, it is a variable orifice in a line. The trim modulates the flow rate and can be a plug, ball, disk, or gate (Borden [10], 1998). Valve seat is the place where the valve plug lands down and remains staying for the fully close condition. It is attached with a layer of protective material (typically metal or soft polymer) inserted around the orifice to provide a tight shutoff. The design of Control valves depends on the construction of the plant and can be either liner or rotary. They are mainly categorized as angle valve, globe valve, diaphragm valve, rotary valve and sliding cylinder valve. For the sake of doing investigation on the faulty control valve, the globe type valve was chosen to do the experiment. The globe valve is named according to the body shape of this valve which has the spherical form and it is separated into two halves by an internal baffle that forms a seat to the movable plug. The plug is connected to automatic controlled stem that transfers the force from the actuator to move the plug. The operating actions for the control valve are repeated when it receives new control signal from the controller.

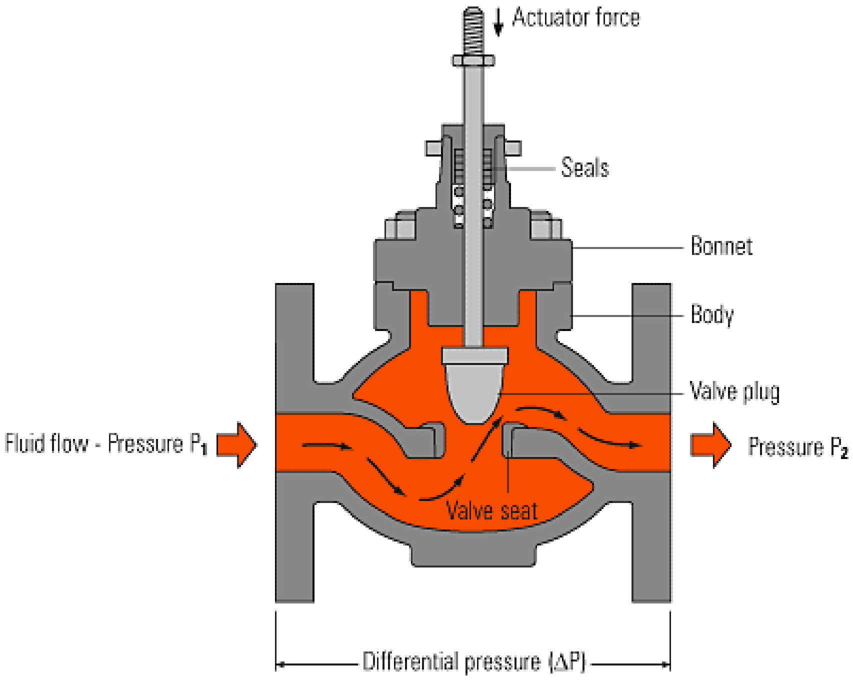


Figure 2: The major constituent parts of a globe valve

2.2. Introduction to Acoustic Emission signal and technique

Acoustic emission (AE) is a type of energy which is rapid released when the material is sustaining a stress. AE signal usually appears in the form of transient elastic sound wave from a source locating within the material. According to Watit Kaewwaewnoi [6] in his research “Measurement of valve leakage rate using acoustic emission”, it is concluded that when a solid material, e.g. metal, is undergoing a stress at some certain levels, it will produce continuous acoustic wave form signal from the surface of the material. The generation of acoustic sound from stressful solid material is defined as acoustic emission. The stress of the solid material represents its unhealthy status, such as cracking, half-breaking, fracture, etc. and it might be caused by the either internal or external force applied to material for a long period of time. There are two classes of AE source mechanism classification, classical source and pseudo source. Classical source locate at the internal structure, such as crack, twisting, etc., and emits AE signal only once at the time when the faults occur. On the other hand, pseudo source is created most of the time when the external impacts occur on the material, such as friction rotation, rubbing or leakage of gas and liquid. In control valve, such mechanisms produce elastic wave signals and propagate through the structure of control valve. In this project, the investigation concentrates on the external mechanism as the source mechanism of AE signal on the control valve by causing the leakage. Kalyanasundaram [7], in his book of "Practical acoustic emission", mentioned that acoustic emission phenomena releases a sound wave with the frequency range extends from the infrasonic (<16Hz) into the ultrasonic range (3MHz). However for practical purpose, it is sensitively captured and processed in the range from 100kHz to 1MHz.

AE technique applies the non-destructive testing method, which does not affect the testing material. It utilizes a digital signal processing system to capture the AE sound and convert the sound signals into frequency domain presentation for processing purposes. The typical AE system consists of AE sensor, amplifiers and signal analyser or data acquisition equipment. AE technique has been applied in various engineering applications such as civil, chemical, physical and biological processes, non-destructive testing of reinforced structures and materials, and etc. [6]. These elastic waves are measured using piezoelectric transducer which is connected to a monitoring system. The detected signals are pre-processed and analysed in order to observe the information from the monitored material.

There are two source mechanisms for acoustic emission. One is defined as classical mechanism which is originated from the material structure's deformation, such as fracture or crack. For this mechanism, the source locates within the material. The other is defined as pseudo mechanism that do not release the AE directly within the material but from external source, for instance, friction from rotating signal, or the leakage of gas or liquid. In this project, AE signal is generated from pseudo source received from liquid movement when passing through the simulated fault. The AE system operates as a monitoring system used to capture the elastic wave signals at the fault area on the control valve. Captured signals are processed and analysed using advance signal processing technique.

2.3. Types of common faults on control valve

The common faults usually occur on the unhealthy control valve could be caused by acoustic noise, vibration, cavitation, and erosion (S.K. Lee [4]). The appearance of the faults is likely scratching, pitted area exposed on the valve plug surface or chipped valve seat which represent the most common phenomenon: erosion and cavitation.

When liquid passes the point of greatest restriction inside the control valve, such as the orifice plate or the pipe throat shown in the figure 3, the liquid velocity reaches maximum and its pressure falls to minimum. This phenomenon is called choked flow. If pressure falls below liquid's vapor pressure, vapor bubbles form within the valve. The pressure drop at which choked flow begin is called the terminal pressure drop. Choked flow produces either flashing or cavitation.

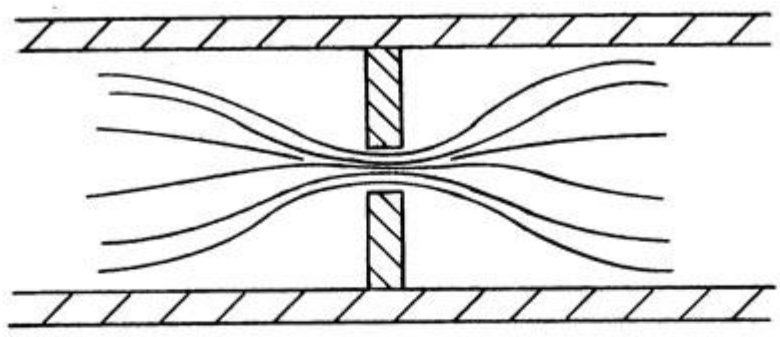


Figure 3: The choked flow mechanism

2.3.1 Cavitation

According to Dale Seborg [9], cavitation is a four stages process:

- The formation of voids and cavities within liquid system.
- The collapse or implosion of this cavities back into in all liquid state

Two types of cavitation require the presence of nucleating agent for their inception is gaseous and vaporous. The nuclei contain either vapour or dissolved gas will enlarge into finite cavities within the liquid. Requirements for occurrence of cavitation:

- The fluid at inlet and outlet must in all-liquid condition.
- The liquid must be subcooled state at the inlet, because if the liquid in saturated state, then any pressure drop across the valve will cause the presence of vapour downstream

Figure 4 below shows the typical cavitation effect on the surface of the metal material.

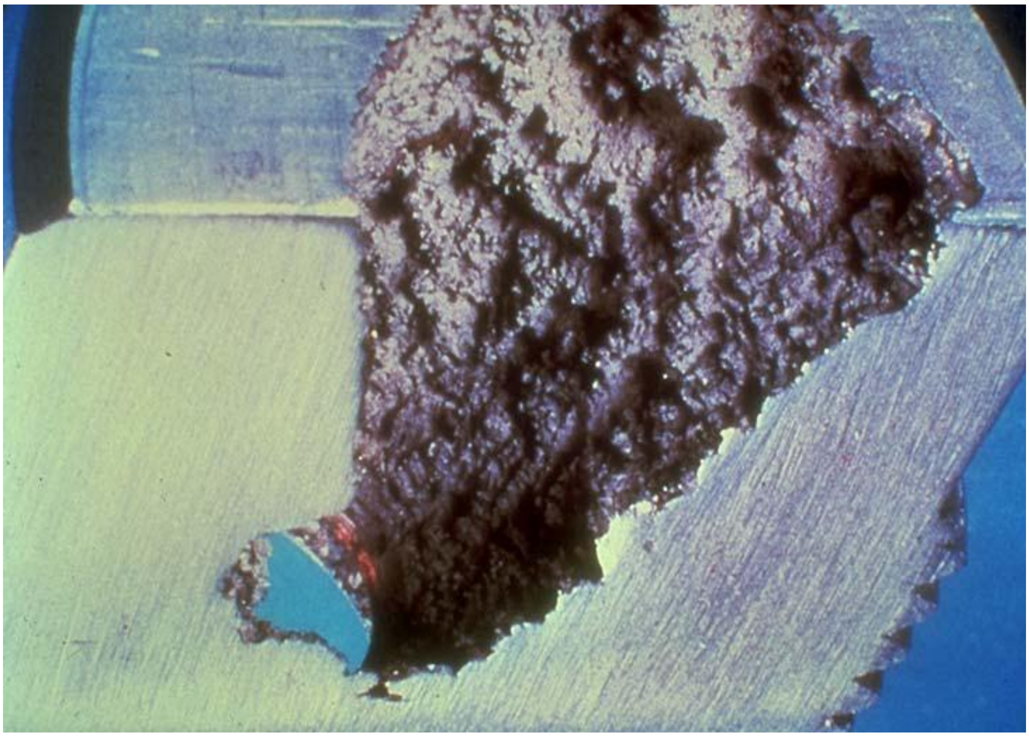


Figure 4: Cavitation effect on the surface on valve plug

2.3.2 Flashing

Flash (or partial) evaporation is the partial vapour that occurs when a saturated liquid stream undergoes a reduction in pressure by passing through a throttling valve or other throttling device. This process is one of the simplest unit operations. If the throttling valve or device is located at the entry into a pressure vessel so that the flash evaporation occurs within the vessel, then the vessel is often referred to as a flash drum [9].

If the saturated liquid is a single-component liquid (for example, liquid propane or liquid ammonia), a part of the liquid immediately "flashes" into vapour. Both the vapour and the residual liquid are cooled to the saturation temperature of the liquid at the reduced pressure. This is often referred to as "auto-refrigeration" and is the basis of most conventional vapor compression refrigeration systems. Flashing can result in significant erosion damage to a control valve and adjacent piping. There is no erosion coefficient, no industry standards, and no scientific means for predicting the intensity of flashing damage.

2.4 Valve leakage detection by Shock pulse method

Recently many researchers have been dedicated to find the ways to overcome the disadvantages of conventional control valve systems. Monitoring technique is one of the techniques that are widely used nowadays to detect faults and failures on the control valves. Monitoring technique usually comprises with several types of method such as vibration spectra analysis, acoustic emission, and nonlinear fuzzy models. But there is no single technique that is universally suitable.

G.Thompson and G.Zolkiewski [1] used a separate vibration sensor in their research of An Experimental Investigation into the Detection of Internal Leakage of Gases through Valves by Vibration Analysis to carry out the vibration spectra analysis. The objective of this research is to detect through-valve leakage by vibration monitoring analysis. Shock Pulse Method is used to process the signals obtained from the valve. Shock Pulse method is widely used to measure the metal impact and rolling noise such as those found in rolling elements such as bearing and gear. Experiments have been performed which demonstrate that a valve leaking internally excites the downstream pipework at particular frequencies in the range below 20 kHz.

