EFFECT OF HIGH FREQUENCY INPUT LOCATION FOR CRACK DETECTION IN NONLINEAR VIBRO-ACOUSTIC METHOD

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This report is submitted
in fulfillment of the requirement for the degree of
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STUDENT'S DECLARATION

I declare that this project report entitled "Effect of High Frequency Input Location For Crack Detection in Nonlinear Vibro-acoustic Method" is the result of my own work except as cited in the references

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

SUPERVISOR'S 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 (Plant & Maintenance).

Signature :. ....

Name of Supervisor : ....

Date : ....

DEDICATION

I would like to dedicate this report to my family for being my supporter along the period of handling this Final Year Project. They have always encourage and advice me to do this research succesfully. Next, to my supervisor, Dr. Ruztamreen Bin Jenal that have been always guide me and willingly share his experiences regarding this project research.

ABSTRACT

Fatigue crack can occur due to the material failure to withstand when load is applied repeatedly. There are a few phases in fatigue life of crack; starting from crack initiation, crack growth and rapid fracture. Basically, from the crack motion, three type of crack modes are formed. Mode I is an opening mode. Mode II is mode of sliding. Mode III is mode of tearing. Even though, crack usually seen in smaller size. But, the growth of it can cause major failure of a structure. Therefore, it is essential to perform inspection in detail. Many methods can be used to detect a crack structure. This involve method of laser vibrometer, eddy current and acoustic emission. In this project, vibro-acoustic method is used for crack detection. Therefore, several step needed to be performed. This includes the process of test specimen preparation, modal analysis test and finally vibro-acoustic wave. Generally, the test specimen preparation involve process of material preparation, tensile test, and dynamic fatigue test. This process essential in way to create the crack on the aluminium plate. Next, the plate will be tested on modal analysis to identify the resonant frequencies of the structure. The resonant frequencies will later be used as the excitation of low frequency in the vibro-acoustic test. As for the acoustic signal, 60 kHz will be used in that test. This vibro-acoustic test is chosen to achieve the main objective of the research; to find the effect of high frequency excitation position in crack detection. The output signal formed is then will be transformed in frequency domain using MATLAB software. Finally, the analysed data result in this research proved that the position of high frequency input does not mainly effect the crack detection process.

ABSTRAK

Retak lesu boleh berlaku disebabkan oleh kegagalan bahan untuk bertahan apabila beban digunakan berulang kali. Terdapat beberapa fasa dalam hayat retak lesu; bermula dari permulaan retak, pertumbuhan retak dan kepesatan patah. Pada asasnya, dari gerakan retak, tiga jenis mod retak terbentuk. Mod I ialah mod pembukaan. Mod II adalah mod gelongsor. Mod III adalah cara terkoyak. Walaupun, retak biasanya dilihat dalam saiz yang lebih kecil. Tetapi, pertumbuhan ia boleh menyebabkan kegagalan utama struktur. Oleh itu, ia adalah penting untuk melakukan pemeriksaan secara terperinci. Banyak kaedah boleh digunakan untuk mengesan struktur retak. Ini melibatkan kaedah meter getar laser, arus pusar dan pancaran akustik. Dalam projek ini, kaedah vibro-akustik digunakan untuk mengesan retak. Oleh itu, beberapa langkah perlu dilakukan. Ini termasuk proses penyediaan ujian spesimen, ujian analisis modal dan akhirnya gelombang vibro-akustik. Secara umumnya, penyediaan ujian spesimen melibatkan proses penyediaan bahan, ujian tegangan, dan ujian dinamik hayat. Proses ini penting dalam cara untuk mewujudkan retak pada plat aluminium. Seterusnya, plat akan diuji pada analisis ragaman untuk mengenalpasti frekuensi salunan struktur. Frekuensi salunan kemudian akan digunakan sebagai pengujaan frekuensi rendah dalam ujian vibro-akustik. Bagi isyarat akustik, 60 kHz akan digunakan dalam ujian itu. Ujian vibro-akustik ini dipilih untuk mencapai objektif utama kajian ini; untuk mencari kesan kedudukan pengujaan frekuensi tinggi dalam pengesanan retak. Isyarat keluaran akan dibentuk kemudiannya akan diubah dalam domain frekuensi dalam menggunakan perisian MATLAB. Akhir sekali, data yang dianalisis hasil carian kajian ini membuktikan bahawa kedudukan masukan frekuensi tinggi tidak menjadi keutamaan dalam melaksanakan proses pengesanan retak.

