FATIGUE CRACK DETECTION IN ALUMINIUM PIPE BY USING NON-LINEAR VIBRO ACOUSTIC METHOD

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FATIGUE CRACK DETECTION IN ALUMINIUM PIPE BY USING NON-LINEAR VIBRO ACOUSTIC METHOD

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This report is submitted
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DECLARATION

I declare that this project report entitled “Fatigue Crack Detection In Aluminium Pipe By Using Non-Linear Vibro Acoustic Method” is the result of my own work except as cited in the references

Signature	:	....
Name	:	....
Date	:	....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering

Signature :. ....

Name of Supervisor : ....

Date : ....

DEDICATION

To my beloved mother and father

ABSTRACT

Fatigue crack presence is the most common structural failure and there are several factors to cause fatigue crack. In this research non-linear vibro acoustic method has been introduced for the crack detection on aluminium pipe. Non-linear vibro acoustic approach is the most appropriate method for detecting the existence of fatigue crack as it is very sensitive even to a very tiny damage severity. The nonlinear vibro-acoustic modulation is a technique which combined the intensive low frequency (modal) excitation and high frequency ultrasonic wave. Several procedures have been taken for this project including the preparation of the test specimen, the modal analysis test and the vibro-acoustic test. The test specimen used in this experiment is a 102.3mm x 114.3mm x 1000mm aluminium pipe (Al-6061). A slot size with dimension 10mm x 2mm was created by using milling machine on test specimen. The test specimen undergoes modal test analysis to determine the resonant frequencies and followed by the vibro-acoustic method. Data from modal analysis is applied in vibro-acoustic test as low frequency excitation with 60kHz high ultrasonic wave. The vibro-acoustic test used is to accomplish the goal of performing the non-linear vibro acoustic test at aluminium pipe with different slot size in detecting the fatigue crack. Modulation intensity (R-value) is obtained by calculation and related to effect of the size dimension.

ABSTRAK

Kehadiran retak adalah kegagalan struktur yang paling biasa dan terdapat beberapa faktor untuk menyebabkan retak. Dalam penyelidikan ini, kaedah akustik yang tidak linear telah diperkenalkan bagi mengesan retak pada paip aluminium. Pendekatan akustik non-linear adalah kaedah yang paling sesuai untuk mengesan kewujudan retak kerana ia adalah sangat sensitif walaupun dengan keterukan kerosakan yang sangat kecil. Modin akustik bukan linear adalah satu teknik yang menggabungkan frekuensi rendah (mod) yang intensif dan gelombang ultrasonik frekuensi tinggi. Beberapa prosedur telah diambil untuk projek ini termasuk penyediaan spesimen ujian, ujian analisis mod dan ujian getaran-akustik. Spesimen ujian yang digunakan dalam percubaan ini ialah paip aluminium 102.3 mm x 114.3 mm x 1000mm (Al-6061). Saiz slot dengan dimensi 10mm x 2mm telah dicipta dengan menggunakan Mesin pengilangan pada spesimen ujian. Spesimen ujian mengalami analisis ujian mod untuk menentukan frekuensi resonant dan diikuti dengan kaedah getaran-akustik. Data dari analisis mod digunakan dalam ujian geto-akustik sebagai frekuensi rendah berdetik dengan gelombang ultrasonik 60kHz yang tinggi. Ujian getaran-akustik yang digunakan adalah untuk mencapai matlamat melaksanakan ujian akustik non-linear getaran pada paip aluminium dengan saiz slot yang berbeza dalam mengesan kelesuan retak. Intensiti nilai (Nilai-R) diperolehi melalui pengiraan dan berkaitan dengan kesan dimensi saiz.

ACKNOWLEDGEMENT

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LIST OF ABBEREVATIONS

DAC	Digital to Analog Converter
DDS	Direct Digital Synthesis
ED	Electrodynamic
FEA	Finite Element Analysis
FRF	Frequency Response Function
HF	High Frequency
LF	Low Frequency
PSB	Persistent Slip Bands
SHM	Structural Health Monitoring
SLDV	Scanning Laser Doppler Vibrometer
VAM	Vibro-Acoustic Modulation

CHAPTER 1

INTRODUCTION

1.1 Background

Structural Health Monitoring (SHM) is the method of introducing a plan to track damage to structural (Farrar and Worden, 2007). Damage identification is performed along with five closely related fields of study including SHM, condition monitoring, non-destructive evaluation, statistical process control, and prognosis of damage.

Vibro-acoustic modulation (VAM) is an example of non-destructive research method used for identification of defects in nonlinear acoustic methods. The VAM comprises twin-frequency sine wave and a analysis of the correlation of this wave with the inherent faults. The existing research on the dynamics of VAM for a standard material body is described in this thesis. The responsibilities of various types of defects on the response of the material are examined. The conceptual study reveals the origin of nonlinear frequencies in the face of rising resonances and sidebands that are frequently found in the VAM output response.

VAM is a concept that focuses on the frequency modulation impact on a not significant high frequency probing wave by a low frequency pumping vibration that happens in fundamental vibrational modes. Due to the modulation effect, the sideband spectral elements around the principal high frequency peak are produced within the fourier series structure when the control structure is concurrently excited by all of these signals. This behaviour is unnoticeable and the spectra of responses will superpose the responses to each specific signal if the structure is undamaged. The modulation effect is easily detectable as the system is slotted and seems to be nonlinear.

Apart from this, the study gives observations into the interactions between the magnitude of nonlinear responses and the magnitudes of input vibrations and the physical sources of nonlinear responses. A finite element analysis of VAM is also conducted for a physical visualisation of the nonlinear vibrations affiliated with the theory. The model explores the scientific validity of applying VAM to map damage in physical structures. The prototype is also applied to further investigate the defect size and depth of the VAM nonlinear mechanism.

1.2 Problem Statement

The occurrence of fatigue crack is the most common structural defect. There are several factors causes fatigue cracks exist in the structures. The existence of cracks can affect a local variation and can have a significant impact on the mechanical behaviour of the whole system. Consequently, a non-linear vibro acoustic approach is particularly suitable for identifying the occurrence of fatigue crack since it is very resilient to only a limited degree of defect and this technique need not involve dense sensor networks. Nonetheless, there are no extensive investigation have been performed to analyse the influence of different slot dimensions on the sensitivity to non-linear effects, so this research is performed using vibro acoustic method to identify fatigue crack.

1.3 Objectives

The objectives of this project are as follow :

1. To perform the non-linear vibro acoustic test at aluminium pipe with different slot size in detecting the fatigue crack.
2. To determine the relationship between the slot size and the effect of fatigue crack.

1.4 Scope of Project

In this project, the scopes need to cover include:

a. Preparation of the test specimen slot with dimension 10mm length , 2mm width and 0 – 6 mm depth by using milling machine.

b. Perform non-linear vibro acoustic test on test specimen (aluminium pipe) to obtain mode shapes and resonant frequencies by using modal test.

c. Determine the relation between the slot sizes with modulation effect.

d. Analysis of the experimental data to obtain the non-linear wave modulation effect

CHAPTER 2

LITERATURE REVIEW

2.1 Damage in Structure

There are a lot of different methods have been established to identify the defect in the structures. Damage usually defined as shift in the system that will affects its performance. Damage was also defined as changes in structural on the material or geometric properties of a mechanical or structural system (Sohn *et al.*, 2004). Besides that, in the view of mechanical damage in solid materials was known as the growth and creation of microcracks or microvoids which will create discontinuities in a medium (Lemaitre and Desmorat, 2005). One of the major damage mechanisms in structural materials is fatigue cracking as shown in Figure 2.1. Normally fatigue cracking happened in structure when cyclic stresses are lower than the ultimate tensile stress or even material yield stress. A component's fatigue life can be defined as the number of loading cycles required to trigger a fatigue crack and propagate the crack to critical size (*Fatigue Properties*, no date). Hence, there are three stages fatigue failure occurs - crack initiation which are slow, stable crack growth and rapid fracture. Dislocations is an important part in the initiation phase of fatigue crack. Persistent slip bands (PSB) was the accumulation of dislocations on the surface near to stress concentrations area after a huge number of loading cycles in the first stage. While in the second stage of fatigue, combination of the tiny microcracks growth and spread along the material toward the maximum tensile stress in the direction with 90º. Continuity growth of cracks until the uncracked compound of the components is no longer supported by continuous cyclic loading.

The third stage of fatigue failure occurred when the fracture strength was exceeded and the remaining cross-section of the material experienced rapid fracture (*Fatigue Properties*, no date).