2.5 Application of AE technique in faulty valve monitoring system

M.A Sharif and R.I Grosvenor [2] in their research of Internal Valve Leakage Detection Using an Acoustic Emission Measurement System used two acoustic emission sensors together with the state-of-the-art data acquisition and processing systems were used to monitor a wide range of leakage rates under different working conditions. The effects of the background noise on the measured AE signal were considerably reduced by using the real-time programmable filters that were part of the AE measurement system. This was carried out to produce more reliable and consistent results. The sensitivity of the AE sensors was improved by using line amplifiers with variable gain. The frequency spectrum analysis of the AE signal indicated that leak-related frequency components can be clearly distinguished from those produced due to background noise. Furthermore, it was evident that the selected leak-related frequency components increased in their amplitude as the leakage rate was increased. The paper concludes by illustrating that AE can be used reliably to detect the onset of air leakage through control valves at a differential pressure that could be as low as 110.3 kPa (1.103 bars) and in a noisy industrial environment.

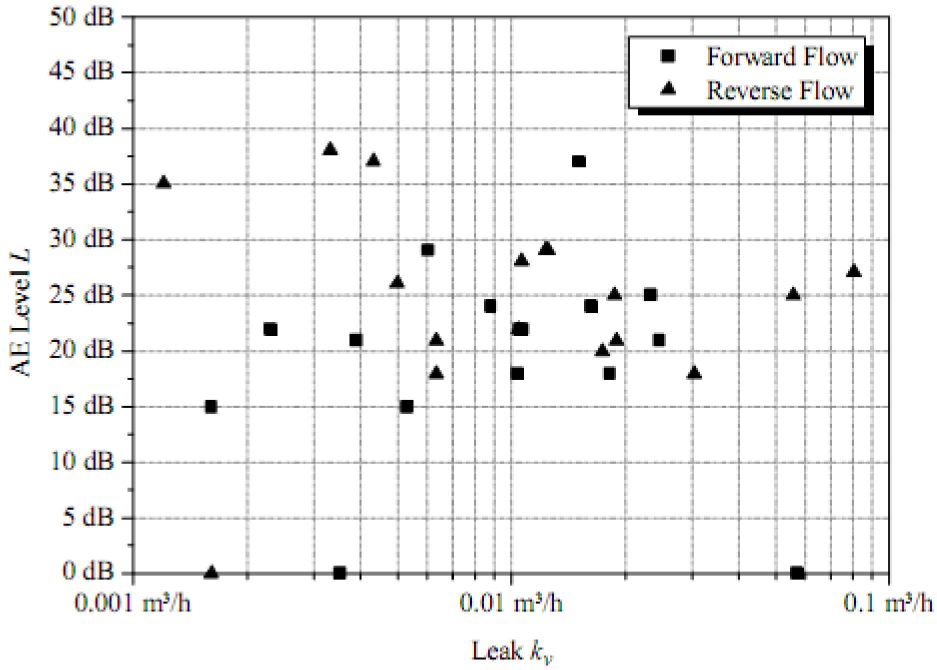


Figure 6: AE level measured for various leak-related values

S.H Seong, J.S. Kim, J.T Kim and W.M.Park [3] in their study of Development of a Diagnostic Algorithm with Acoustic Emission Sensors and Neural Networks for Check Valves suggested acoustic emission sensors for detecting the failures of check valves through measuring and analyzing backward leakage flow. They have designed a hydraulic test loop with a check valve for validate the suggested acoustic emission sensor methodology. In addition, this paper also had developed diagnostic algorithms by using Neural Network model to identify the type and size of the failure in the check valve. This paper was concluded that that the proposed diagnostic algorithm can identify check valve failures early and wide range acoustic emission sensor attached to the backward leakage side can detect check valve failures.

S.G.Lee, J.H Park, K.B.Yoo, S.K.Lee, and S.Y.Hong [4] in their study of Evaluation of Internal Leak in Valve Using Acoustic Emission Method used two types of valves glove steam valve and ball water valve leak tests using three different leak path and various leak rates were performed in order to analyze AE properties when leaks arise in valve seat. The main objective of this study is to estimate the feasibility of acoustic emission (AE) method to for the internal leak from the valve. They confirmed that leak sound amplitude increased in proportion to the increase of leak rate, and leak rates were plotted versus acoustic amplitude recorded within those two narrow frequency bands on each spectrum plot. From the experimental results, it was suggested that AE method for monitoring of leak was feasible.

A. Puttmer and V.Rajamaran [5] used Acoustic Emission technique in their research of Acoustic Emission Based Online Valve Leak Detection and Testing. A measurement principle for quantitative control valve seat leakage classification, in accordance with ANSI/FCI 70-2 and IEC 60534-4, based on the ultrasonic range is presented. It was mentioned that the acoustic measurement of control valve internal leakage rates was describe for various valve sizes, leak sizes and media like air, stem, hydraulic oil, and water. It was shown that the level of acoustic emission is related to the leakage of air and stem. For hydraulic oil and water, it was shown that the acoustic emission is not only related to the leakage but also to the back pressure of the valve. The approached of the current work used AE base detection of incipient cavitation as a measurement characteristic for leak size with different type of plus (Figure 7) instead of the AE level measurement. It was concluded that Control valve leakages could be classified as classes II-IV as per the norms mentioned in ANSI/FCI 702 and IEC 60534-4.

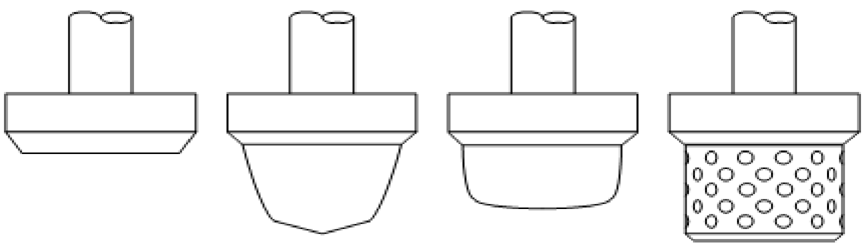


Figure 7: Different type of plug used in control valve

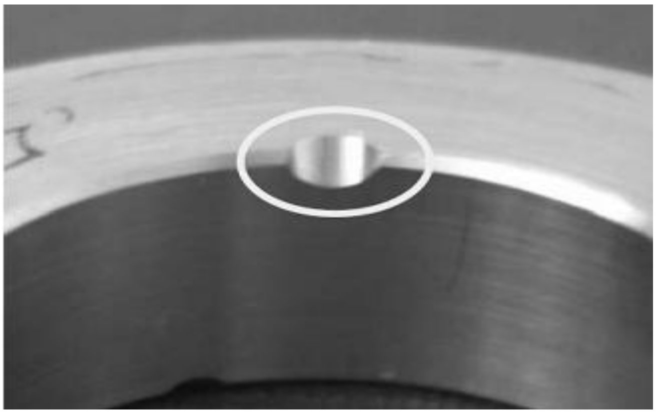


Figure 8: An example of damaged valve seat with oval shaped leak

In a study of Investigation of the Relationship between Internal Fluid Leakage through a Valve and the Acoustic Emission Generated form the Leakage [6] by W. Kaewwawnoi, A. Prateepasen, and P.Kaewtrakulpong mentioned that the detection of Acoustic Emission (AE) signals produced by liquid and gas leakage through the valves fault (Figure 8) can be related directly to the qualitative leakage rate. The effect of the influenced factors of leakage rates, inlet pressure levels, valves size and valves type, on AE parameter, AErms, were explained in this paper. It was concluded that the results of theoretical and experimental showed AE signal power computed from the power spectral density (PSD) correlated well with influenced factors of leakage rates. Furthermore, this research is successful in inventing an inexpensive AE instrument for predicting qualitative leakage rate using microprocessor and derived relationship.

There is strong reason why acoustic emission has been chosen to be the best technique for monitoring system of the control valve faults. Even though there are another sensor available such as accelerometers, ultrasonic sensors, and magnetic sensors however most of the researchers are preferable looking for acoustic emission sensors. In a study of Development of Diagnostic Algorithm with Acoustic Emission Sensors and Neural Networks for check valves by S.H.Seong, J.S Kim, and J.T. Kim [7] proved that the monitoring system method that uses acoustic emission sensors is feasible to detect the failures of the valves. This research is to detect the failure of the check valves by measuring and analysing the sound wave originating from the backward leakage flow through the failed section of the check valves. Two sensors were tested which are acoustic emission sensor and the accelerometers detect sound waves originating from the flows through pipes in similar ways. Based on the experiment, acoustic emission sensors can generally measure a wider ranged sound wave than the widely used accelerometers. Also, a method using acoustic emission sensors has a simple architecture because the sensor does not require the source signal and the dedicated system that are required by methods that use ultrasonic sensors and magnetic sensors.

Chapter 3: METHODOLOGY

3.1 Research methodology flow chart

The purpose of this project is to evaluate the conditions of the unhealthy control valve. The problem on the control valve commonly occurred when the component, such as plug or seat, inside the control valve body is defected. The experiment for control valve will be performed by using acoustic emission technique. The project is conducted stage by stage representing the research activities.

Stage 1: Preliminary research on AE technique and control valve

Stage 2: Experiment work implementation

Stage 3: AE signal processing and analysis

Figure 9 below shows the flow chart of the project methodology.