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All praise to Allah S.W.T; Grateful to God as I had finished my final year project successfully as the time required. Without further ado, I would like to express my thankful to my supervisor Dr. Ruztamreen Bin Jenal for giving me an opportunity to do this final year project with him. He never tired in giving me an advice and guide me every time I encountered problems.

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LIST OF ABBEREVATIONS

FFT	Fast Fourier Transform
CWT	Continuous Wavelet Transform
NEWS	Nonlinear Elastic Wave Modulation Spectroscopy
TRA	Time Reversal Acoustic
MNLW	Modulation Nonlinear Lamb Waves
SHM	Structural Health Monitoring
TSP	Temperature Sensitive Paint
AE	Acoustic Emission
VAM	Vibro-Acoustic Modulation
PZT	Piezoelectric
FRF	Frequency Response Function

LIST OF SYMBOL

f_n	=	resonant frequency at n-th mode
m	=	mass of structure
k	=	stiffness of structure
A_0	=	ultrasonic amplitude
A_1	=	first sideband amplitude on the left of the ultrasonic spectrum
A_2	=	first sideband amplitude on the right of the ultrasonic spectrum
A_3	=	second sideband amplitude on the left of the ultrasonic spectrum
A_4	=	second sideband amplitude on the right of the ultrasonic spectrum

CHAPTER 1

INTRODUCTION

1.1 Background

Fatigue crack is common maintenance problem in industry application such as steam turbine (Bagaviev and Sheng, 2005) steel bridge (Ichinose, et.al, 2007) and beams (Eroglu and Tufekci, 2016). Fatigue crack occur due to compressive loads. The cyclic stress are below the ultimate tensile stress that also can be refer to the strength of the material. The word “fatigue” is relevant to materials cannot withstand or fails at the loads applied repeatedly. The fatigue failure or crack occurs in three phases which includes the initiation of crack, stable crack growth and rapid fracture. There are three form of crack modes which result from motion of a crack. These modes are opening mode (mode I), sliding mode (mode II) and tearing mode (mode III) which shown in Figure 1.1. Mode I form in way of crack face move directly apart from each other in y-direction. Next, mode II refer to a shear stress which are parallel to the plane of the crack and perpendicular to the crack front. Lastly, if the crack faces act perpendicular to the crack front, this is known as mode III.

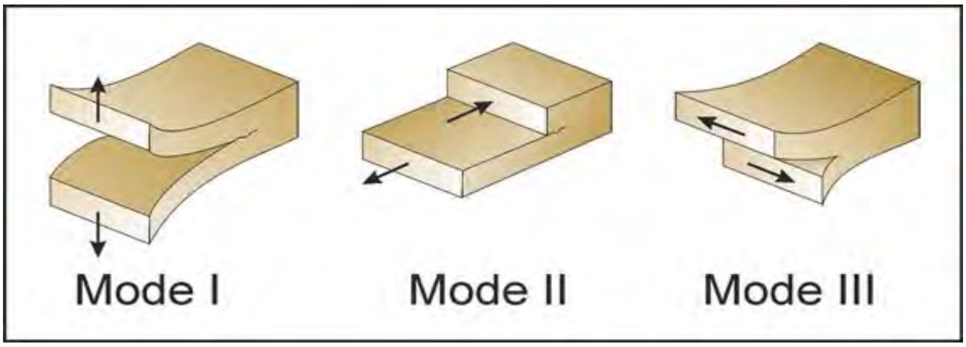

Figure 1.1: Fatigue crack modes.

1.2 Problem Statement

Vibro-Acoustic method technique is a method of introducing two signal frequencies in solid structure for crack detection. The two frequencies are high frequency acoustic wave and low frequency vibration mode. This techniques requires some parameters that can control the non-linear effect such as excitation location of high and low frequency and location of measurement point. However, there are still no detail study that show the effect of high frequency location for crack detection. Thus, this project is carried out to reveal the effect of high frequency location in presence of crack.

1.3 Objective

The objectives of this project is seek to:

1. Create a 20 mm crack at the middle of the plate.
2. Determine the effect of high frequency excitation location in crack detection by using vibro-acoustic method.