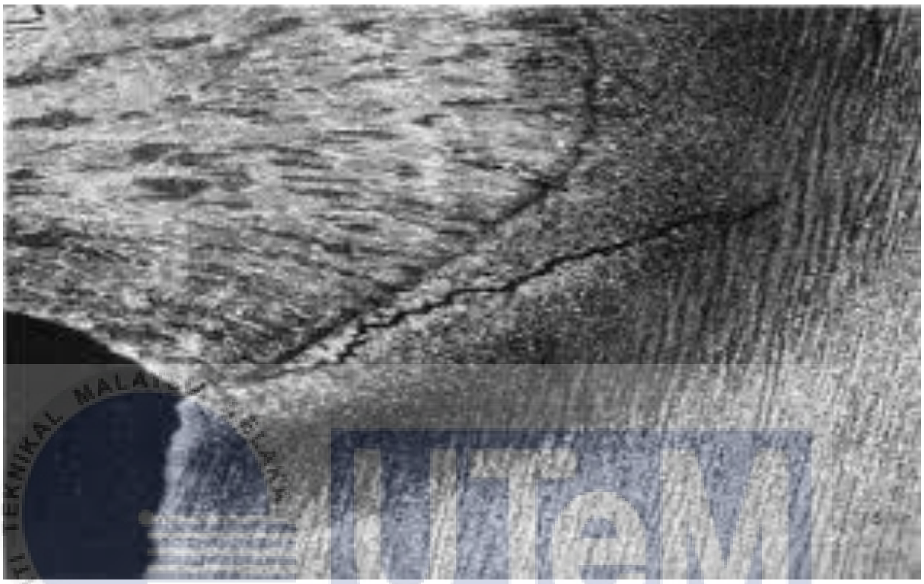

Figure 2. 1 : Fatigue crack in structure

2.2 Modal Test

Modal analysis is an essential technique to describe the vibration behaviours of mechanical structures. It transforms the excitation dynamic response and measured responses to a complicated system that is hard to interpret into a series of modal parameters that can be easy to predict. The application of modal analysis is helpful in data obtaining and visualization techniques. Modal analysis often transmit a complicated system which is hard to observe in a series of separable only degree systems of independance that are easily to identify. Besides that, the modal analysis is used to define resonant frequency, modal damping and mode shapes of a structure with reference to FRF measurements (*Basics of Modal Testing and Analysis*, 2016). Mode shapes and natural frequencies able to forecast by applying statistical method named Finite Element Analysis (FEA) models, which are named the modal parameters for short. Modal analysis is an essential tool to identify and resolve problems related to structural vibration. When an excitation mechanism interacts with the structure's natural frequency, a common vibration problem that can be detected with modal analysis occurs. In order to identify its frequency components, the excitation function can be analysed in the frequency domain. When the excitation frequency overlaps with the structure's natural frequency, the structure can display very high vibration levels that can cause to fatigue and failure of the structure. The structure's natural frequencies, coefficients of damping, and mode shapes can be determine in modal analysis. The arrangement may be adjusted or updated to alter the frequency response apart from the vibration response as it is determined that the intensity of vibration corresponds to another of the natural frequencies used in the modal analysis.

Measurement of the excitation and response of the structure under experiment is the initial action in experimental modal analysis. The system must be excited and both the excitation force applied and the resulting vibrations of response, generally accelerations, are measured resulting in a set of data for the Frequency Response Function. The modal parameters can be determined by using the FRF data set which comprising natural frequencies, damping coefficients, and mode shapes (Daniel J.Inman, 2001). Data can be then animated visually when the mode shaper. To have the vibrating reactions, the system needs to be excited. Two general methods of excitation normally used in experiment are impact hammer and modal shaker. The hammer is equipped with a testing machine that produces an electrical signal proportional to the toggle force whereby the maximum force is determined when the experiment is carried out. Typically, modal analysis on simple structures uses impact hammer or it is not feasible to add a modal shaker. With the hammer, various hardness impact tips can be used to change the impact frequency range of the measurement. If measurements of low frequency are desired, a soft rubber tip could be applied, and a hard metal tip could be applied if measurements of high frequency are desired.

A modal shaker is usually applied for laboratory modal test measurements. Modal shaker are different in size as they are rated by the force produced by them. The driving forces acquired by the shaker is the key for choosing the modal shaker size to make sure enough level of response on the structure during experiment. To test the excitation force, a impact device is mounted at the operation position on the structure and attached to another side of the stinger. A shaker is often powered by the DAC (digital to analog converter) of the dynamic signal analyzer, an electronic device which produces carefully tuned electronic signals that are then magnified and transformed into the excitation signals. The structure can be excited by multiple types of excitation signal profiles.

The next step is to determine the excitation and also the responses once the mechanism is excited. This is usually performed by using a Dynamic Signal Analyzer to position force sensor and accelerometers on the system and record the response of force and acceleration. Conversion of electronic signal into acceleration and measurement on it have been performed by an electronic sensor which called accelerometer (*Basics of Modal Testing and Analysis*, 2016). Two types of accelerometer are available which are uniaxial and tri-axial accelerometers. In addition, a tri-axial accelerometer is combination of three accelerometers together, positioned right angle to everyone to ensure the measurement of vibration across 3 axes. An instrument called the Dynamic Signal Analyzer used for measuring and capturing signals and processing those signals to the frequency domain data.

Frequency Response Functions (FRFs) and Coherence are the common kinds of signals applied in modal analysis. Frequency Response Function (FRF) is derived through two signals which called response (output) and excitation (input) and also known as “transfer function”. The FRF represents the ratio of one signal over the appropriate frequency range with respect to another signal.

Normally, this is applied in a modal analysis where the pulse power of the mechanism is evaluated on the basis of impact stimulation from the hammer or modal shaker. Coherence is connected to the FRF and informs what section of the response to the excitation is attributed. This is a frequency function which do shift from null to one (Daniel J.Inman, 2001). To evaluate the quality of a measurement, the signal is applied in modal analysis. Nonetheless, it is common for consistency to be low in an anti-resonance or structural nodes with very low vibration responses. One block of time data have been used usually for calculating frequency domain data. Some irregular noise that could distort true resonant frequencies and mode shapes has been covered in every block of time data. Uncorrelated random noise will be minimized by averaging a few blocks of data. The advantage of averaging is that it minimizes the impact of random noise and results in smoother data.

2.3 Vibro-acoustic Method

Non-linear vibro-acoustics have been used for detecting crack in solids for many years. The approach uses a variety of nonlinear phenomena correlated with surface imperfections and thermo-elastic actions of interfaces. Hence, it is specifically for detecting crack in metallic structures (Hu *et al.*, 2010). The nonlinear vibro-acoustic modulation is a methodology that mixes extreme low-frequency (modal) signal with high-frequency ultrasonic pulse. Such two excitations are concurrently added to the structure as shown in Figure 2.2 (Klepka *et al.*, 2014). The prevailing opinion of all these studies is that nonlinear crack effects are greater than crack-induced variations found in standard linear characteristics (Klepka *et al.*, 2012). When supervised structures are untouched or undamaged, only the two main frequency components corresponding to the propagating ultrasonic wave and low frequency excitation are demonstrated in the signal response spectra as illustrated in Figure 2.3. As shown by the Figure 2.4, when the monitored components are disrupted, the response signals spectra include additional sidebands around the ultrasonic core portion (Klepka *et al.*, 2014).

The modulation intensity was tracked by using the parameter R defined as

$$R = \frac{A_1 + A_2}{A_0}$$

Where A_0 is the spectral amplitude of the carrier acoustical frequency, A_1 and A_2 are the spectral amplitudes of the first pair of sidebands.

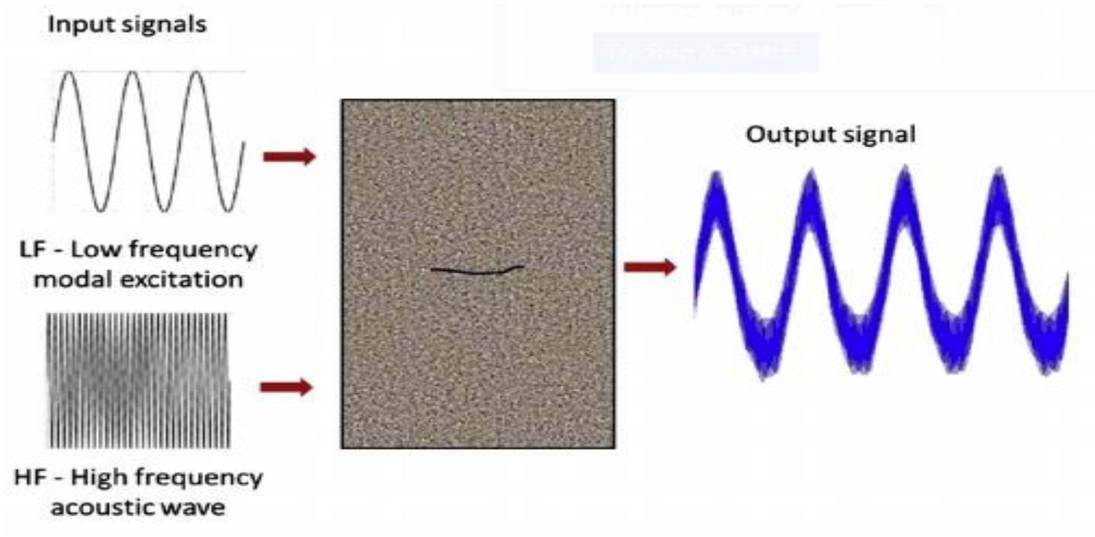

Figure 2. 2 : The principle of nonlinear vibro-acoustic wave modulation technique: schematic diagram illustrating the method.