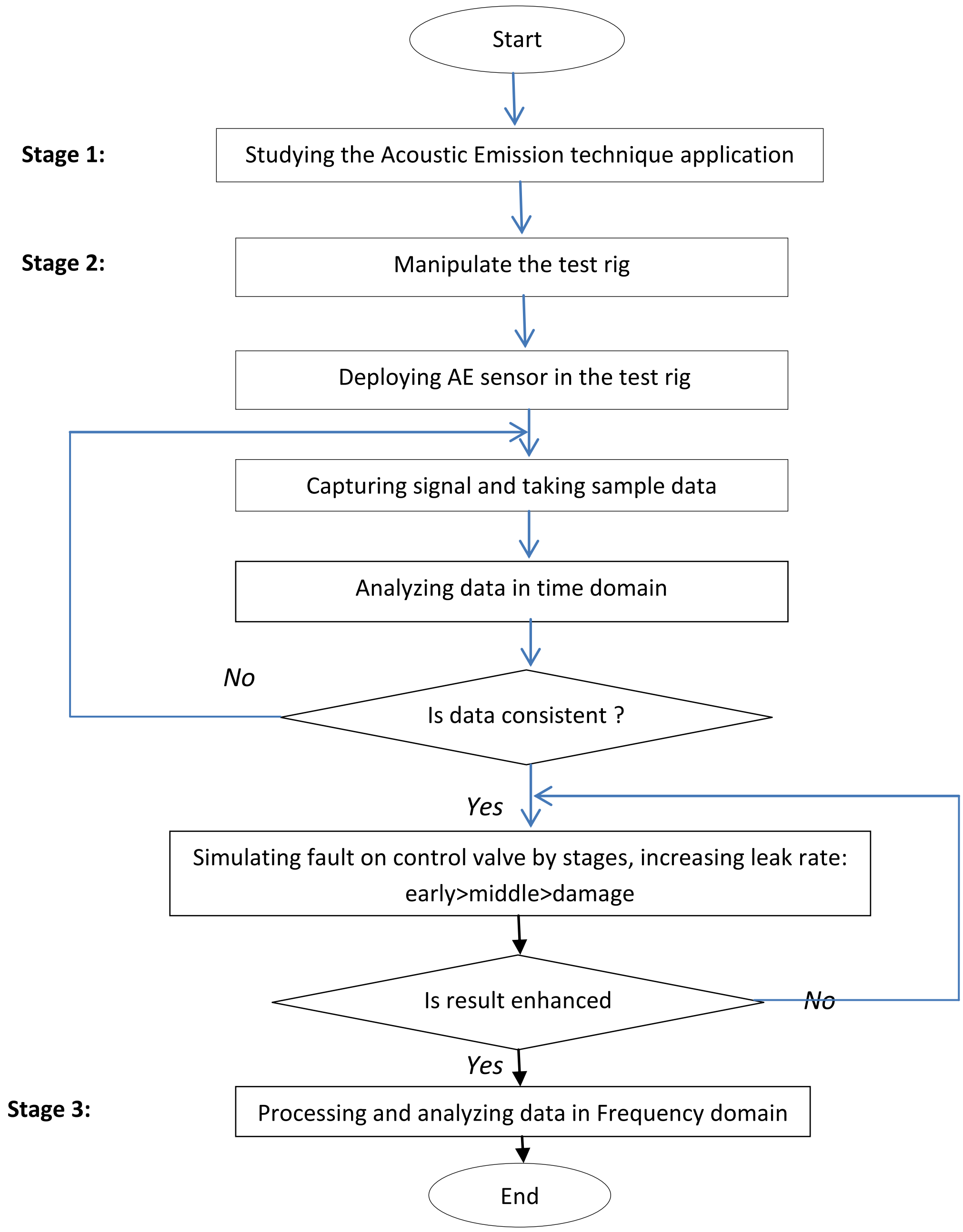


Figure 9: Project Flowchart

3.2 Equipment specification

AE sensor which designed to measure the peak signal amplitude within the range of 100kHz to 150kHz is utilized to capture the AE signal which emitted from the control valve. The R3132 Spectrum analyser, which the maximum sampling rate is up to 3Ghz, is used to sample the data and display the whole signal spectrum, from 9kHz to 1MHz. PAC 2/4/6 Preamplifier with 20dB gain accompanies with post amplifier with 3dB gain in order to get the best bandwidth AE signal amplification.

The maximum allowable leakage for this valve is 34ml/min. If the leak rate exceeds the tolerance amount, the valve is considered as damaged valve. The AE system is required to display the valve's unhealthy symptom before the considerable fault occurs in the valve. In the other words, the AE technique will help to detect the abnormal signs during the control valve's operation, therefore a proper maintenance plan could be set up effectively and in a good time manner. In order to fulfil that objective, five stages of unhealthy status are created at the valve plug: good, early damage, middle damage and damaged stage represented different leakage rates at fully close condition. Leak tests are performed accordingly to define the difference between damaged stages.

To determine the best location of AE source on the control valve, the AE sensor is attached to capture emitted AE signal at different positions on the valve body and valve flanges, i.e. valve middle body, inlet flange and outlet flange as shown in the Figure 10. The position which produces the highest energy of AE signal will be chosen as the best AE source for monitoring the unhealthy status. The steps implemented for experiment process: following the order of breaking up test rig's component system, dissembling control valve, simulating fault on valve plug by hacksawing and carving the plug's surface, assembling test rig's component, implementing leak test, capturing and analysing data. During the data capturing process, the AE signal processing system is set up by connecting the following components together: AE sensor, pre and post amplifier, spectrum analyser and spectrum displayer. Before running the experiment, the AE sensor is applied multipurpose wax to increase the capturing ability and attached to the testing location by strong adhesive tape. A strong contact between the AE sensor and the testing location must be maintained throughout each experiment session.

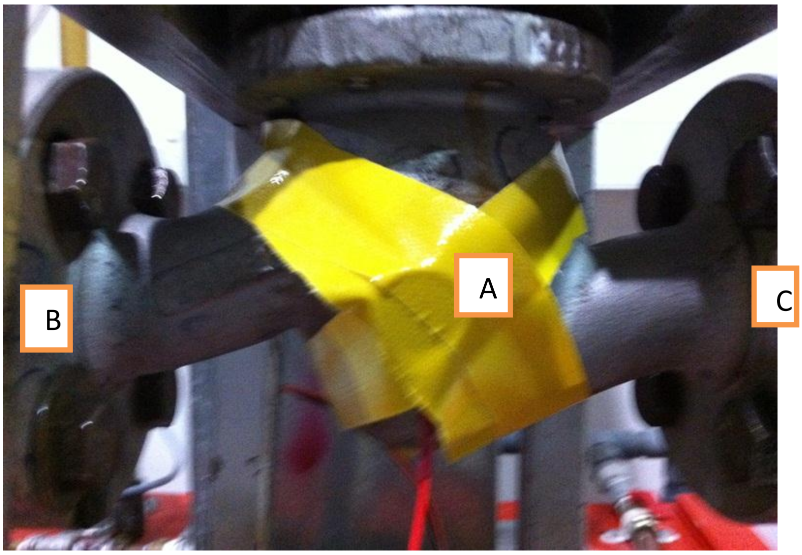


Figure 10: Different test locations to capture AE signal

3.3 Experiment procedures:

In order to obtain the most consistent AE signal and maintain the same experiment conditions for each AE measurement, the experiments were implemented following the below procedures:

1. Carve gradually the valve plug at the landing area by using hacksaw.
2. Implement leak test to check the leakage rate.
3. If the leakage rate is desired, proceed to the AE signal capturing process.
4. Measure AE data for these valve opening percentages : 0%, 3%, 6%, 9%,
    5. 12%, 15%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%.
5. Before taking data, run the pump for 5 minute to stabilize AE signal.
6. Note down the pump pressure corresponding to each valve opening.
7. Taking 15 data samples for each valve opening.
8. Repeat #4 to #6 for 3 different locations: middle valve body, inlet flange and outlet flange.
9. Repeat #1 to #6 for other stages of unhealthy valve with different leakage rates.

3.4 Signal analysis method:

The method used to analyse the AE data is statistical method. Since the AE signal is non-stationary signal, varying from time to time, the most suitable parameters used to evaluate the signal characteristics are the average energy (AE_{rms}) and the average signal level (ASL). The AE_{rms} is the root mean square value, also known as quadratic mean, used to represents the average energy emission of AE signal over a period or a spectrum. AE_{rms} can be calculated for AE signal in time domain or frequency domain by using the formula below:

$$AE_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} v^2(t)\,dt} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} v^2(n)}$$

Where v: signal's voltage from an AE sensor

t_0= initial time

T= integration time of the signal

N= number of discrete AE data within the interval T

3.5 Project Activities

3.5.1. Preliminary research

For these first stage of the project, together with studying on the theories of acoustic emission and control valve operation, together with the coordinator supervisor, the process of setting up the test rig to prepare for the experiment is being implemented. The main components are control valve, transmitter, pump, tank...Inside each of component, it contains other smaller parts which are heavy, for instance orifice plate, pipe, connection, etc.

3.5.2. Fault simulation on control valve

Under the scope of this project, to simulate the fault representing the unhealthy status of the control valve, a scratch was created on the valve plug, thus causing leakage flow of liquid during zero percentage (0%) valve opening (fully closed position). The method of creating of scratch is trial and error, which simultaneously deepen the scratch while keeping record on the leak rate until the leakage rate reaches the desired amount.

Base on the technical manual attached to the control valve, the cut off leak rate, corresponding to the class IV of control valve damage [5], is stated 34 ml/min. Whenever a control valve with the leak rate less than or equal 34min/min, it is considered as unhealthy status. The main purpose of trial and error method is to ensure the leak rate of the valve will not exceed the cut off rate for class IV damage, thus the AE characteristic for pre-damaged control valve is observed.

The procedure of creating fault includes:

- Gradually rub the valve plug using the light saw to make the scratch.
- Straighten the scratch until it reaches the area where it lands on the valve seat.
- Gradually make the scratch deeper until obtain the expected valve leak. This step is implemented by trial – error method. (shown in Figure 11).
- Assembly the affected valve plug to the test rig and implement the leak test by fully closing the valve and running the pump in 10 minutes.

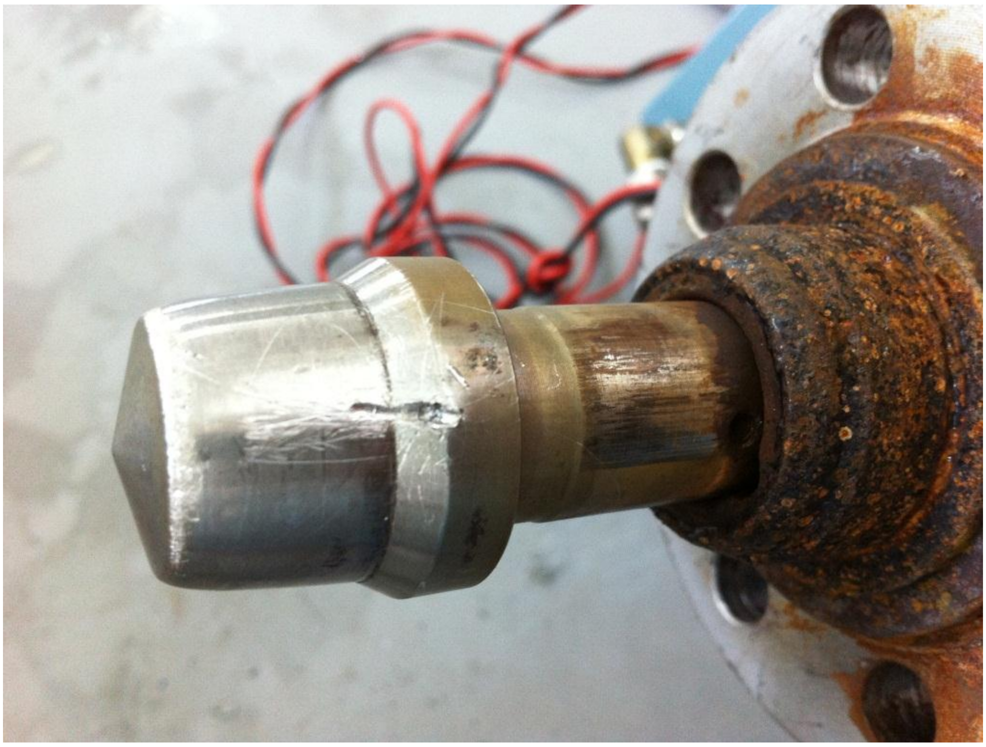


Figure 11: simulated fault on valve plug

To fulfil the project objectives, several samples of leaking control valve was prepare for the experiment. Six different simulated faults were created on the valve and divided into four stages: **initial stage** (0.5ml/min), **early stage** (4ml/min and 11ml/min), **middle stage** (24ml/min and 32ml/min) and **damaged stage** (80ml/min).

CHAPTER 4: RESULT AND DISCUSSION

4.1 Preliminary research stage (stage 1)

For the stage 1 research, there are some observation is made. There is strong reason why acoustic emission has been chosen to be the best technique for monitoring system of the control valve faults. Even though there are several technique available for the equipment monitoring, such as accelerometers, ultrasonic, and magnetic technique, however most of the researchers are preferable looking for acoustic emission sensors. It is proved that the monitoring system method that uses acoustic emission sensors is feasible to detect the failures of the valves [7]. Based on this experiment, acoustic emission sensors can generally measure a wider ranged sound wave than the widely used accelerometers. Also, a method using acoustic emission sensors has a simple architecture because the sensor does not require the source signal and the dedicated system that are required by methods that use ultrasonic sensors and magnetic sensors.

4.2 Test rig setup (stage 2)

4.2.1 Test Rig Development and Commissioning

The schematic diagram of the test rig is illustrated in Figure 12 below. Main components and the criteria are shown in Table 1. Voltage distributor is used to convert 1-5 Volt to 4-20mA. Pressure transmitter and level transmitter are calibrated from 0-10kPa and 0-100 mmHG respectively.