1.4 Scope of Project

The scopes of this project are:

1. The preparation of specimen which involve some process that includes cutting an aluminium plate with dimension of 400mm*150mm*2mm , drilling hole using EDM wire cutter, line cutting for fatigue crack initiation and fatigue crack creation.
2. Modal analysis for determination of natural frequency and mode plates and which require an experimental works, theoretical and calculation.
3. Vibro-acoustic test to evaluate the correlation between parameters involves and the nonlinear effect in damage detection.

CHAPTER 2

LITERATURE REVIEW

2.1 Damage in Structure

In diagnose the structural damage, an approach of signal based pattern is determined. Each type of damage will form a unique pattern of itself. This studies in observing the features of frequency-based and time-frequency based. This two features is obtained from vibration signals that form through fast fourier transform (FFT) and continuous wavelet transform (CWT). In comparison of CWT and FFT, CWT have higher resolution of pattern matching because of the preservation of time sensitive and time. (Qiao et al., 2012).

Discontinuity is one of damage in structure where there is a nonlinear dynamic structures. The development of discontinuity in cracked bar can be analysed using nonlinear integral equations and Matlab-Simulink computation (Babitsky and Hiwarkar, 2016).

Damage in plate structure can be detected using Lamb wave and time reversal theory. The complicated of Lamb wave propagation are due to dispersion and multimode feature. Based on this application of time reversal method and propagation of Lamb wave provide clear image of damage and crack position can be detected (Liu et al., 2012).

2.2 Fatigue Crack

(Masserey and Fromme, 2013) states "the growth of fatigue crack can be monitored by using laser interferometer." It has high accuracy which can detect defects of medium with long distances. The propagation of high frequency guided ultrasonic wave can be delivered as a Rayleigh wedge transducer is use for excitation. The growth of fatigue crack can result in signal changes.

Next, the thickness of a crack can be analysed and studied through the Lamb wave propagation. Transmission and reflection mode conversion show the interaction of Lamb waves and crack. This mode of conversions are used to calculate the time domain and frequency coefficients. As result, as the crack length increase, the coefficient of transmission will be decreased. Plus, the diffraction of wave is vital in coefficient of transmission when there is short crack length (Lu et al., 2008).

An aluminium alloy plate in presence of crack can be studied through the combination of nonlinear elastic wave modulation spectroscopy (NEWS) and time reversal acoustic (TRA). The purpose of this methods combination are for better focussing the elastic wave of a crack. PZT transducer were used as the source of excitation and using equipment such as laser vibrometer, computer and digital oscilloscope (Gao et al., 2011). There is also a combination of modulation nonlinear lamb waves (MNLW) and time reversal method in determination of crack on aluminium alloy plate. Basically, the equipment used is the same as combination methods of NEWS and TRA. In this duo-technique, there is a presence of harmonics and sideband which indicate the crack in sample. Meanwhile, no occurrence of harmonics and sideband in uncrack sample (Guili et al., 2012).

There is a study of performance of patch repair between composite and metallic patches of crack aluminium plates under fatigue loading. Therefore, each type of patch will be conducted through fatigue test and the growth of crack behaviour will be analysed. The result show that the fatigue life of aluminium plate when patches with metal material lower than composite patches; even though metallic patches are weaker than composite (Saeed and Abid). There is numerical tool to study the propagation of fatigue crack in aluminium plates when repaired it with composite patch. The tool involve is finite element analysis and ABAQUS software. Through this method, parameter such as stress intensity factor can be determined (Maligno et al., 2013).

In studies of turbine blade application, in monitoring condition, parameter of natural frequencies should be considered. This is essential to determine the conditions and fatigue life time of blade turbine (Lecheb et al., 2013).

2.3 Method to Detect Fatigue Crack

The development of structural health monitoring (SHM) increasing in demand of accurate fatigue crack detection. This include the method of elastic wave.The initiation of fatigue crack of shell structure can be detected through the propagation of elastic wave. The detection of fatigue crack normally being observed near the hole. The analysis of this technique is based on frequency domain and time (Stawiarski et al., 2016).

A nonlinear acoustics method of damage detection involve classical and non-classical type. The non-classical type consist of propagation of elastic wave and wave interaction with damage. It has a good sensitivity and also can applied to undamaged structures, structural damage and structural joints. Example of phenomena of nonlinear vibration is open and closes of crack under dynamic loading (Pieczonka et al., 2016).

Next, the technique of laser ultrasonic is applied through propagation of Rayleigh wave in aluminium crack plate inspection. As result, higher number of components with low frequency will be obtained as the increasing crack depth. So, the characteristic of fatigue crack is depend on the changes in signal amplitude and centre frequency (Zhao et al., 2013).