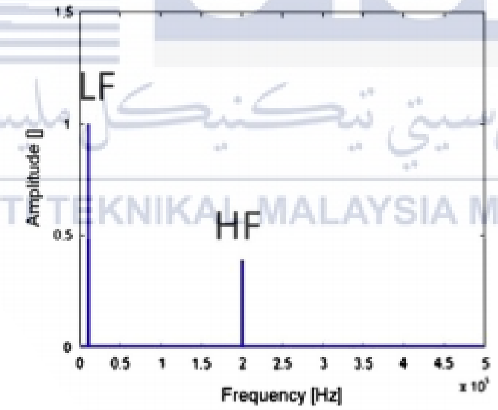

Figure 2. 3 : Power spectrum of response signal for undamaged structure.

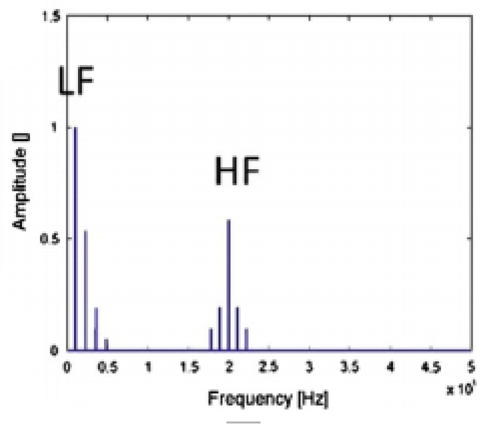

Figure 2. 4: Power spectrum of response signal for damaged structure.

Nonlinear vibro-acoustic modulation (VAM) is one non-destructive evaluation tool that has been shown to be prone to cracks in complex geometric structures (Sutin and Nazarov, 1995). Although there are other types of VAM (Zaitsev, Gusev and Castagnède, 2002) the type of VAM applied is based on the modulation of a high-frequency ' probing ' signal with a lower frequency ' pumping ' signal occurring in the existence of structural nonlinearities (Sutin and Nazarov, 1995). If the structure is undamaged and linear, the response of the structure will simply be the superposition of its response to each of the signals individually (Yoder and Adams, 2010). Nevertheless, additional non-linear components are generated in the broken structure due to non-linear effects resulting in the combining of two input signals. Yoder also showed that the amplitude of the power spectra is magnified while the ultrasonic signal co-occur aligns the frequency response of the structure (Yoder and Adams, 2010).

There are a number of past experimental works for the non-linear vibro acoustic method. (Donskoy, Sutin and Ekimov, 2001) have set up a non-linear experimental work as shown in Figure 2.5. In the set-up of the experiment, low-frequency signals triggered with the application of an impact hammer and the output obtained and conveyed by the use of a piezoceramic transducer. The similar experimental set-up by (M. Morbidini, P. Duffour, 2005) as seen from Figure 2.6. The crucial distinction between two installations is the placement of the signal receiving transducer. Based on experiments carried out by Morbidini et al., the signal is transmitted through the crack but reflective signal is used for studies by Donskoy et al. The first sideband effect was used to evaluate the sensitivity effect against the size of the defect in both cases.

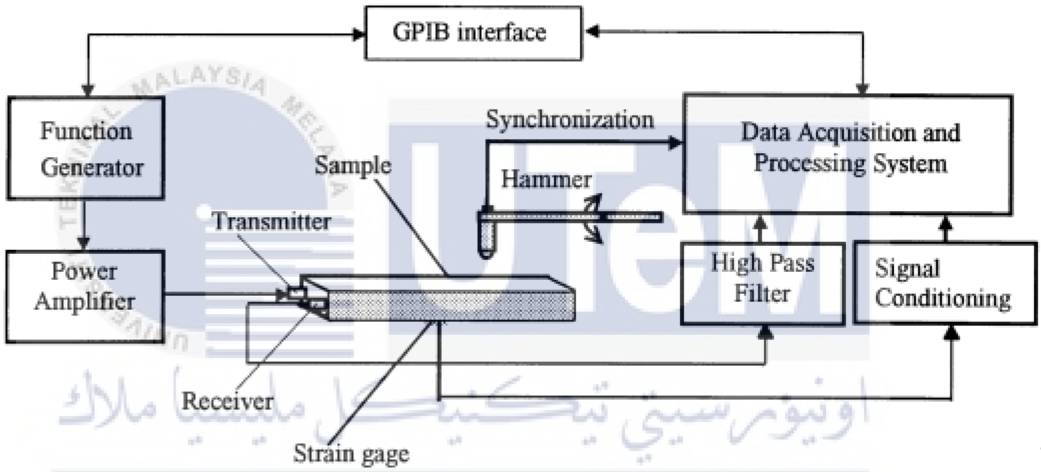

Figure 2. 5 : Schematic of Impact Modulation (IM) technique on a beam

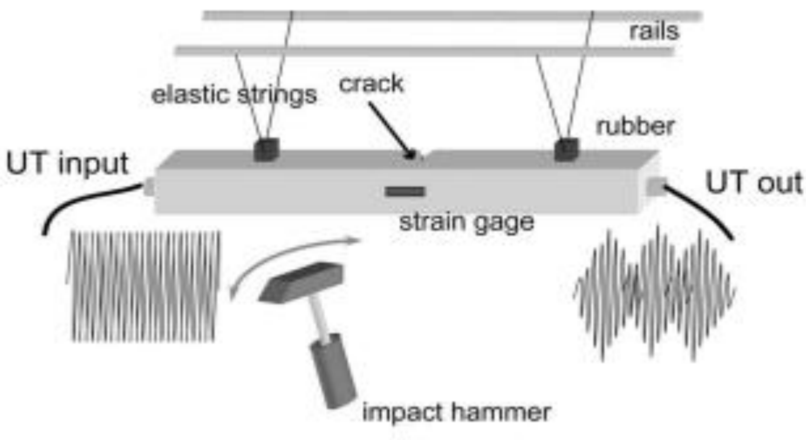

Figure 2. 6: Schematic of Impact Hammer Suspension (IHS)

(Donskoy, Sutin and Ekimov, 2001) technique is able to differentiate between integrity reducing defects and other structural inhomogeneity while (M. Morbidini, P. Duffour, 2005) discover that this technique can be one of NDT fault diagnosis when there is an adequate correlation between low and high-frequency vibration and a narrow ultrasonic signal frequency range. Approach of (Donskoy, Sutin and Ekimov, 2001) is able to discern the difference between integrity reduction defects and other structural inhomogeneity, while (M. Morbidini, P. Duffour, 2005) discover that this technique can be one of NDT fault diagnosis when there is an adequate correlation between low and high-frequency vibration and a narrow ultrasonic signal frequency range. Morbidini et al. have discovered a more reliable and stable regulated shaker to incorporate low-frequency signals. As illustrated in Figure 2.7, it might also substitute the application of impact hammer to vibrate the specimen.

(Parsons and Staszewski, 2006), which implemented innovation in smart material technology, introduced the best method. As shown in Figure 2.8, the piezo-ceramic stack actuator will be applied to excite the specimen and the specimen will be connected to the elastic string and minor in size compared to the actuator. Although the peak excitation rate of the piezo-ceramic stack actuator is lower than the shaker, the result illustrates a good sideband impact signature against the defects.

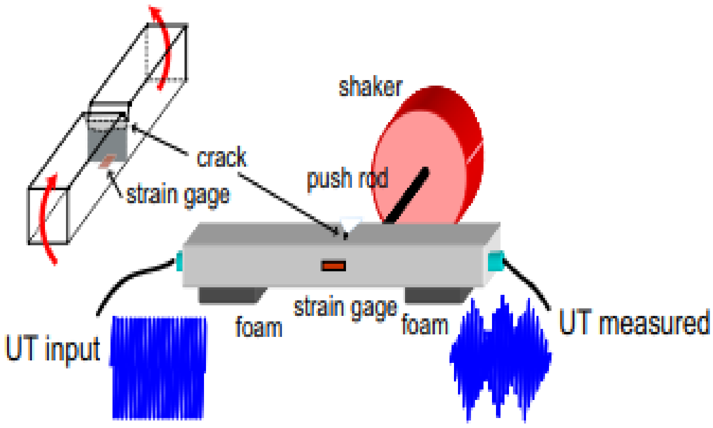

Figure 2. 7 : Schematic of the VAM testing using a shaker as excitation.

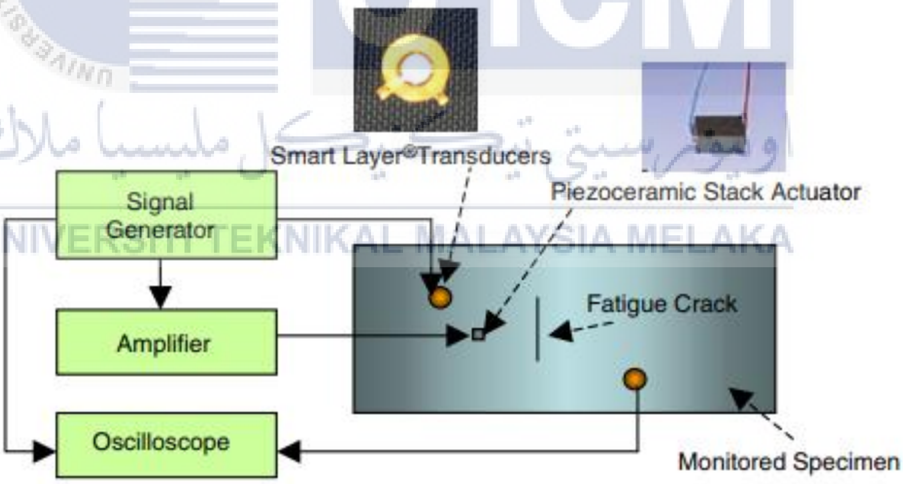

Figure 2. 8 : Experimental arrangements for the low-frequency piezoelectric excitation.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section discusses the methodology included in this project to diagnose fatigue cracking in aluminum pipe by using non-linear vibro acoustic method and shows that how the objective can be accomplished. The flow diagram of the project is shown in Figure 3.1 which illustrate the progress of the project from the beginning to the end of experiment with technical report of the project. The steps covered in this project are preparation of the test specimen, modal analysis and vibro-acoustic method (VAM).