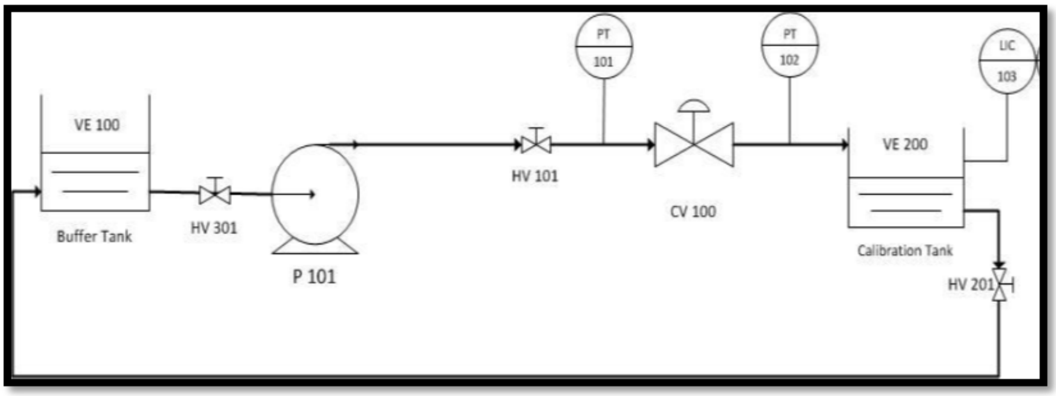


Figure 12: Schematic Diagram of the Test Rig

Table 1: Main Components in the Test Rig and the Criteria

Component	Tag No	Input	Output	Function
Control Valve	CV100	Current (4-20mA)	0-10 kPa	Control the stem opening 0-100%
Pressure Transmitter	PT101 PT102	Inlet Pressure Outlet Pressure	Current (4-20mA)	measure inlet and outlet pressure
Level Transmitter	LC103	Level of water	Current (4-20mA)	measure level of water
PID Controller	LC103	PV (level)	MV(CV)	Control the level of water in calibration tank by adjusting MV
Pump	P101	240 Vac	Water	Pumping water to tank
Tank	VE100 VE200	-	Buffer tank Calibration tank	Replace water

4.2.2 Experimental Setup

The objective of doing the leak test is to validate the health condition of the control valve. If the control valve is in good condition, there will be no leaking or water passing through during the fully closed condition. The bigger the source of the fault (erosion-crack, dent), the greater the leak, and the more amount of water will be produced at the downstream of the valve flange. Therefore this test is made to verify the health of the valve either is good, early fault, middle fault or in damaged stage based on the actual leakage rate. To run the test, 4mA current is injected to the control valve in order to dictate the valve to be at fully closed position. Test rig is running for 5 minutes to monitor the valve leak.

Experimental setup is shown in Figure 13 below.

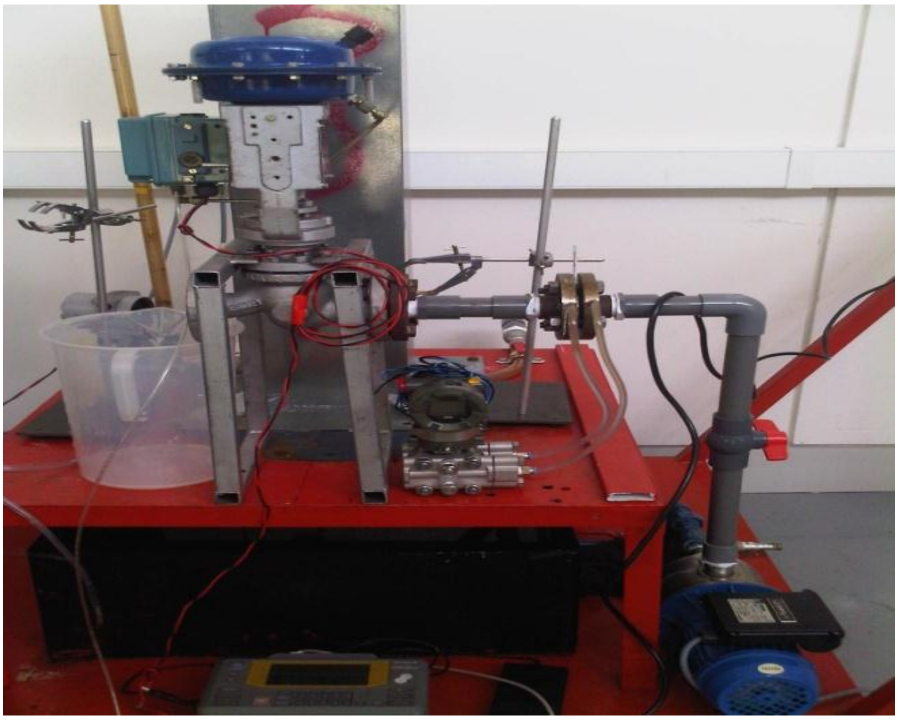


Figure 13: Leak Test Experimental Setup

4.2.3 Acoustic Emission system Setup

The AE sensor is calibrated first by using pencil lead break test method. The 0.5mm lead pencil is guided obliquely towards the surface of the valve body and the lead is broken in order to stimulate AE signal and to maximize the sensitivity of the detection system and reduce the attenuation in the detected AE signal. The sensor is attached at the middle of valve body by using strong adhesive tape in order to be strongly contact with the location where the fault will be created. The sensor must be placed as close to the source of leakage as possible [8, 9]

The sensor is connected to the pre-amplifier which is used to amplify the signal from AE sensor. Pre-amplifier is connected to post-amplifier to amplify and filter incoming AE signals from the preamplifier. These signals will be transfer to the computer by using Spectrum analyzer. The input range for single ended mode sensor is 10V.

The experimental setup for Acoustic Emission System is shown in Figure 14.

Figure 14: Experimental setup of Acoustic Emission system.

4.3 Experiment result and data processing (stage 3)

4.3.1 Leak test result

The observation from the leak test showed that there is small water passing through at the downstream of the valve flange when the valve is set at fully closed condition and pump is running for 5 minutes. Leak tests were conducted for three (3) times at different period of time. The leak test results prove that the control valve was initially in good condition since the leak rate is around 0.5ml/min. In order to simulate the unhealthy status of the valve, an artificial scratch was made on the plug. The scratch was lengthen and deepened gradually to increase the leak rate when needed

Following the same leak test procedures, at the valve's middle damage stage, the average leak rates are 11ml/min, 24ml/ and 32ml/min and 80ml/min. The final created fault produced the 80ml/min leak rate and it is considered as damaged control valve.

4.3.2 AE signal of representation of 0ml/min leakage rate in time domain

This part is aimed to introduce the research results from the author's research partner about the AE characteristics on healthy control valve. Ms. Intan Najiha, in her research of “A study of control valve fault incipient detection monitoring system using acoustic emission” [8], implement an AE system that monitoring the valve status by using AE method. The non-leaking control valve was first chosen to measure the emitted AE signal. The samples were taken during the valve was in manual mode and varied among 0%, 25%, 50%, 75%, 100% opening. Signals from AE sensor, signals from level transmitter, and signal from both inlet and outlet pressure transmitter are also monitored and recorded. AE signals in time domain will be analysed using Statistical Method Analysis in order to differentiate between normal and abnormal valve. Figure 14, Figure 15, Figure 16, Figure 17, and Figure 18 show the signals from AE, level transmitter, inlet and outlet pressure transmitter for 0%, 25%, 50% and 75% opening in manual mode.

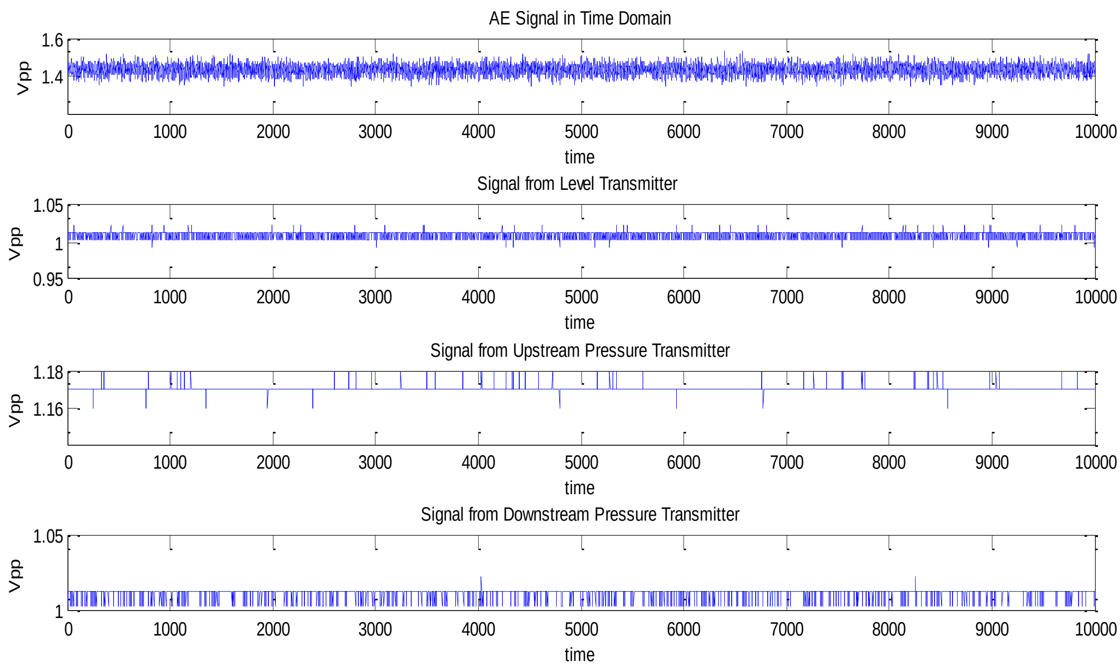


Figure 15: Signals from AE, level transmitter, inlet and outlet pressure transmitter for 0%

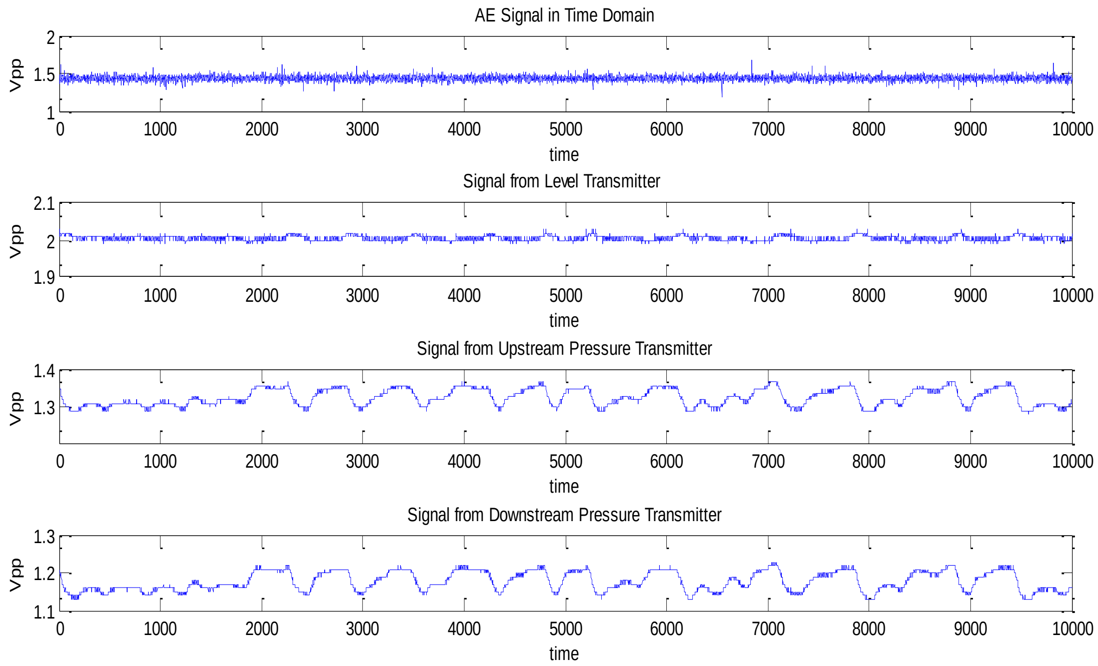


Figure 16: Signals from AE transmitter, inlet and outlet pressure transmitter for 25%