Eddy current is an electromagnetic technique which can also be use in crack detection. This technique can be applied to weld metal such as steel bridges which can go through the conductive and paint coatings. Basically, eddy current can be as method of bridge inspection (Ichinose et al., 2007).

(Caizzone and DiGiampaolo, 2015) states that "In demand of using rapid tools in tracking structural damage; there is an increasing of using structural health monitoring (SHM) system. There were three type of category involve in this system. First, regarding the coupling of some local sensors and structural elements which include accelerometer, ultrasonic devices and fiber optics. Second, regarding on bringing instrumentation to demand of measurement site which consists of laser scanning, X-ray and infrared thermography. Lastly, based on the long distance of sensor to infrastructure site include the techniques of photogrammetry and interferometry. But, there are improvement of SHM systems that categorized in two groups regarding the in-situ monitoring techniques. This includes wired and wireless group. The wired group has great resolution and it is precise. However, there are a few lack found because of high cost, longer time of installation and complicated. In comparison, wireless group is a fast and easy installation. There were divided into active and passive technique. Active technique used battery powered and can be use in transmission of long distances. But, it is expensive and lifespan is limited that depend on the battery usage. Meanwhile, in passive technique, use environment as energy source and also during the wireless communication, powered read out unit is collected. It can be obtained with low cost and chipless; as example the RFID sensor. It is used in identification of enlargement crack through wireless technique."

The fatigue crack in aerospace structure application can be detected by using an optical technique; temperature sensitive paint (TSP) technology. The technology involve the temperature sensitivity and there is elimination of pressure sensitive as the dynamic fatigue increase. Electrodynamic transducer is used in this technology. The appearance of a crack can be the criterion of failure through this method (Banaszak et al.).

Another method to detect fatigue crack is through acoustic emission (AE). The fatigue crack will generate elastic wave by using a piezoelectric transducer that mounted on the surface. The amplitude of the wave modes differ in crack depth (Kin LEE et al., 2006). The effect of loading ratio is studied by using AE experiments which can be seen through the relationship of AE count rates and rates of crack growth (Keshtgar et al., 2013). In addition, the entropy of AE can also be used in determination of fatigue crack behaviour. The entropy o AE is estimate through time domain. This way of detection is useful in using the AE signal's amplitude (Amiri et al., 2015).

Vibrothermography is a transmission of mechanical wave technology that useful in detecting the hidden crack. It is very quick method; the presence of crack can be detected less than one second due to the quick propagation of ultrasound wave. Thus, it does not affect the higher rising of temperature of structure compare to implusive thermography. This technology is sensitive and can be applied to any metal cracks such as vertical cracks. However, it is a high cost and not precise in determine the location of crack depth (Rimare et al., 2012).

In comparison of acoustic emission (AE) and vibration technique on detection of bearing fault with three condition of different speeds. Result shows that AE signals will not present as the high frequency of above 50 kHz is involved. The AE signals has disadvantage where it has limitation on frequency. Thus, AE signals is not precise in diagnose small fault as the rotary speed slows down compare to the vibration techniques (Liu et al., 2011).

2.4 Vibro-acoustic Method

Vibroacoustic modulation (VAM) method is common used in crack detection where it is based on the low frequency vibration and high frequency acoustic wave. The sideband intensity correlated to the presence of damage. This study observing the Zhao-Atlas-Marks (ZAM) distribution in analysis of time-frequency. The result shows that the low frequency vibration modulate the amplitude of the sideband. Plus, the amplitude of sideband depend on the crack size (Trochidis et al., 2014).

Vibroacoustic modulation (VAM) also can be used to detect damage in composite materials. There are two conditions was determined in this study. First, opening and closing action due to the acoustic nonlinearity. Next, the frictional sliding which result from mechanisms dissipative (Pieczonka et al.).

Another method of structural health monitoring (SHM) system in detecting damage is through vibro-acoustic technique. It a non-classical technique type. It is has excitation combination of low frequency and high frequency. There will be two output of undamaged structure which is the excitation of low frequency and high frequency. However, if there is a damaged structure, a vibro-acoustic wave will appear. This wave will be observed as sideband pattern in ultrasonic response spectra (Dziedziech et al., 2016).