3.2 Flow Chart and Experiment Overview

In this experiment, there are embedded with two important test which are modal test and non-linear vibro acoustic test as shown in Figure 3.1. In the modal test, aluminium pipe without slot as test specimen are used to determine the resonant frequency. While several frequencies modes are obtained and the data are kept in thumb drive during the modal test. The several frequencies will be used to execute the test in vibro acoustic test. Next, the MATLAB software is applied to look into the wave modulation that are represent by R-Value. A slot is to be create after the modal test to undergoes vibro-acoustic test with different dimension of the slot and the step is repeated to get another modal test.

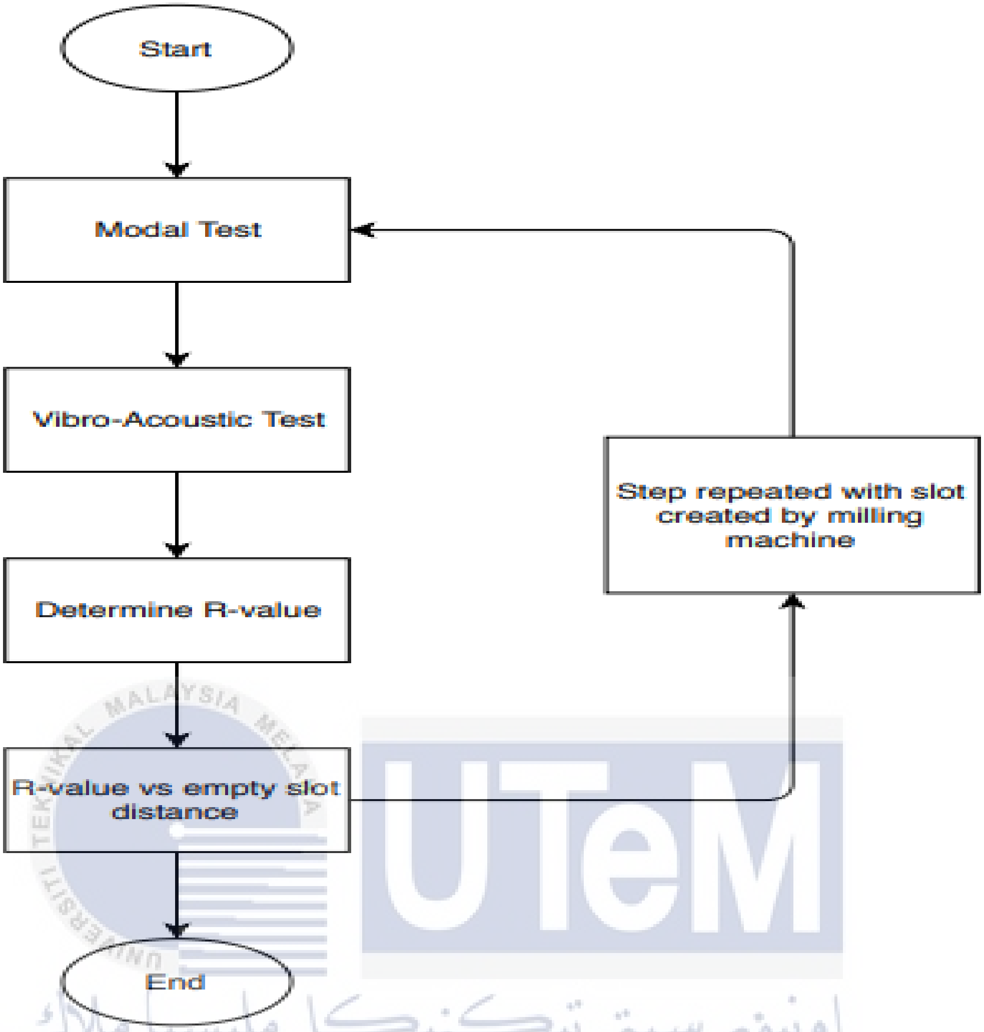

Figure 3. 1: Overview of project flow diagram

3.3 Methodology Flow Chart

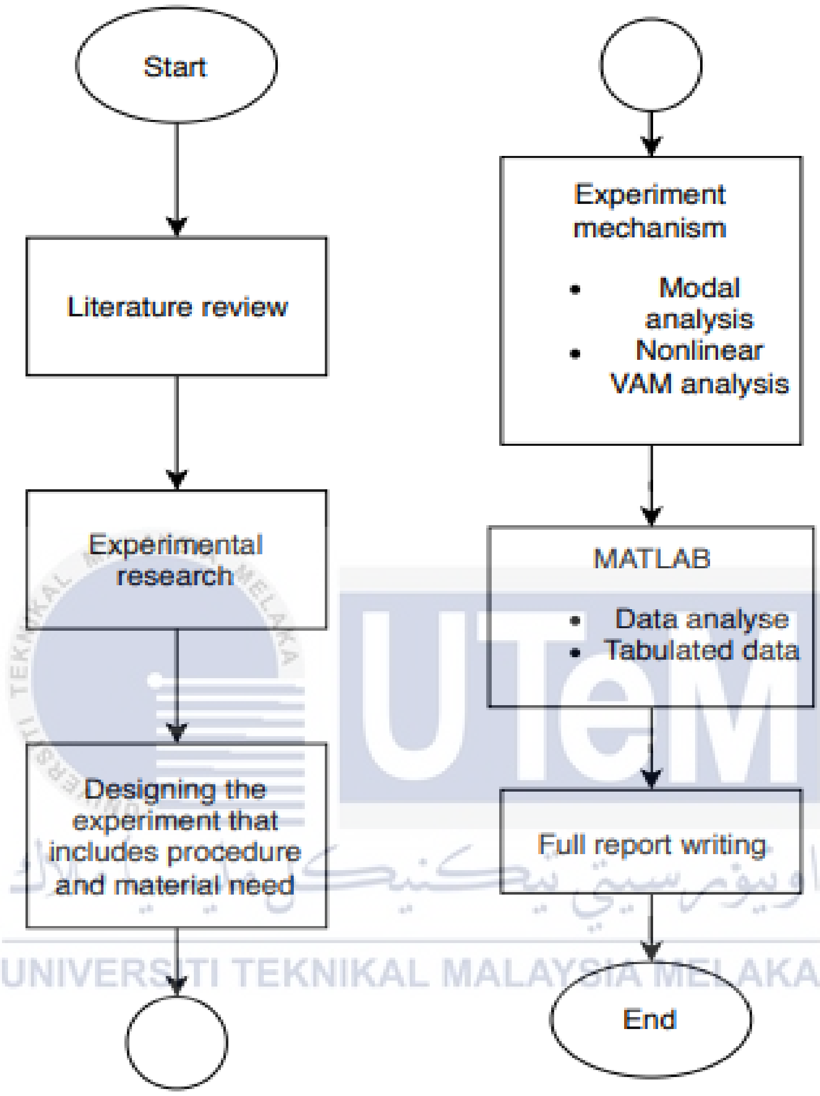

Figure 3. 2 : Methodology Flow chart

The step of the project is clearly stated in Figure 3.2. First and foremost, literature review was completed by doing on several researches related to the experiment to make understanding on concepts. Follow by doing experiment research, there are a many sources of research can be obtained such as internet, journal, articles, books and the past research book. Next, designing the experiment means the ways to carry out the experiment include how the material need is prepared and the procedure need to be undergone in the experiment. While there are two types of experiment mechanism is applied which are modal analysis and nonlinear VAM analysis. The experimental data is collected and applied in MATLAB to convert it into frequency domain. To obtain a better graph, average of the data was taken in this study. Data and result is recorded and final report is completed and submit.

3.4 Equipment and Specimen

1. Laser Vibrometer

Figure 3. 3: Laser Vibrometer

Laser vibrometer is a device that perform as transducer which used for visualization, structural vibration analysis and non-contact vibration measurement. It is possible to automatically analyze entire surfaces using adaptable estimation frameworks. The laser light is directed from the device to the target object.Due to the vibration of the surface, the frequency and the vibration amplitude can be obtained from the reflected laser beam intensity.

2. Electromagnetic Shaker

Figure 3. 4: Electromagnetic Shaker

Electrodynamic (ED) shakers are well designed for vibration analysis and offer many advantages over alternative techniques. ED shaker produces significant higher of frequencies as compared to hydraulic shaker. When analyzing electronics and electronic devices these high frequencies can be very obvious. In addition to general vibration testing, ED shakers are also capable of duplicating a broad range of shock and SRS pulses. At last, ED shaker can be controlling the test of vibration easily because of its linear behaviour.