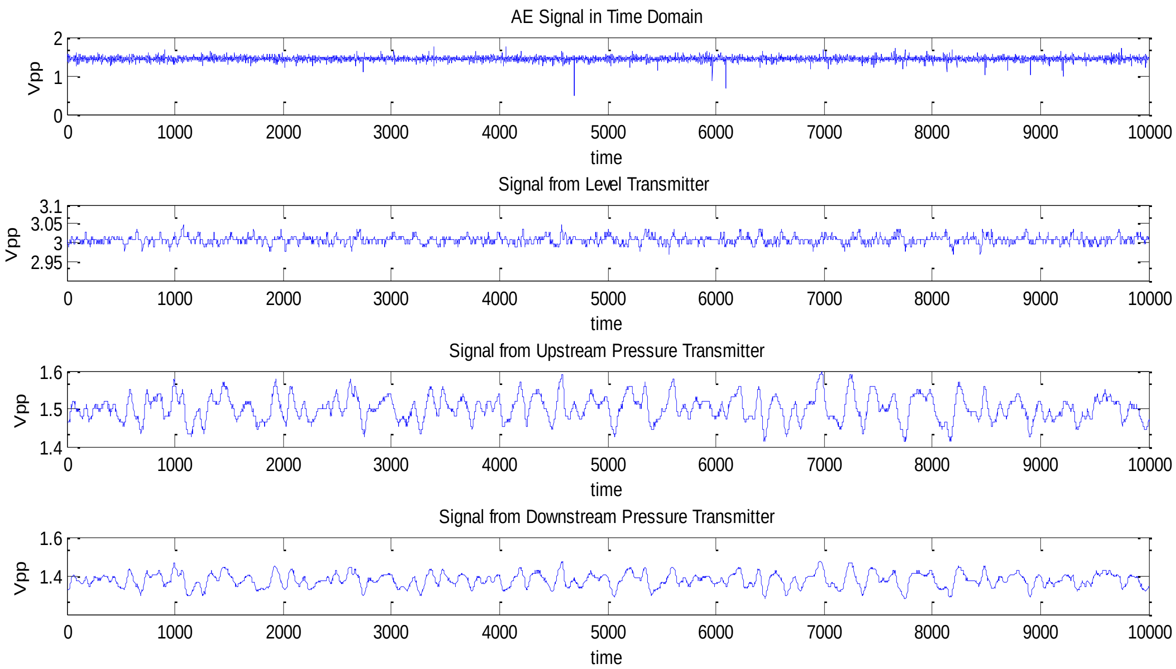


Figure 17: Signals from AE, level transmitter, inlet and outlet pressure transmitter for 50%

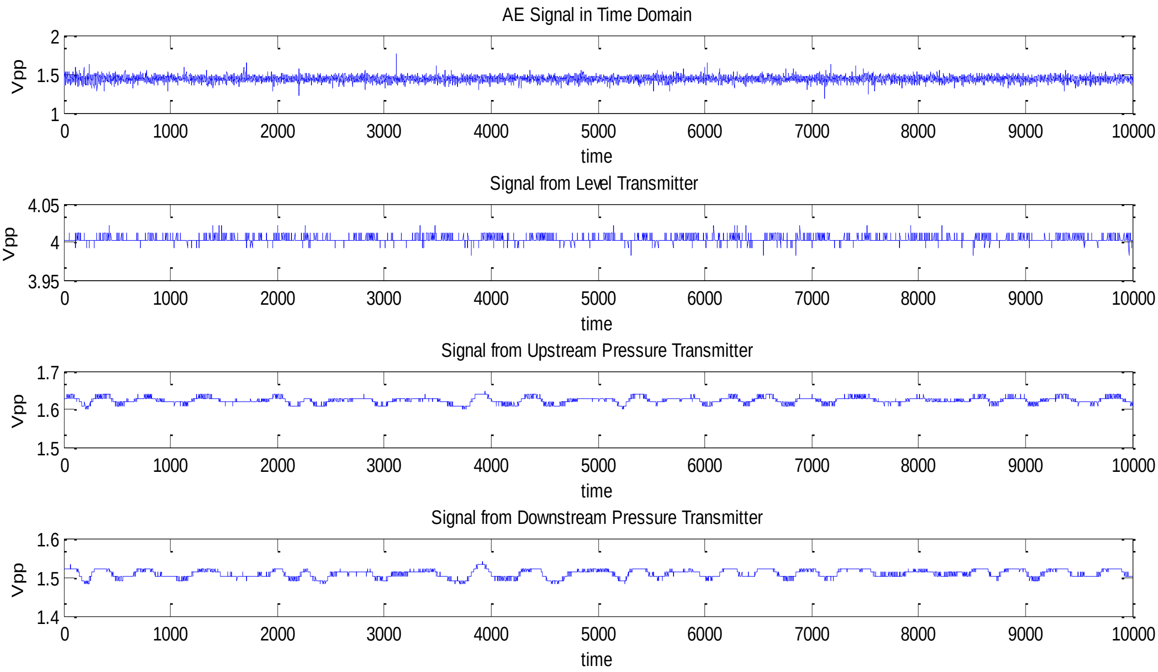


Figure 18: Signals from AE, level transmitter, inlet and outlet pressure transmitter for 75%

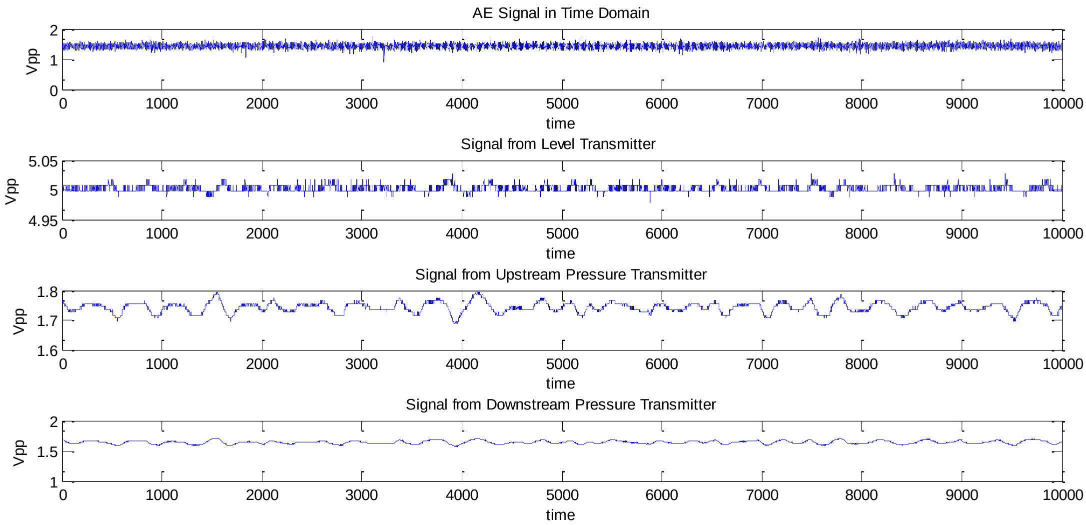


Figure 19: Signals from AE, level transmitter, inlet and outlet pressure transmitter for 100%

Table 2: Level value, inlet pressure, outlet pressure, maximum amplitude and standard deviation

Opening	Level	Inlet Pressure	Outlet Pressure	Maximum Amplitude	Standard Deviation
0	1.0232	1.1795	1.0232	1.531	0.02691
25	2.0293	1.3651	1.2283	1.6679	0.02970
50	3.0452	1.5995	1.4725	1.7656	0.04630
75	4.0220	1.6484	1.5409	1.7656	0.0315
100	5.0281	1.7949	1.7070	1.7656	0.0660

Table 3: Statistical analysis base line for healthy and unhealthy control valve

	Healthy Valve	Unhealthy Valve
Standard Deviation	<0.5	>0.5
Max Amplitude	<2.0	>2.0

Applying the statistical analysis in time domain, Ms. Najiha proved that the maximum amplitude of the AE signals for the non-leaking control valve is less than 2.0 Vpp at different opening. However, the maximum amplitude is increased with the increased of the opening. This is due to the different energy of AE signals. When opening increased, the water flow rate is also increased which cause, the higher the flow rate which could be considered as the higher leakage rate, the higher acoustic emission energy in the signals. While the standard deviation values do not alter for more than 0.5 for all the opening, the stipulations that proves the healthy condition of the control valve.

4.3.3 AE signal representation indicating different leakage status in frequency domain

During these steps, the unhealthy control valve, with the artificial damage to create leakage, was investigated. To observe the characteristic of the AE signal captured from control valve, an Advantest R3132 spectrum analyser was utilized. The sampling frequency of the spectrum analyser is up to 3 MHz, while the AE sensor can capture the AE signal within the frequency range from 10kHz to 100Khz. According to Nquyst theorem, the sampling frequency is required at least 200KHz to sample the AE signal in time domain. Therefore R312 was used to display the frequency spectrum of captured AE signal from 9kHz to 1MHz to filter all the noise and display the expected AE signal.

Figure 20: Advantest R3132 Spectrum analyser

During the experiment process, the valve was manually controlled to open step by step starting from 0%. The step change was chosen to be small enough so that it could not take long time for the spectrum analyser to stabilize the result and the graph could be recorded properly. Some of the expected frequency was picked up and marked on the screen table. Until the spectrum was stable, the whole frequency spectrum was saved as shown in the Figures 21 below as a typical example.

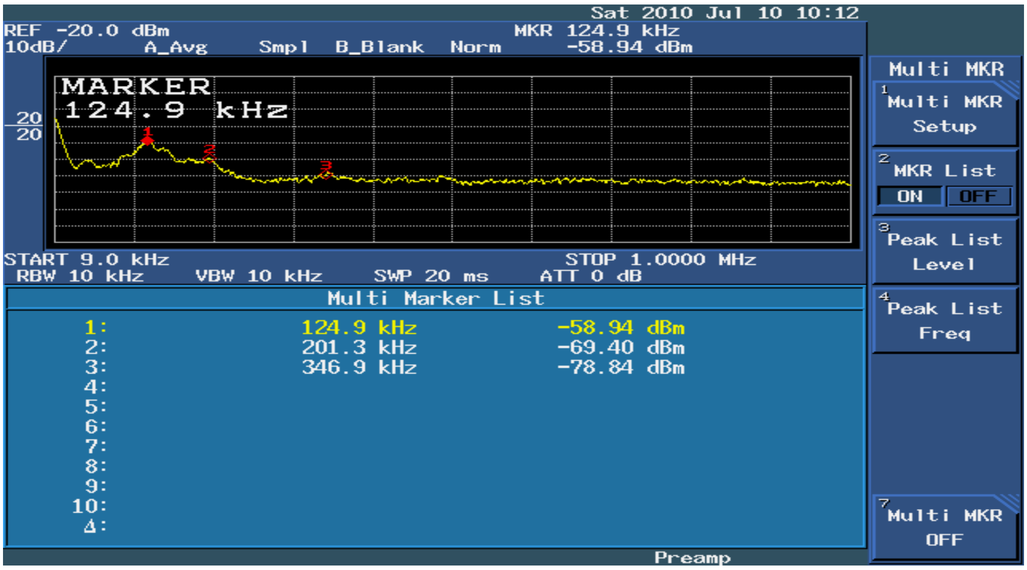


Figure 21: Example of frequency spectrum representation in Spectrum analyser displayer

The AE sensor utilized throughout the experiment is resonant sensor which is designed to capture the peak AE signal at 125 kHz. Therefore, the frequency spectrum always shows the peak amplitude at 124.9 kHz. In the example of AE frequency spectrum in Figure 20, the peak amplitude at 124.9 kHz is -58.94dBm.