Vibroacoustic modulation (VAM) and low frequency of vibration damping are methods that used in detection of fatigue crack. They have similarities in both techniques which they are very sensitive to the baseline level of damping and they work best on low baseline damping. From this study, the sensitivity is same for both techniques; but, VAM is slightly sensitive than damping (Duffour et al., 2005).

Vibracoustic method can be used in many industrial application. This includes gas tubine engines. This method able to the hidden defect of composite parts and welds structures (Kochergin, 2016). Next, in honeycomb lightweight panels where this method is essential at early stage of design (Vivolo et al.). Then, followed by the high voltage electric power transformer. It purpose to see the vibroacoustic signals during process of switching electric power transformer. In this study, involve three cases which are non-defect transformer, slackened pressing screw of upper yoke and slackened pressing screw on upper and lower yoke beam (Zmarzly, 2014). It also useful in detecting the hidden canals and pipelines (Gaponenko, 2016).

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used in this project. The flow chart of the methodology which show the step of conducting this project research accordingly is shown in Figure 3.1. Firstly, the test specimen which specifically an aluminium plate need to be prepare. Secondly, the plate need to create a crack slot at the middle of the plate, followed by running the tensile test and fatigue test. Next, modal analysis test need to be carry out by an electrodynamic shaker on the plate. Lastly, handling the method of vibro-acoustic which is the main experiment in this project research.

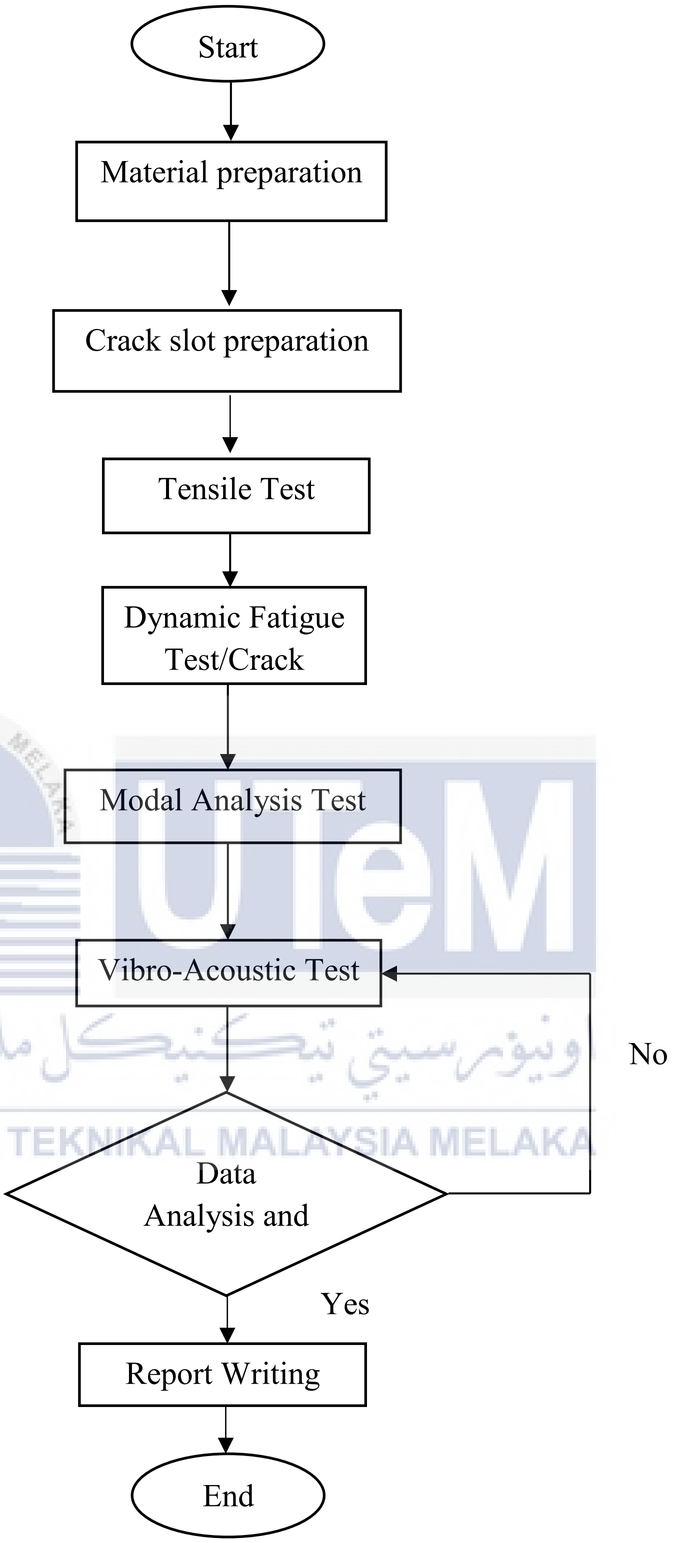

Figure 3.1: Flowchart of methodology.