3. DPO4000 Series Digital Phosphor Oscilloscopes

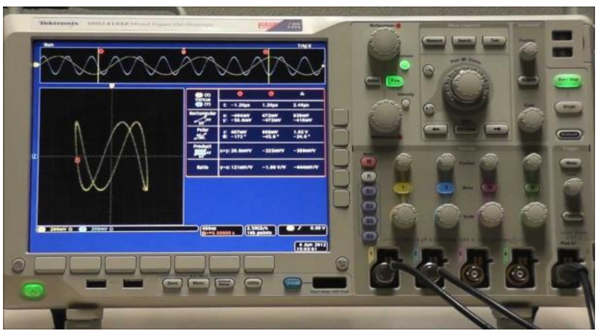

Figure 3. 5 : DPO4000 Series Digital Phosphor Oscilloscopes

The DPO4000 Series Digital Phosphor Oscilloscopes have equipped with the function of USB plug 'n' play process and PC connectivity. To obtaining data and measurements from the device can be easily done by link a USB cable from the oscilloscope to the PC. Based on the software which contain NI LabVIEW SignalExpress™ Tektronix Edition LE, OpenChoice® Desktop, and Microsoft Excel and Word toolbars allow fast and easy direct communication with Windows PC. Transferring of screenshot, instrument setting and waveform data can be done by pressing the device after the plug in of USB. The front panel have a play/pause button with function of rolling the waveform across the screen automatically. Intuitive pan knob was used to control the rerun speed and track.

4. Function Generator

Figure 3. 6: Function Generator

The overall work of the function generator creates sine, square , triangle, ramp and pulse output. A broad range of parameters can be produced by function generator. When the Function Generator includes Direct Digital Synthesis (DDS), a particular cycle of the standard output signal is accessed through the look-up table, and the system selects samples from storage to conduct the continuous spectrum at specific frequencies instead of developing all waveform samples.

5. Power Amplifier BAA 60

Figure 3. 7: Power Amplifier BAA 60

The digital power amplifier BAA 60 TIRA has been designed for the regulation of acceleration hardware implementations with a limitation of 60 VA. The maximum power of the RMS is calibrated with a load impedance of 4 Ohm. The power amplifier frequency varies from 40 Hz to 10 kHz at maximum power or with compact power from 5 Hz to 100 kHz with minimal harmonic distortion. The system performs highly stable performance within the quantified voltage and temperature spectrum, and is thus incredibly effective. The current RMS performance restriction can be adjusted.

6. Piezo-Ceramic Transducers

Figure 3. 8: Piezo-Ceramic PIC 155

High technology PIC 155 ceramics convey sound one step ahead advanced metals used in conventional transducers. Ceramically stacked high frequency piezoelectric transducers are formulated to fulfill the requirements of high-tech applications where submicron cleaning is the demand. Greater sound transmission at higher frequencies that lead to improved removal of impurities and minimized damage to sensitive parts. This sophisticated filtration technology has the advantage of mutually beneficial filtration applications. Piling a piezoelectric ceramic transducer to a certain frequency results in a dramatically improved operation level and avoids degradation to delicate metal stacking-related pieces.

3.5 Test Setup

3.5.1 Test Specimen Preparation

A test specimen with the fatigue crack is required to conduct the non-linear vibro acoustic. In this experiment, an aluminium pipe Al-6061 with 102.3mm internal diameter, 114.3mm outer diameter, 6mm wall thickness and 1000mm length is used as the test specimen. The material properties of the aluminium pipe used in this experiment as displayed in Table 3.1. Al-6061 is a high strength aluminium alloys and have excellence resistance of fatigue. Normally, this material Al-6061 is applied in aircraft structural component, yacht construction, automotive parts and aluminium can for packaging. This aluminium pipe Al-6061 has the criteria as such 2 700 kg/m^3 , Young's Modulus with 68 900 MPa and Poisson's ratio with 0.33.

Property Name		Details
Material	Name	Aluminium Al-6061
	Density	2 700 kg/m^3
	Young's Modulus	68 900 MPa
	Poisson's ratio	0.33

Table 3. 1: Material properties of aluminium pipe

3.5.2 Crack Slot Preparation

A 2mm width of crack is created in the middle of the aluminium pipe as illustrated in Figure 3.9. Milling drill with 2mm diameter is used in milling machine as shown in Figure 3.10 to produce the crack. Milling is the operation of machining using rotary cutters to eliminate material by inserting a tool into a piece of work. This can be achieved by changing directions on one or more axes, cutting head speed, and pressure. The milling machine comes with tolerances of + /-0,005 which can be accomplished and with complicated structures and thin walled configurations without disruption.

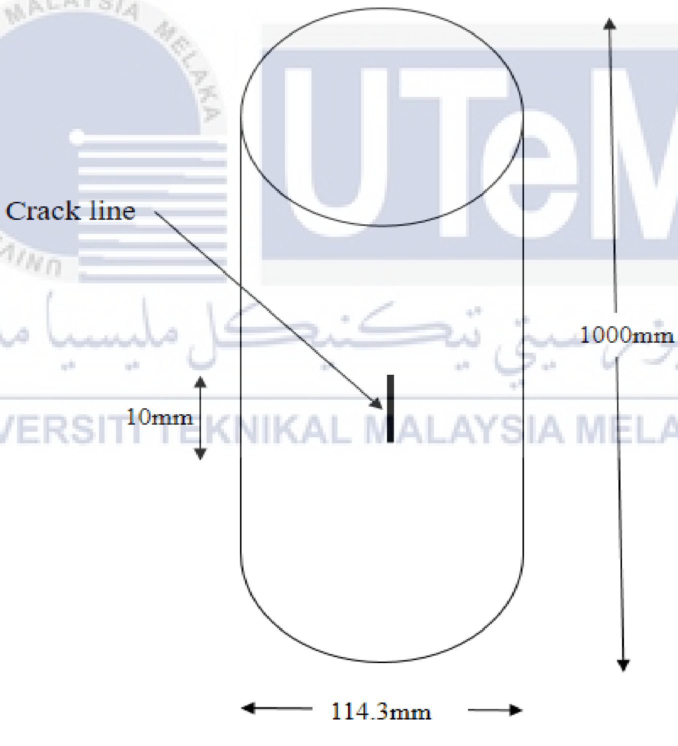

Figure 3. 9 : Schematic diagram of the aluminium pipe

Figure 3. 10 : Milling machine

3.6 Modal Analysis

Experimental modal test was conducted to identify the natural acoustic characteristics or material's dynamic response, mode of vibration and every mode shape. Besides that, imposing an excitation into the mechanism and locating the resonance frequencies are also involved in modal analysis. A 100V swept sine signal, initiating at 1Hz and raising to 2000Hz within 2s use to excite the unslot test specimen. The aluminium pipe is attached to the electrodynamics shaker by using the stinger to ensure there is no gap between the connection. The laser beam from Digital SWIR Scanning Laser Doppler Vibrometer (SLDV) is directly point to the surface of aluminium pipe to measure the output signal from the excitation. Function generator is used to control the low-frequency signal while the electromagnetic shaker operates as a low-frequency signal that is amplified by an instrument called a power amplifier. While the vibration response has been detected and collected by the SLDV will be sent to the oscilloscope. A experimental setup for modal analysis is shown in Figure 3.11.