4.3.4 AE frequency spectrum at different leakage rates

In order to investigate the AE characteristic of unhealthy control valve, an artificial fault was created on the valve plug by hacksawing the plug body. There are six different leakage rate levels were created to represent three different unhealthy status: normal, early damage, middle damage and damage stage. The 0.5ml/min leakage rate is considered as normal control valve. The 4ml/min leakage rate is categorized as early damage stage of control valve. The 11ml/min, 24ml/min and 32ml/min represent the leakage rate for middle damage stage of unhealthy control valve. Eventually the control valve with leakage rate 80ml/min is considered as unhealthy control valve, since the leakage rate already exceeds the cut-off amount 34ml/min. The experiments were implemented for all six leakage rates, representing different unhealthy stages of the control valve. AE signal data were recorded for these valve opening percentages : 0%, 3%, 6%, 9%, 5. 12%, 15%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100% and tabulated in table 4, 5 and 6 below. Since the AE signal is non-stationery, the peak amplitude of the spectrum varies continuously. At each opening percentage of the valve, 15 AE spectrum data were captured, containing 15 peak amplitudes. The 15 peak amplitudes for each opening percentage are grouped up in range then the process is repeated for other opening percentage within the range 0% to 100%

All the ranges of values for different opening percentage of different leakage rates and shown in the Table 4,5,6 below.

Table 4: The range of AE amplitude at Outlet flange

Valve opening (%)	Inlet pressure (psi)	AE amplitude **range** at Outlet flange (dBm)					
		0.5 ml/min	4 ml/min	11ml/min	24ml/min	32ml/min	80 ml/min
0	[42, 44]	[-83, -81]	[-83, -80]	[-83, -80]	[-77, -81]	[-78, -74]	[-63, -55]
3	[39, 40]	[-74, -70]	[-68, -66]	[-66, -63]	[-65, -60]	[-62, -58]	[-54, -60]
6	[36, 38]	[-66, -64]	[-64, -59]	[-60, -57]	[-56, -55]	[-56, -54]	[-52, -47]
9	[32, 34]	[-62, -60]	[-59, -56]	[-57, -55]	[-59, -54]	[-54, -49]	[-50, -47]
12	[28, 30]	[-59, -56]	[-55, -52]	[-54, -52]	[-52, -50]	[-50, -48]	[-47, -44]
15	[26, 27]	[-55, -54]	[-54, -51]	[-49, -52]	[-47, -49]	[-48, -44]	[-50, -46]
20	[22, 24]	[-57, -55]	[-56, -54]	[-55, -52]	[-56, -52]	[-52, -49]	[-53, -49]
30	[14, 18]	[-63, -62]	[-63, -60]	[-62, -59]	[-58, -56]	[-56, -53]	[-66, -62]
40	[6, 14]	[-67, -68]	[-68, -66]	[-66, -63]	[-65, -62]	[-62, -61]	[-60, -65]
50	[4, 8]	[-72, -70]	[-71, -68]	[-71, -68]	[-69, -65]	[-67, -64]	[-74, -68]
60	[2, 4]	[-75, -74]	[-74, -71]	[-74, -70]	[-71, -69]	[-71, -68]	[-76, -73]
70	[0, 1]	[-78, -76]	[-78, -75]	[-77, -73]	[-76, -72]	[-76, -70]	[-82, -79]
80	0	[-80, -78]	[-80, -77]	[-79, -77]	[-78, -76]	[-77, -75]	[-84, -81]
90	0	[-81, -80]	[-81, -80]	[-81, -80]	[-79, -81]	[-78, -81]	[-83, -81]
100	0	[-82, -80]	[-81, -80]	[-81, -80]	[-81, -80]	[-81, -80]	[-83, -81]

Table 5: The range of AE amplitude at Middle body

Valve opening (%)	Inlet pressure range (psi)	AE amplitude **range** at Middle body (dBm)					
		0.5 ml/min	4 ml/min	11ml/min	24ml/min	32ml/min	80 ml/min
0	[42, 44]	[-83, -81]	[-83, -80]	[-83, -80]	[-77, -81]	[-78, -74]	[-60, -52]
3	[39, 40]	[-72, -68]	[-67, -64]	[-65, -62]	[-64, -60]	[-61, -58]	[-54, -58]
6	[36, 38]	[-64, -62]	[-61, -58]	[-59, -56]	[-56, -54]	[-56, -53]	[-50, -45]
9	[32, 34]	[-60, -58]	[-58, -54]	[-56, -54]	[-57, -54]	[-52, -49]	[-48, -45]
12	[28, 30]	[-57, -54]	[-54, -50]	[-53, -51]	[-51, -49]	[-49, -47]	[-45, -42]
15	[26, 27]	[-53, -52]	[-53, -49]	[-48, -51]	[-46, -49]	[-47, -44]	[-49, -44]
20	[22, 24]	[-55, -53]	[-54, -53]	[-54, -51]	[-55, -51]	[-51, -48]	[-52, -49]
30	[14, 18]	[-61, -60]	[-62, -58]	[-61, -58]	[-57, -55]	[-55, -53]	[-63, -60]
40	[6, 14]	[-65, -64]	[-67, -64]	[-65, -62]	[-64, -61]	[-69, -52]	[-68, -64]
50	[4, 8]	[-70, -68]	[-69, -67]	[-70, -67]	[-68, -65]	[-66, -63]	[-71, -67]
60	[2, 4]	[-73, -72]	[-72, -70]	[-73, -69]	[-71, -68]	[-70, -67]	[-76, -72]
70	[0, 1]	[-76, -75]	[-76, -74]	[-76, -72]	[-75, -72]	[-74, -70]	[-81, -79]
80	0	[-79, -78]	[-79, -77]	[-79, -77]	[-78, -75]	[-77, -74]	[-83, -81]
90	0	[-81, -80]	[-81, -80]	[-81, -80]	[-79, -81]	[-78, -81]	[-83, -81]
100	0	[-82, -80]	[-81, -80]	[-81, -80]	[-81, -80]	[-81, -80]	[-83, -81]

Table 6: The range of AE amplitude at Inlet flange body

Valve opening (%)	Inlet pressure (psi)	AE amplitude **range** at Inlet flange (dBm)					
		0.5 ml/min	4 ml/min	11ml/min	24ml/min	32ml/min	80 ml/min
0	[42, 44]	[-83, -81]	[-83, -80]	[-83, -80]	[-77, -81]	[-78, -74]	[-61, -54]
3	[39, 40]	[-73, -69]	[-68, -65]	[-66, -63]	[-65, -60]	[-62, -58]	[-53, -59]
6	[36, 38]	[-65, -63]	[-62, -59]	[-60, -57]	[-56, -55]	[-56, -54]	[-51, -46]
9	[32, 34]	[-61, -59]	[-59, -55]	[-57, -55]	[-58, -54]	[-53, -49]	[-49, -46]
12	[28, 30]	[-58, -55]	[-55, -51]	[-54, -52]	[-51, -50]	[-49, -48]	[-46, -43]
15	[26, 27]	[-54, -53]	[-54, -50]	[-49, -52]	[-47, -49]	[-48, -44]	[-49, -46]
20	[22, 24]	[-56, -54]	[-55, -54]	[-55, -52]	[-55, -52]	[-51, -49]	[-53, -48]
30	[14, 18]	[-62, -61]	[-63, -59]	[-62, -59]	[-58, -55]	[-56, -53]	[-66, -60]
40	[6, 14]	[-66, -65]	[-68, -65]	[-66, -63]	[-64, -62]	[-62, -60]	[-6, -65]
50	[4, 8]	[-71, -69]	[-70, -68]	[-71, -68]	[-69, -65]	[-67, -63]	[-72, -68]
60	[2, 4]	[-74, -73]	[-73, -71]	[-74, -70]	[-71, -69]	[-70, -68]	[-76, -73]
70	[0, 1]	[-77, -76]	[-77, -75]	[-77, -73]	[-76, -72]	[-76, -70]	[-81, -79]
80	0	[-79, -78]	[-79, -77]	[-79, -77]	[-78, -76]	[-77, -75]	[-83, -81]
90	0	[-81, -80]	[-81, -80]	[-81, -80]	[-79, -81]	[-78, -81]	[-83, -81]
100	0	[-82, -80]	[-81, -80]	[-81, -80]	[-81, -80]	[-81, -80]	[-83, -81]

5. AE root mean square (AE_{rms}) value calculation at different valve openings for different leak rates

To characterise the continuous signal, the root mean square value of each data range is calculated to represent the average energy emission of AE signal over a period or a spectrum. Fifteen (15) data samples were taken to represent each range.

AE_{rms} can be calculated for AE signal in time domain or frequency domain by using the formula below:

$$AE_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} v^2(t)\,dt} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} v^2(n)}$$

Where v: signal’s voltage from an AE sensor

t_0= initial time

T= integration time of the signal

N= 15, number of discrete AE data within the interval T

The AE_{rms} calculation method examples were shown in table 7 and table 8 at 0.5ml/min leakage rate for 0% to 100% valve opening.

Table 7: AE_{rms} value for 0.5ml/min for 0% to 15% valve opening

AE amplitude (V) at different % valve opening							
Valve opening		0%	3%	6%	9%	12%	15%
Data sample	1	1.4876E-05	5.33316E-05	0.00014	0.00022	0.0003	0.00048
	2	1.72578E-05	5.39492E-05	0.00014	0.00022	0.00031	0.00051
	3	1.70799E-05	5.48258E-05	0.00014	0.00027	0.00038	0.00045
	4	2.05109E-05	5.98391E-05	0.00017	0.00028	0.00036	0.00046
	5	1.47057E-05	5.92905E-05	0.00017	0.00023	0.00034	0.00045
	6	1.95878E-05	6.8153E-05	0.00016	0.00023	0.00043	0.00053
	7	1.9906E-05	6.47866E-05	0.00017	0.00022	0.0004	0.00051
	8	2.17763E-05	7.62931E-05	0.00015	0.00022	0.00034	0.00055
	9	1.85347E-05	7.72654E-05	0.00016	0.00027	0.0003	0.00047
	10	2.05109E-05	7.61176E-05	0.00014	0.00025	0.00043	0.00045
	11	2.09645E-05	8.66932E-05	0.00014	0.00027	0.00038	0.00046
	12	1.87493E-05	8.2411E-05	0.00014	0.00022	0.00036	0.00052
	13	1.85133E-05	6.06017E-05	0.00016	0.0002	0.00034	0.00051
	14	2.07723E-05	5.21777E-05	0.00014	0.00022	0.00034	0.00048
	15	1.92081E-05	6.13035E-05	0.00014	0.00023	0.0003	0.00045
AErms(V)		1.89744E-05	6.67052E-05	0.00015	0.00024	0.00036	0.00049

AE amplitude (V) at different % valve opening									
Valve opening		30%	40%	50%	60%	70%	80%	90%	100%
Data sample	1	0.000212807	0.000135358	8.6E-05	5.2E-05	3.8E-05	2.4E-05	1.9E-05	1.9E-05
	2	0.000217763	0.000114944	8.6E-05	5.2E-05	3.8E-05	2.7E-05	1.8E-05	1.8E-05
	3	0.000191639	0.000122457	6.9E-05	5E-05	3.4E-05	2.7E-05	2E-05	1.9E-05
	4	0.000189228	0.000136768	7E-05	4.8E-05	3.2E-05	2.5E-05	2.1E-05	1.9E-05
	5	0.000180503	0.000133963	6.5E-05	5.2E-05	3.3E-05	2.6E-05	1.9E-05	1.8E-05
	6	0.000217763	0.000137399	6.7E-05	5.3E-05	3.3E-05	2.4E-05	1.7E-05	1.7E-05
	7	0.000194082	0.000120916	7.6E-05	4.7E-05	3.8E-05	2.3E-05	1.9E-05	1.6E-05
	8	0.000191639	0.000137399	8.6E-05	4.5E-05	3.6E-05	2.4E-05	1.6E-05	1.7E-05
	9	0.000215023	0.000127639	7.1E-05	4.9E-05	3.8E-05	2.7E-05	1.8E-05	1.7E-05
	10	0.000182173	0.000120916	6.8E-05	4.5E-05	3.6E-05	2.4E-05	1.8E-05	1.8E-05
	11	0.000182804	0.000121195	7.6E-05	4.7E-05	3.8E-05	2.6E-05	1.9E-05	1.9E-05
	12	0.000214035	0.000117081	7.7E-05	4.5E-05	3.4E-05	2.5E-05	1.9E-05	1.7E-05
	13	0.000211585	0.000137399	6.5E-05	5.4E-05	3.5E-05	2.6E-05	1.6E-05	1.7E-05
	14	0.000190539	0.000122457	8.7E-05	5.1E-05	3.4E-05	2.3E-05	1.7E-05	1.9E-05
	15	0.000207962	0.000122457	8.8E-05	5.3E-05	3.8E-05	2.7E-05	1.8E-05	1.7E-05
AErms(V)		0.000200434	0.000127472	7.6E-05	4.9E-05	3.6E-05	2.5E-05	1.8E-05	1.8E-05

Table 8: AE_{rms} value for 0.5ml/min for 30% to 100% valve opening

Base on the root mean square formula above, the AE average energy level was calculated for each valve opening percentage as shown is the last row of table 7 and 8.