3.2 Test Specimen Preparation

In preparation of test specimen, a few steps and tests need to be carry out before run the experiment project. This includes material preparation, crack slot preparation, tensile test, dynamic fatigue crack, modal analysis test and vibro-acoustic test.

3.2.1 Material Preparation

In this project, an aluminium plate is used as a specimen where its material properties is shown in Table 3.1. The plate dimension is 400mm x 150mm x 2mm. Therefore, to get the dimension, the cutting process is carried out by using hydraulic cutting machine.

Table 3.1: Material properties of an aluminium plate.

Property name		Details
Material	Name	Aluminium Al-2024
	Density	2780 kg/m^3
	Young's Modulus	72 400 MPa
	Poisson's ratio	0.33

3.2.2 Crack Slot Preparation

A hole at the centre of a plate is needed for crack initiation and to lock the plate into fatigue testing machine. So, the plate was drilled to make a hole with diameter of 1.5mm by using an EDM hole drilling machine as shown in Figure 3.2. There is a tolerance of ± due to the error of the machine. The hole was located at 200 mm x 75mm of the plate. It is basically was made to allow a line cutting process. An EDM wire cut machine that shown in Figure 3.3 is use for the line cutting process with 0.2mm wire. Thus, a crack slot was formed with measurement of 4mm line length and 1.5mm hole diameter as shown in Figure 3.4.

Figure 3.2: EDM hole drilling machine.

Figure 3.3: EDM wire cut machine.

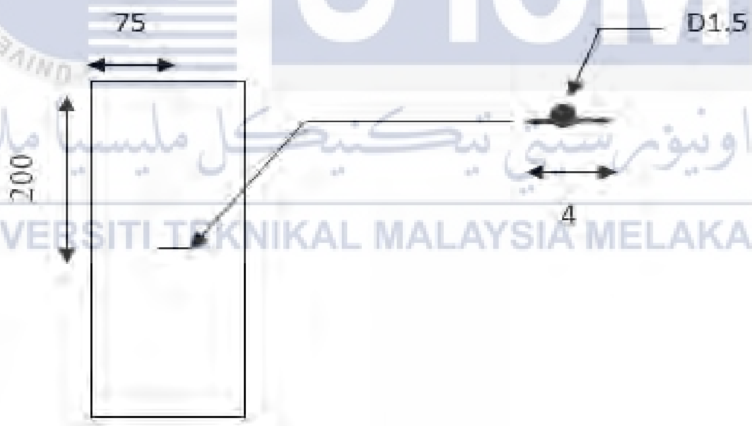

Figure 3.4: Creation of a slot on an aluminium plate.

3.2.3 Tensile Test

Tensile test is carried out in order to get the mechanical properties of an aluminium plate as shown in Table 3.2. This test is perform by applying an axial load to the standard tensile of aluminium plate until failure occurs. In stress and strain calculation, the load applied and extension need to be recorded.

Table 3.2: Mechanical properties of plate needed to carry out fatigue test.

	Yield load (kN)	Tensile stress at yield load (MPa)	Maximum load (kN)	Tensile stress at maximum load (MPa)	Tensile stress at break (standard) (mm)
1.	35.62	118.73	35.62	118.73	6.28

3.2.4 Dynamic fatigue Crack

A Universal Testing Machine (UTM) is use to create a crack. Generally, this process is known as fatigue test where specimen is subjected to cyclic loading to failure. Several mechanical properties are needed to carry out the fatigue test and to obtain a target crack length. This includes maximum, minimum, mean and amplitude load which can be calculated from data obtained in tensile test as shown in Table 3.2. Before carrying out the test, a gridline is made to let the test run smoothly. The size of a jigsaw with the size of 75mm x 150 mm is considered in the gridline measurement.

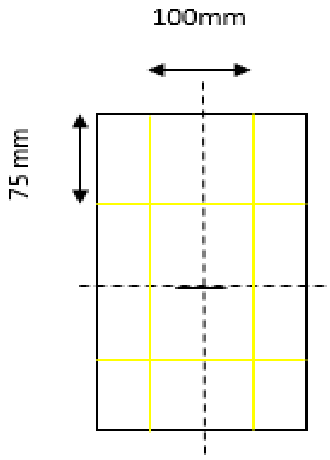

Figure 3.5: Gridline of aluminium plate for fatigue crack.