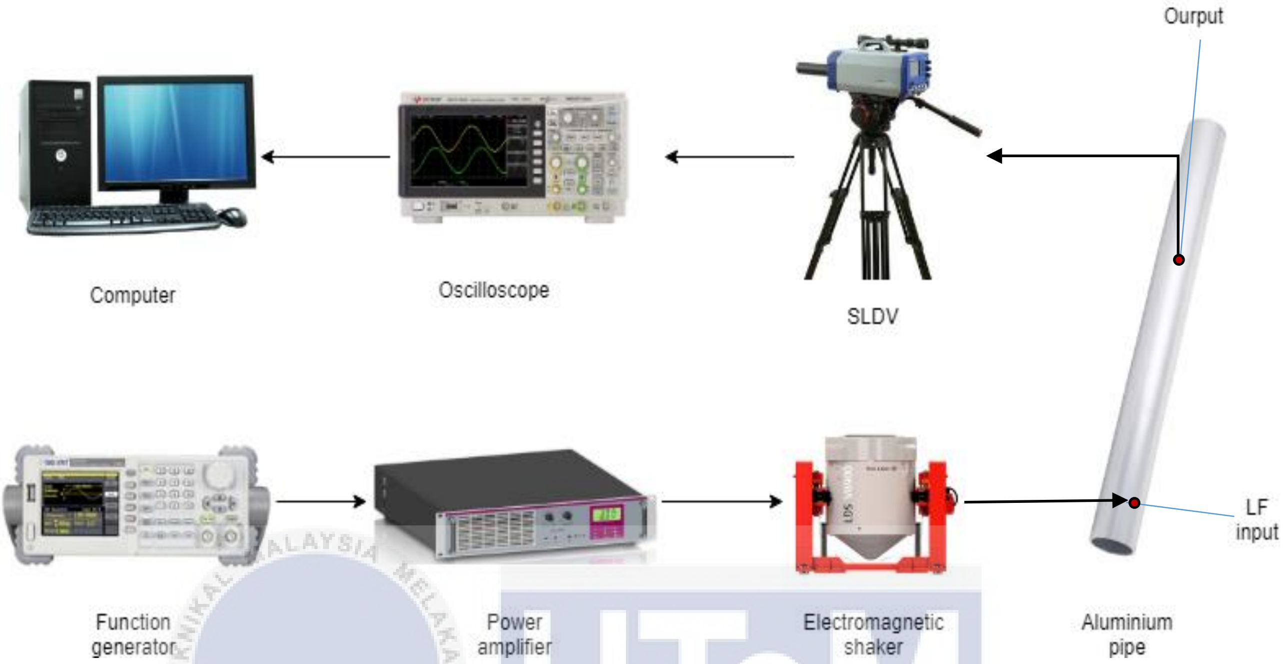

Figure 3. 11 : Schematic diagram of modal analysis experimental setup

3.7 Non-linear Vibro Acoustic Modulation Test

The non-linear vibro acoustic modulation test is conducted using the similar aluminum pipe which slotted after the modal test has been completed. During undergoes non-linear vibro acoustic modulation, the point of measurement used the similar area but with different slot dimension from the piezoceramic transducer (PZT). This is to fulfill the goal of the slot dimension analysis of the non-linear vibro-acoustic modulation test. The nonlinear vibro-acoustic modulation is a methodology that mixes extreme low-frequency (modal) signal with high-frequency ultrasonic pulse. The test specimen hanged by using a pair of string. An electromagnectic shaker function as a low frequency exciter whereas a piezoceramic transducer is functioning as the high frequency input. A function generator produces the excitation waveform and a power amplifier has been used to amplify the shaker's signal. A schematic diagram of the experimental arrangement has been seen in Figure 3.12. Figure 3.12 displays the aluminum pipe with 60kHz High Frequency (HF) ultrasonic wave input power, which has the greatest fault response in the system. At the same time, the low frequency (LW) input frequency was introduced to the pipe which attached with piezoceramic by electromagnectic shaker. The output data in the time domain format was created from the oscilloscope, and then transferred to FFT using MATLAB software.

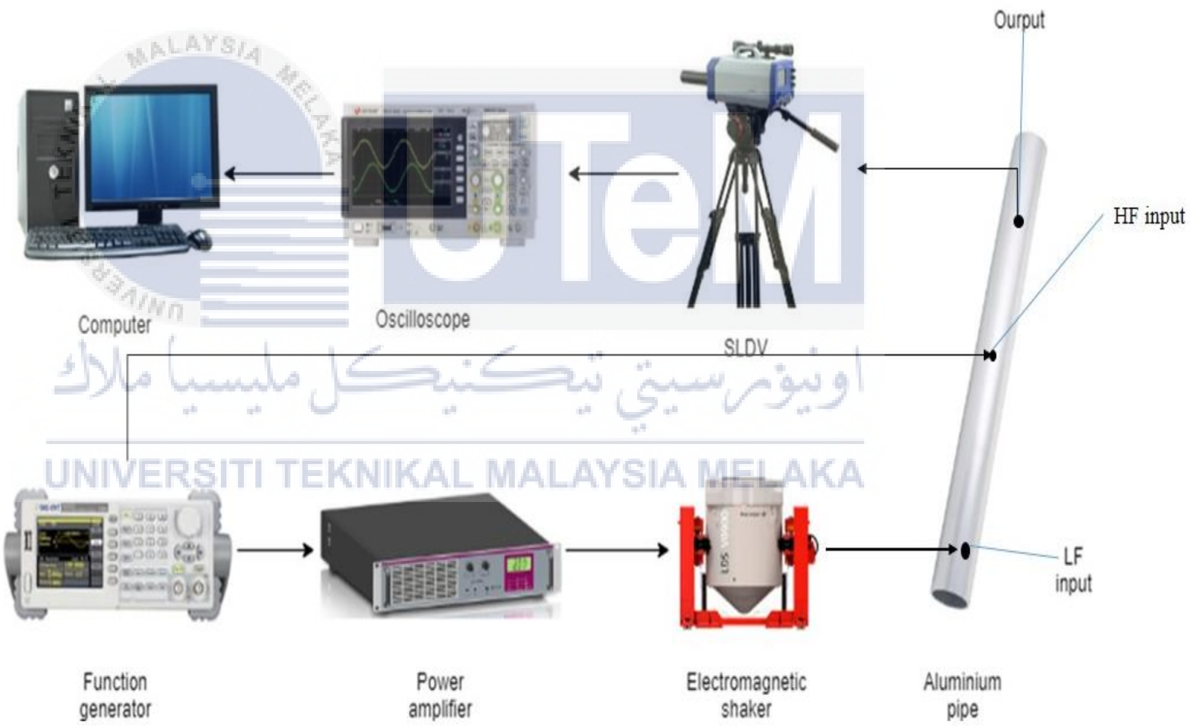

Figure 3. 12 : Schematic diagram of vibro-acoustic test.

3.8 MATLAB

MATLAB (matrix laboratory) is a programming language of professional level for numerical computation, visualization and networking technology. MATLAB also offers an immersive framework for the discovery, creation and problem solving in iteratives. It equipped with a built-in graphics for data visualization, and custom plot creation tools. MATLAB 's programming software offers development tools to enhance quality of code and optimize performance. MATLAB enables manipulation of matrix; functions and data plotting; algorithm implementation; user interface creation; communicates with programs programmed in different languages such as C , C++ , Java, and FORTRAN; interpreting data; designing algorithms; and performing calculations and applications. MATLAB usually applied as a analytical resource in science and engineering, including the fields of research, chemistry , mathematics and other technological processes.

CHAPTER 4

RESULT ANALYSIS AND DISCUSSION

4.1 Modal Analysis Test

A 100V swept sine signal, initiating at 1Hz and raising to 2000Hz within 2s use to excite the test specimen. SLDV capture and record the vibration response. Transfer function in MATLAB software is applied for converting the recorded data to frequency domain. The Frequency Response Function (FRF) graph is usually applied in modal analysis to determine the peak response of the resonant frequency of the system shown in Figure 4.1. Input excitation and output response are measured simultaneously by the frequency domain.

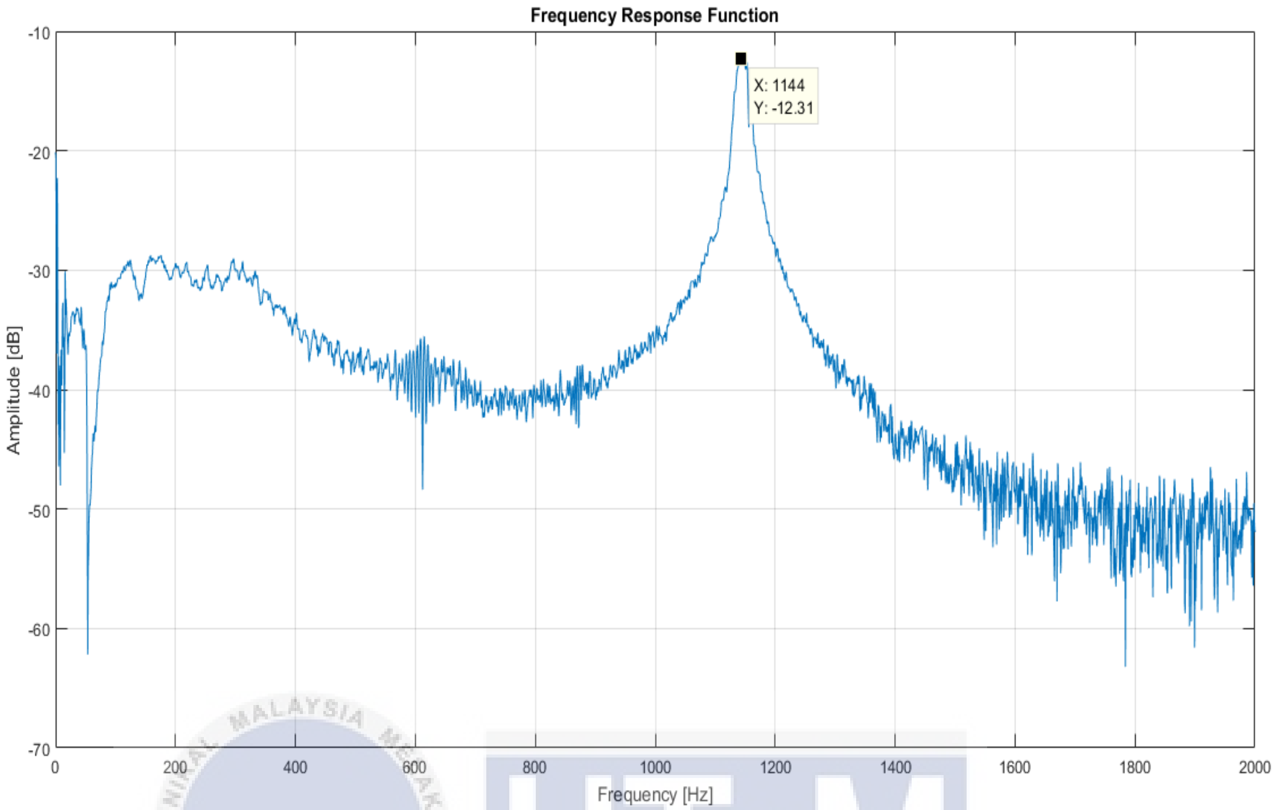

Figure 4. 1: Modal analysis result for vibration Frequency Response Function (FRF) of slotted (10mmx2mm) aluminium pipe

From the Figure 4.1, the graph shown the modal analysis result for slotted (10mm x 2mm) aluminium pipe which the laser point on the specimen 50mm around above and below from the middle of slot. There were only one peak as shown in the graph which were 1144Hz and this data used to apply in vibro-acoustic test. The only peaks value was selected to apply for the low frequency (LF) signal in vibro-acoustic analysis as shown in table 4.1. There are other external vibrations that may cause the resonant frequency including the room temperature and noise, which is one of the challenges during the experiment. A solution to solve this is to set up a test in a controlled situation so no external vibrations will influence the experiment. Some possible approaches are to do the research study or simulation.