The data collection process was repeated every time a new unhealthy stage of the valve was created to fill up the data table. The AE_{rms} values were calculated automatically from the data table through the MATLAB function. The tables 9, 10, 11 below shows the calculated AE_{rms} values at all the valve openings at different leakage rates, measured at different three different positions: middle valve body, outlet flange and inlet flange.

Table 9: AE_{rms} values for different opening % at Middle valve body

Valve opening (%)	AErms (V) at **Middle valve body**					
	0.5 ml/min	**4ml/min**	**11ml/min**	**24ml/min**	**32ml/min**	**80 ml/min**
0	1.94082E-05	2.13052E-05	2.17513E-05	2.44335E-05	3.29598E-05	0.000324702
3	0.000133809	0.000144705	0.00013567	0.000162737	0.000212073	0.000671406
6	0.000166527	0.000174979	0.000345132	0.000414462	0.000429027	0.001154742
9	0.000231465	0.000311878	0.000429027	0.000592223	0.000762931	0.001632996
12	0.000330739	0.000504644	0.000648612	0.000727755	0.000927865	0.001472262
15	0.000517589	0.000621563	0.000772654	0.001062882	0.001373995	0.000861956
20	0.000365162	0.000402703	0.000459182	0.000614448	0.000834613	0.000546368
30	0.000214529	0.000233338	0.000258812	0.000364741	0.000479717	0.000204402
40	8.34613E-05	9.50572E-05	0.000129266	0.000186847	0.000244335	0.00014876
50	6.5991E-05	5.72117E-05	9.71594E-05	0.000120916	0.00014655	8.55037E-05
60	4.52361E-05	4.93725E-05	6.56878E-05	8.44277E-05	9.74956E-05	7.73544E-05
70	3.20247E-05	3.45927E-05	5.13434E-05	5.21777E-05	6.62956E-05	5.09313E-05
80	2.36584E-05	2.05109E-05	3.60566E-05	3.61814E-05	4.04562E-05	3.6727E-05
90	1.94082E-05	2.02528E-05	2.41816E-05	2.38773E-05	2.44898E-05	2.26979E-05
100	1.91639E-05	1.9186E-05	1.8556E-05	1.96555E-05	1.89228E-05	1.94978E-05

Table 10: AE_{rms} values for different opening % at Outlet flange

Valve opening (%)	AErms (V) at **Outlet flange**					
	0.5 ml/min	**4ml/min**	**11ml/min**	**24ml/min**	**32ml/min**	**80 ml/min**
0	1.92081E-05	1.94305E-05	2.04873E-05	2.16514E-05	3.74098E-05	0.000299906
3	0.000113106	0.000140762	0.000141412	0.000155412	0.000247449	0.000606017
6	0.000151875	0.000157574	0.000264536	0.00044054	0.000454449	0.00084525
9	0.000215519	0.000225676	0.000400392	0.000546368	0.000875961	0.001024436
12	0.000306538	0.000504644	0.000578076	0.000702239	0.00110277	0.001255987
15	0.000483042	0.000556525	0.000696602	0.000980584	0.001224574	0.001124566
20	0.000340396	0.000383253	0.000413985	0.000573436	0.000904659	0.000468797
30	0.000185133	0.000224122	0.000247164	0.000321355	0.000538251	0.00020021
40	7.64689E-05	9.0154E-05	0.000126761	0.000178643	0.000274148	0.000153987
50	6.13741E-05	6.87836E-05	7.3703E-05	0.000111426	0.000181128	9.24666E-05
60	4.32001E-05	4.52882E-05	6.03233E-05	7.90651E-05	0.00010814	5.90181E-05
70	2.98872E-05	3.18409E-05	4.71504E-05	4.86951E-05	6.86254E-05	4.09247E-05
80	2.44898E-05	2.01365E-05	3.81931E-05	3.45529E-05	4.28041E-05	3.24702E-05
90	1.80296E-05	1.96555E-05	2.13052E-05	2.36312E-05	2.44335E-05	2.26457E-05
100	1.92081E-05	1.81128E-05	1.90539E-05	2.20539E-05	1.91199E-05	1.95652E-05

Table 11: AE_{rms} values for different opening % at Inlet flange

Valve opening (%)	AErms (V) at **Inlet flange**					
	0.5 ml/min	**4ml/min**	**11ml/min**	**24ml/min**	**32ml/min**	**80 ml/min**
0	1.91419E-05	1.88793E-05	2.08202E-05	2.10371E-05	3.21355E-05	0.000282153
3	0.000164431	0.000129415	0.000132277	0.000126324	0.000220539	0.000560383
6	0.000206531	0.0001524	0.000241816	0.000345132	0.000364741	0.000809068
9	0.000266984	0.000233069	0.000381492	0.000494294	0.000764689	0.000894304
12	0.000345132	0.000480269	0.00053209	0.000564267	0.001006897	0.001137588
15	0.000540113	0.000500017	0.000706293	0.000893275	0.001196699	0.00082411
20	0.000423628	0.000356029	0.000383253	0.000541982	0.000985111	0.000429027
30	0.00020183	0.000205109	0.000214529	0.000286738	0.00044873	0.00025792
40	0.000123164	8.47198E-05	0.000118164	0.00016519	0.000244898	0.000142228
50	9.23602E-05	6.87045E-05	6.77618E-05	8.97398E-05	0.000163112	8.26009E-05
60	5.43857E-05	4.09247E-05	5.58451E-05	6.82315E-05	9.71594E-05	6.03233E-05
70	2.98872E-05	3.11519E-05	4.54449E-05	4.76963E-05	5.78076E-05	3.82371E-05
80	2.44335E-05	2.12807E-05	3.40396E-05	3.365E-05	3.93536E-05	3.03728E-05
90	3.18409E-05	1.9186E-05	2.10129E-05	2.17513E-05	2.50026E-05	2.35226E-05
100	1.93859E-05	1.85133E-05	1.95652E-05	1.80919E-05	1.94082E-05	1.89228E-05

From the tables 9, 10 and 11 of all the AE_{rms} values, the graphs representing the AE_{rms} values versus opening percentage are introduced below to present the trend of the AE signal in unhealthy control valve.

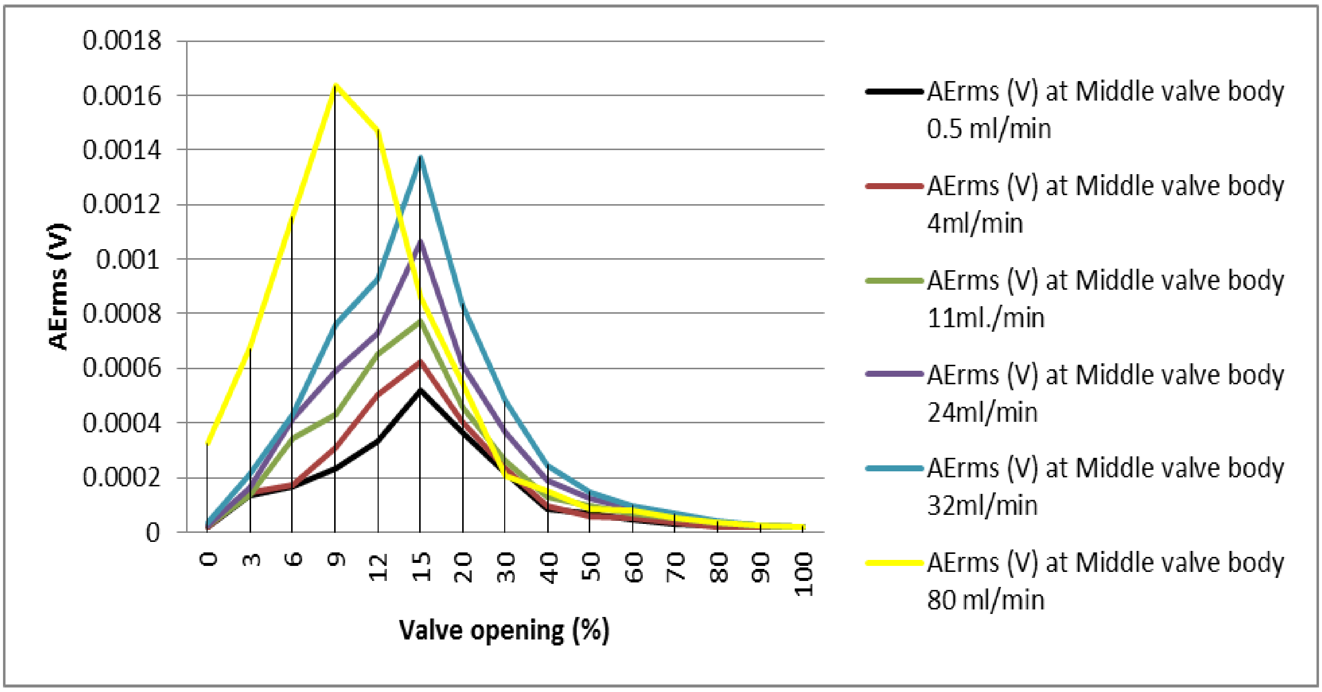


Figure 22: Frequency spectrum of AE signal at ***middle body*** *for different valve's unhealthy stages*

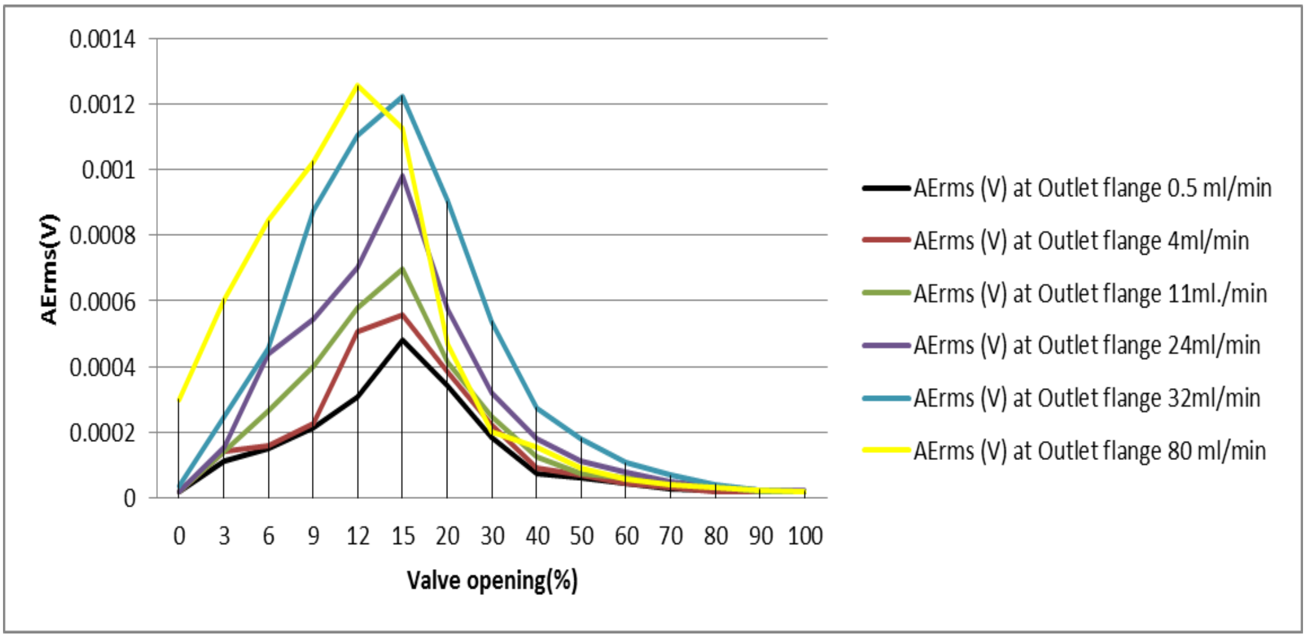


Figure 23: Frequency spectrum of AE signal at ***Outlet flange*** *for different valve's unhealthy stages*