Vibration Mode	Frequency (Hz)
1	1144

Table 4. 1: Vibration mode and frequency value for slotted aluminium pipe FRF

4.2 Non-Linear Vibro Acoustic Test

The experimental technique has been mentioned previously in part 3.7 was conducted to evaluate the non-linear vibro-acoustic test. Vibro-acoustics were conducted on a 10 mm x 2 mm damaged aluminum pipe using the modal frequency reported in section 4.1 with varying depths of 1 mm, 3 mm (half depth) and 6 mm (thru-pipe) respectively.

There was only one vibration mode was applied for the vibro-acoustic test which is 1144Hz that was used as a low-frequency excitation arising from the modal test experiment. The resulting signal response can be converted to an amplitude-to-frequency graph using the MATLAB program. The sideband of the spectrum is clearly stated for the occurrence of a damaged pipe. Then, the modulation intensity was tracked by using the parameter R defined as

$$R = \frac{A_1 + A_2}{A_0}$$

Where A_0 is the spectral amplitude of the carrier acoustical frequency, A_1 and A_2 are the spectral amplitudes of the first pair of sidebands.

The value differences of first and second spectral amplitudes A_1 and A_2 with the spectral amplitude of the carrier acoustical frequency should be identical with the low excitation frequency value. Therefore the signal is acknowledged as accurate data. Figures below shows the FRF graph of slotted aluminium pipe with different depth size for the 1144Hz excitation vibration mode.

i. 1mm depth

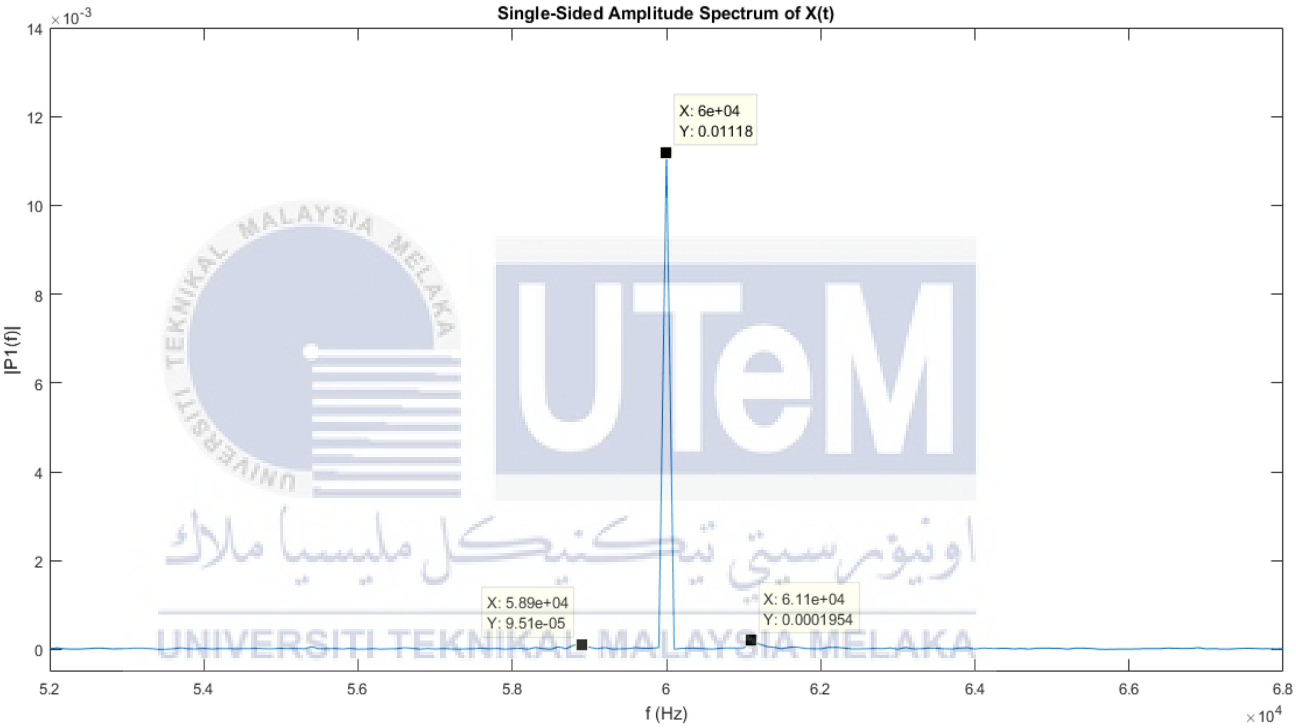

Figure 4. 2: Graph of FRF for slotted aluminium pipe with 1mm depth

Peak No.	Amplitude value
A_0	0.01118
A_1	0.0000951
A_2	0.0001954

Table 4. 2 : Amplitude value for FRF Graph of slotted aluminium pipe with 1mm depth

Calculate R-value by using

$$R = \frac{A_1 + A_2}{A_0}$$

$$= \frac{0.0000951 + 0.0001954}{0.01118}$$

$$= 0.02598$$

ii. Half-depth 3mm

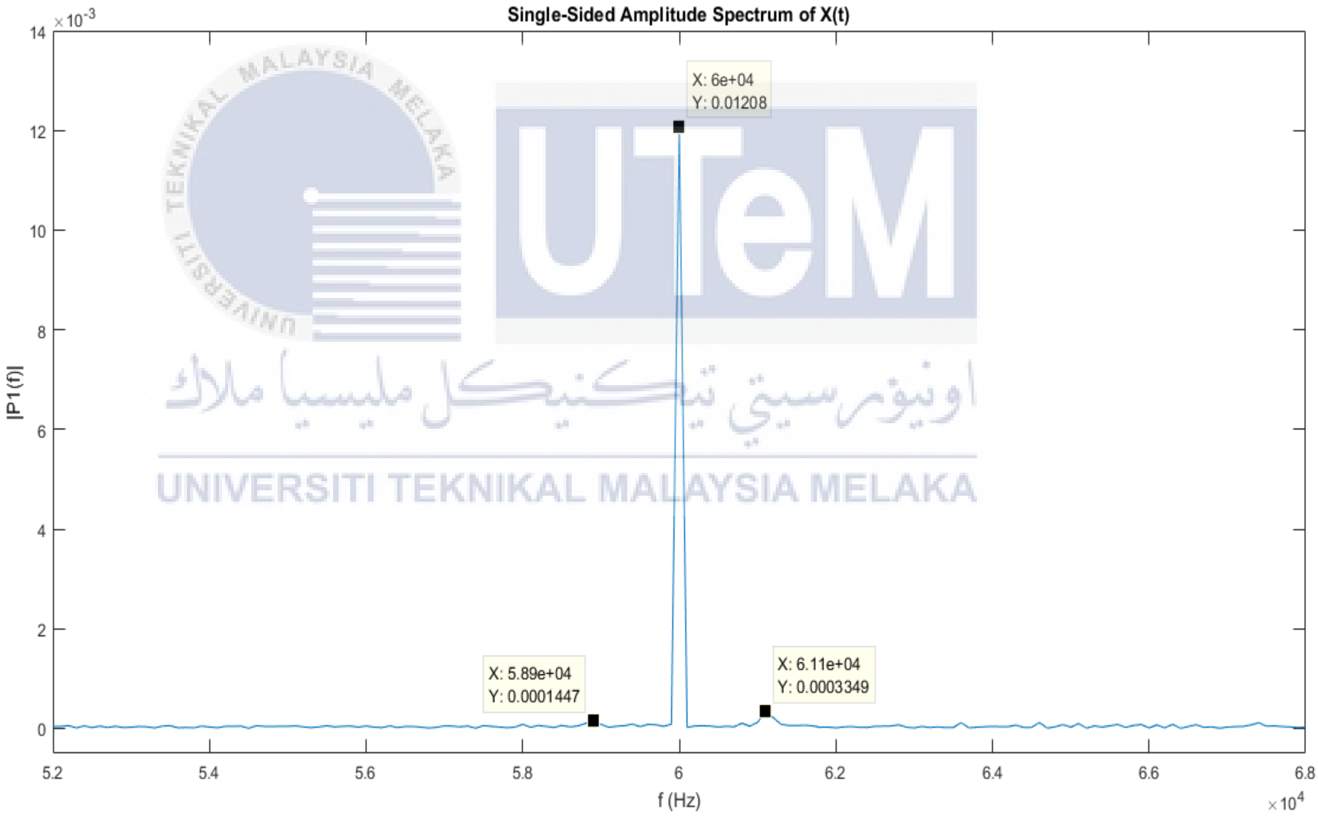

Figure 4. 3 : Graph of FRF for slotted aluminium pipe with half-depth 3mm

Peak No.	Amplitude value
A_0	0.01208
A_1	0.0001447
A_2	0.0003349

Table 4. 3 : Amplitude value for FRF Graph of slotted aluminium pipe with half-depth 3mm

Calculate R-value by using

$$R = \frac{A_1 + A_2}{A_0}$$

$$= \frac{0.0001447 + 0.0003349}{0.01208}$$

$$= 0.03970$$

iii. Thru-pipe depth 6mm

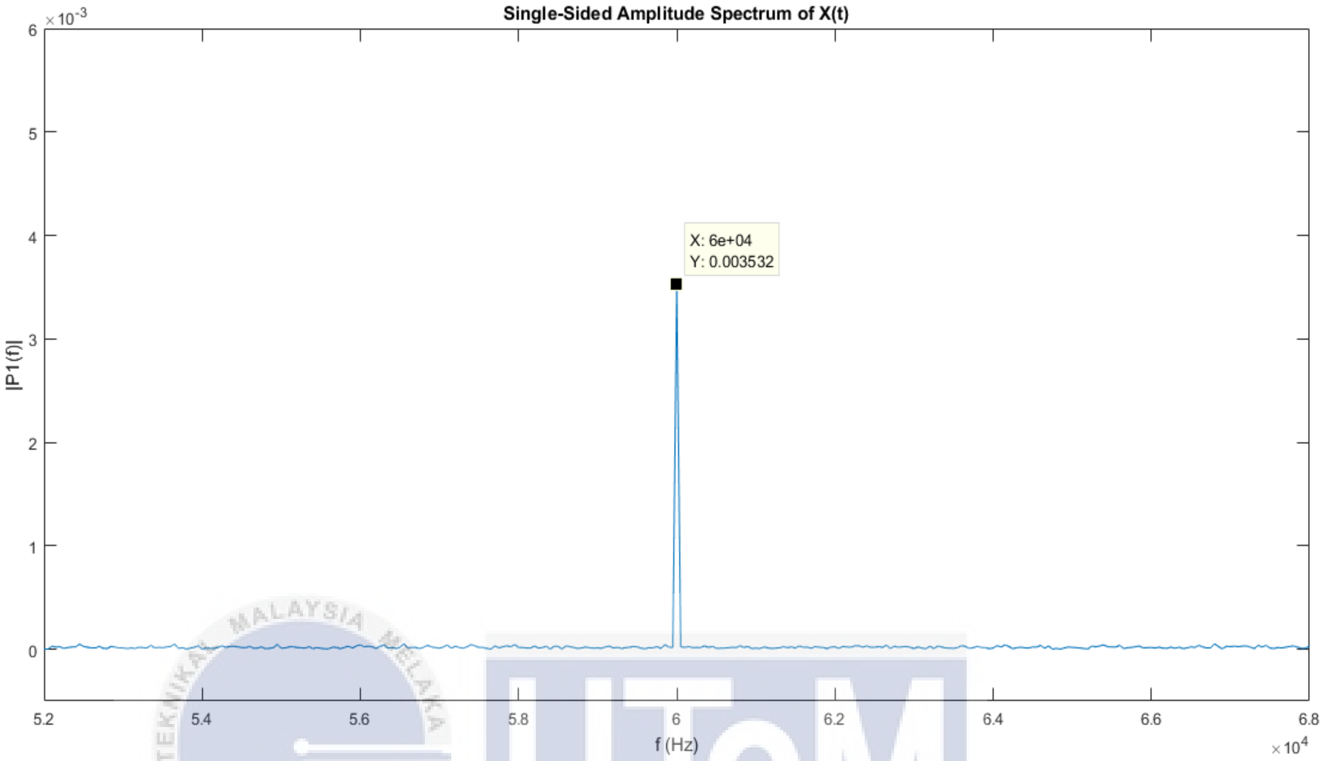

Figure 4. 4 : Graph of FRF for slotted aluminium pipe with thru-pipe depth 6mm

4.3 Analysis of Non-Linear Vibro-Acoustic Test

From Figure 4.2 to Figure 4.4 illustrates the FRF graph for slotted aluminium pipe with different depth of 10mm x 2mm. Amplitude modulation has been found on the damaged aluminium pipe because of the ultrasonic wave which is modulated by the low frequency vibration wave as shown in the figures. The measured vibration response signal spectrum demonstrates only significant fundamental frequency when no damage has been detected while a pair of sidebands or harmonic will occur around the fundamental frequency when damaged has been detected as explained in previously chapter. Figure 4.2 and Figure 4.3 showed that a pair of sideband around the 60kHz fundamental frequency. The gap between the fundamental frequency excitation and the low frequency excitation with 1144Hz was clearly shown. But for the Figure 4.4 there is only the 60Hz fundamental frequency and no sidebands found.

4.4 Discussion

The pair of the sideband are not obviously to be observed when using low amplitude level. In this experiment, the amplitude level from 2Vpp, 4Vpp, 6Vpp, 8Vpp and 10Vpp had been used. But the pair of small sidebands had been clearly observe when using 8Vpp and 10Vpp in the 1mm depth and half-depth with 3mm respectively while no sideband observed for the thru-pipe depth with 6mm. R-value has been calculated by using the formula given for the purpose of determine the relationship between the depth variable and modulation intensity (R-value). From the calculation result obtained, there are slightly different of the R-value of 1mm depth and half-depth 3mm which is 0.02598 and 0.03970. There was an increase of the R-value when the depth increases. Due to the lack of available data, the graph of R-value against depth variable was unable to perform smoothly in this study. However, it can be inferred that the vibro-acoustic modulation method is appropriate to identify the defect occur in the aluminium pipe. This can be achieved by studying the sidebands found in the spectrum, which is the amplitude modulation signal on the wave that travels through the slot on the aluminium pipe.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The purpose of this project is to perform the non-linear vibro acoustic test at aluminium pipe with different slot size in detecting the fatigue crack and to determine the relationship between the slot size and the effect of fatigue crack. As a conclusion by using non-linear vibro acoustic modulation method is a suitable method for identify the defect occur in the aluminium pipe. This can be achieved by studying the sidebands found in the spectrum, which is the amplitude modulation signal on the wave that travels through the slot on the aluminium pipe. The experimental result showed that with an increase of depth will slightly increase the R-value.

After the whole research has been carried out, a set of recommendations may be provided for the upcoming project. Firstly, the experimental data taken for the depth variable should be more than five for a better graph plot usage. Besides that, simulation analysis should be performed in order to evaluate the forms, frequencies and position of the mode in order to cause excitation by using Finite Element modeling before experimental study is carried out.

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APPENDIXES

Appendix A - 1

MATLAB code for determining modal analysis of the aluminium pipe

```
clear;

clc;

in1=data(:,1);

out1=data(:,2);

in2=data(:,3);

out2=data(:,4);

in3=data(:,5);

out3=data(:,6);

in4=data(:,7);

out4=data(:,8);

in5=data(:,9);

out5=data(:,10);

fs=20000;

[TF1,f]=tfestimate(in1,out1,[],[],[],fs);

TF1dB=20*log10(abs(TF1));
```

```
[TF2,f]=tfestimate(in2,out2,[],[],[],fs);

TF2dB=20*log10(abs(TF2));

[TF3,f]=tfestimate(in3,out3,[],[],[],fs);

TF3dB=20*log10(abs(TF3));

[TF4,f]=tfestimate(in4,out4,[],[],[],fs);

TF4dB=20*log10(abs(TF4));

[TF5,f]=tfestimate(in5,out5,[],[],[],fs);

TF5dB=20*log10(abs(TF5));

TFavg=(TF1+TF2+TF3+TF4+TF5)/5;

TFdBavg=(TF1dB+TF2dB+TF3dB+TF4dB+TF5dB)/5;

plot(f,TF1dB);

xlabel('Frequency [Hz]');

ylabel('Amplitude [dB]');

title('Frequency Response Function');

grid on;

hold on;

xlim([0,60000]);

hold off;
```

Appendix A – 2

MATLAB code for determining fast fourier transform (FFT) of the cracked aluminium pipe

```
t1 = highfreq(:,1) ;

amp1 = highfreq(:,2) ;

t2 = highfreq(:,3) ;

amp2 = highfreq(:,4) ;

t3 = highfreq(:,5) ;

amp3 = highfreq(:,6) ;

t4 = highfreq(:,7) ;

amp4 = highfreq(:,8) ;

t5 = highfreq(:,9) ;

amp5 = highfreq(:,10) ;

tavg=(t1+t2+t3+t4+t5)/5

ampavg=(amp1+amp2+amp3+amp4+amp5)/5

L = length(tavg) ;

N = length(ampavg);

dt =(0.0000001) ;

Fs = 1/dt ;

%% Single-Sided Amplitude Spectrum of X(t)
```

```
Y = fft(amp1);

P2 = abs(Y/L);

P1 = P2(1:L/2+1);

P1(2:end-1) = 2*P1(2:end-1);

f = Fs*(0:(L/2))/L;

plot(f,P1)

title('Single-Sided Amplitude Spectrum of X(t)')

xlabel('f (Hz)')

ylabel('|P1(f)|')

xlim([52000 68000])

ylim([-0.0005 0.014])
```