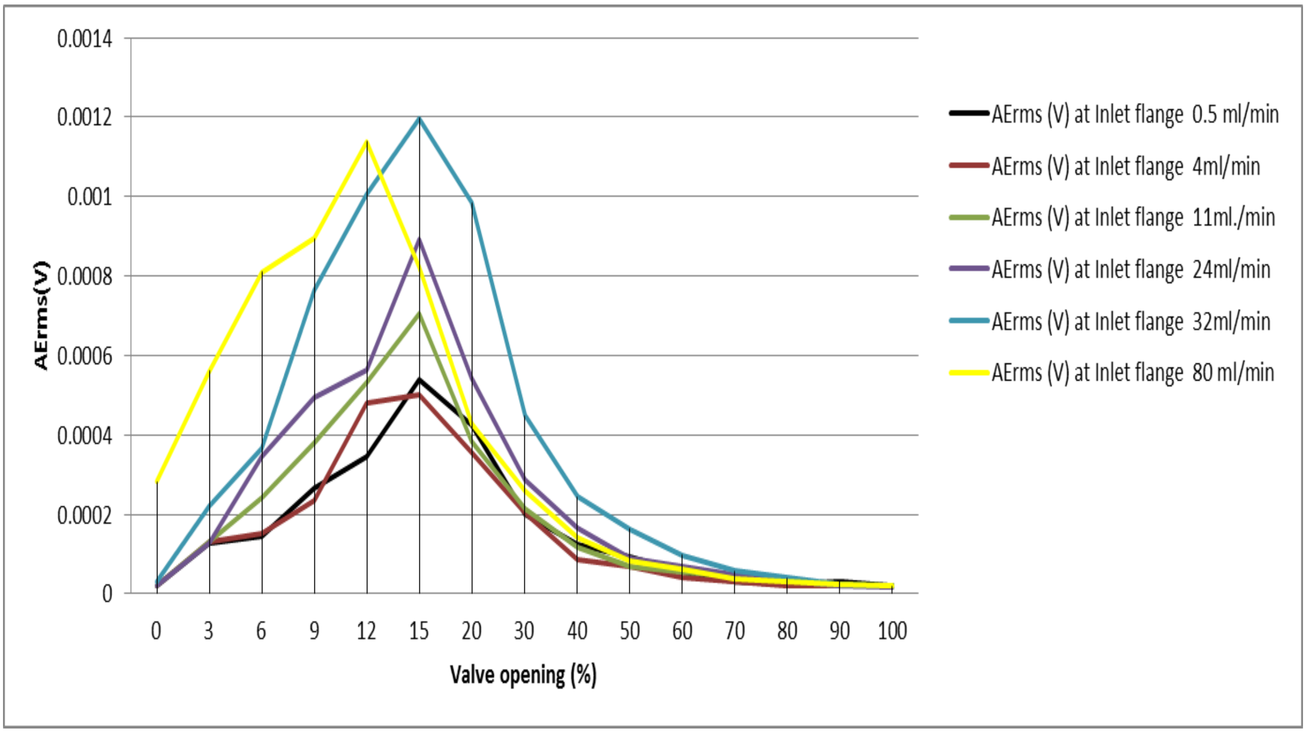
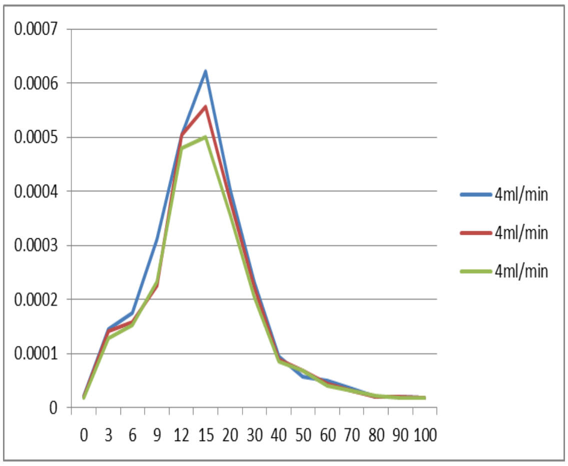


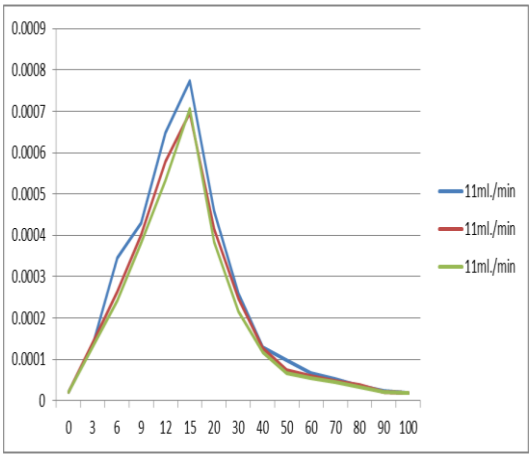
*Figure 24: Frequency spectrum of AE signal at **Inlet flange** for different valve's unhealthy stages*

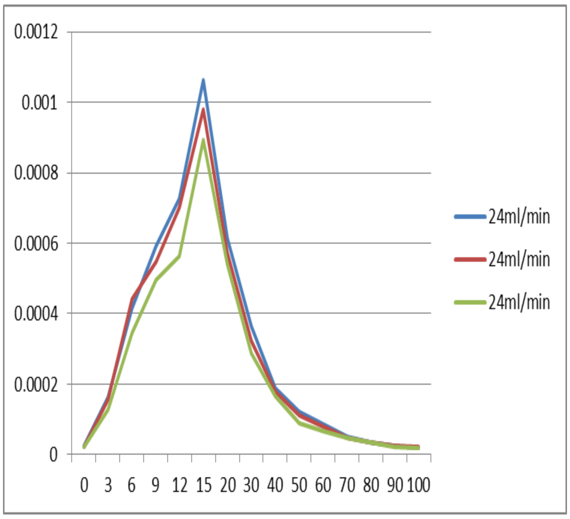
It was found that the amplitude of the signal increases when the valve opening percentage is increased from 0% to 15% for all the unhealthy stages: at 0.5ml/min, 4ml/min, 11ml/min, 24ml/min, 32ml/min. But for the faulty stage of control valve, when the leakage rate is 80ml/min which is greater than 34ml, the signal increases and reaches maximum value only at the 12% opening. After reaching the maximum value at 15% valve opening for unhealthy valve and 12% valve opening for faulty valve, the AE signal starts gradually decreasing to initial value when the valve opening is continuously increased to 100%. The results of AE signal measurement at three different locations on the valve body confirm this trend of AE signal on unhealthy control valve and faulty control valve. On the other hand, the AE spectrums at three different location for unhealthy valve (from 0ml/min to 32ml/min leakage rate) display the same characteristic that when the leakage rate increases, the AE signal's amplitude tends to increase at the same valve opening. At the same valve opening level: AE_{rms} for 32ml/min > AE_{rms} for 24ml/min > AE_{rms} for 11ml/min > AE_{rms} for 4ml/min.

Based on the observation for frequency spectrum of AE signal at different unhealthy stages of the valve, the results affirmed the ability of AE method to detect leakage the fault or unhealthy status of the control valve. For the faulty valve (leakage rate: 80ml/min), the fact that AE signal only reaches maximum value at 12%, not 15% for unhealthy valve, could be explained by the theory of leakage flow rate. At 12% opening of faulty control valve (80ml/min), the liquid flow rate reach the maximum value, the same phenomenon occurs for unhealthy control valve at 15% valve opening. As a result, the AE signal's average energy levels created from these valve openings are the maximum values in the throughout valve opening from 0% to 100%.

According to the Figure 25 below of AE frequency spectrum for different valve leakage comparing the AE magnitude at three different locations, the AE_{rms} results indicate that the signal recorded at the middle valve body (the graph in blue colour) is always higher than the AE_{rms} values at outlet flange and inlet flange. As a conclusion, middle valve body is the best location to find the AE source in the control valve when the fault occurs and causing leakage.







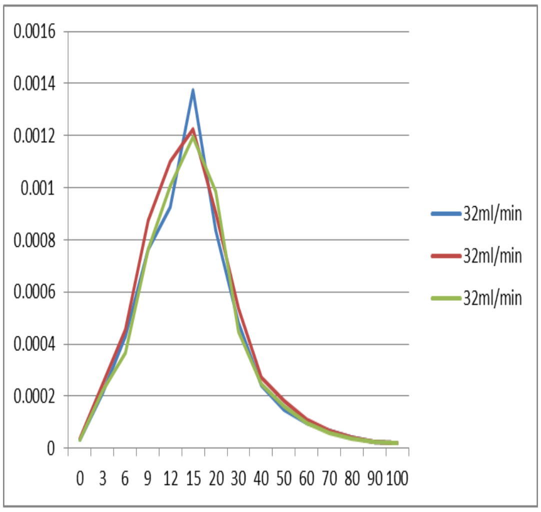


Figure 25: AE Frequency spectrum comparison at different locations

V. Conclusion and future improvement suggestion

Based on the results from the experiment, it is concluded that the project objectives were accomplished. The Acoustic Emission technique was applied successfully to measure the unhealthy characteristics of the control valve. Analysing the signal generated from the fault in control valve, we can describe a common characteristics of unhealthy valve case and apply the result into the fault monitoring system in control valve. The unhealthy control valve is proved that it can emit the acoustic signal in high frequency range. The AE signal amplitude gets increased and reaches the maximum value when the valve opening increases only within the range from 0% to 15% opening. At different pre-damaged stages of control valve (when leakage rate < 34ml/min), the leakage rate increases causing the AE signal amplitudes to increase. Besides, the strongest source of AE signal emission is at the middle body where the leakage starts occurring on the valve plug.

The project also affirms the important of using the proper signal processing system. The heart of the signal processing system is the acoustic sensor. A proper sensor with the system needs to be selected carefully to display the expected signal spectrum at desired frequency. Besides, the noise filter system is also a big issue in signal system design to eliminate the interference.

Finally, from the observed AE spectrum, the Acoustic Emission technique is proved to be able to display the unhealthy status of the control valve without disassemble the valve and implement the physical check, thus the process interruption is not required. As a result, it could be applied to improve the maintenance system and help to reduce the operation cost in a long time.

For future improvement, this final year project could be developed into higher level project, where the healthy and unhealthy control valves are both studied to obtain their AE characteristics. On the other hand, many high level analysis methods, for instance, Neural network tool on MATLAB, can be applied to process the AE data. As a result, a monitoring system can be implemented to evaluate and automatic detect the fault on control valve without interrupting the process, which will greatly contribute to an effective maintenance system.

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