Figure 3.5 shows the gridline measurement of an aluminium plate.

3.3 Modal Analysis Test

Modal analysis is extremely important in determining the modal parameters (natural resonant frequencies and mode shape) of a cracked plate. The physical properties such as mass, damping and stiffness of a structure contribute in the mode formation. So, there will be a changes on modal properties if the physical properties of the structure is modified. Generally, there are four categories of excitation mechanisms which include shaker, impactor, self-operating and step relaxation. In this experiment, modal analysis is carried out by using modal shaker testing (electrodynamic) as shown in Figure 3.6. In this shaker system requires a power amplifier as a signal source. Piezoelectric (PZT) stack actuator is attach to the left corner edge at the back of the plate. The stack actuator position is at 17mm x 30mm and laser pointed at 75mm x 230mm of the plate structure. The frequency response of the system is measured through sweep signal excitation and followed with a raise of 10 Vpp by low PZT amplifier. There are also several input parameters required in this experiment which are shown in Table 3.3. The output signal from low frequency shaker will be transfer to the oscilloscope. Specifically, modal experiment is carried out through an input excitation that will be insert with certain frequency range on a point of structure. Next, the structure's response will be measured from a several output points which will be analysed from the plotted frequency domain. The frequency domain (frequency response function) will be transformed using MATLAB software.

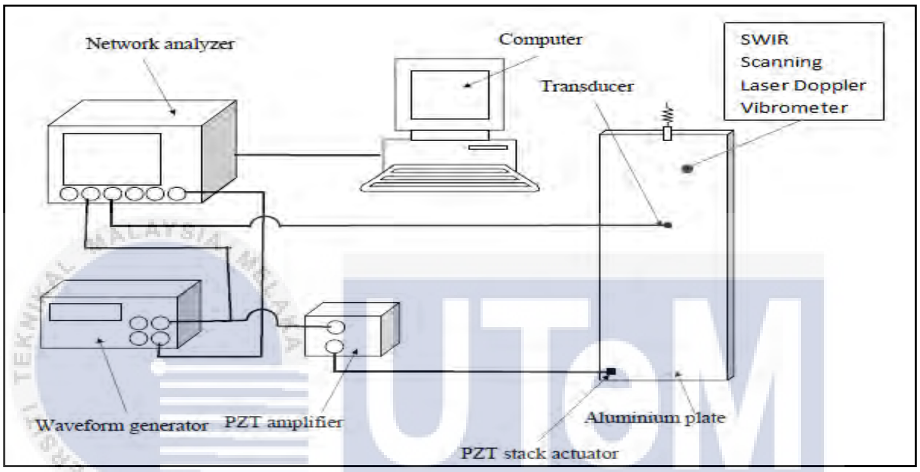

Figure 3.6: Experimental setup for modal analysis test.

Table 3.3: Input parameters needed in modal experiment.

Items	Parameter details
Sweep frequency	1 ~ 2000 Hz
Sweep time	2 s
Amplitude	10.0 Vpp
Sampling size	20 kS/s
Sampling	100 Ksample (3 sweep for one trigger)

3.4 Vibro-acoustic Test

Vibro-acoustic test is carried out after obtaining the natural frequency of the plate. This test is applied to get the correlation between the nonlinear acoustic modulations and test parameters (crack sizes, excitation level, and vibration modes excitation). The interaction of vibro-acoustic (low frequency pumping wave and high frequency probing wave) will form a sideband. Generally, this test is perform to examine the effects of nonlinear acoustic modulation that caused by the nonlinearities of a crack's plate. It is also performed as to find the relation of high frequency input location in crack detection. Therefore, 10 points of PZT transducer which will induce the high frequency input were selected to be tested in the experiment which can be shown in Figure 3.7. At the first column line which consisting of point 1, 2, 3, 4 and 5 in an ascending order. Meanwhile, on the second column line have point 6, 7, 8, 9, and 10 ascendingly which start from below crack formation area. The measurement of PZT transducer location is stated on Table 3.4. In preparation of PZT transducer; two cables need to be cut and solder carefully on the surface of piezo element. Then, it must be glued to attach it at the plate's surface.

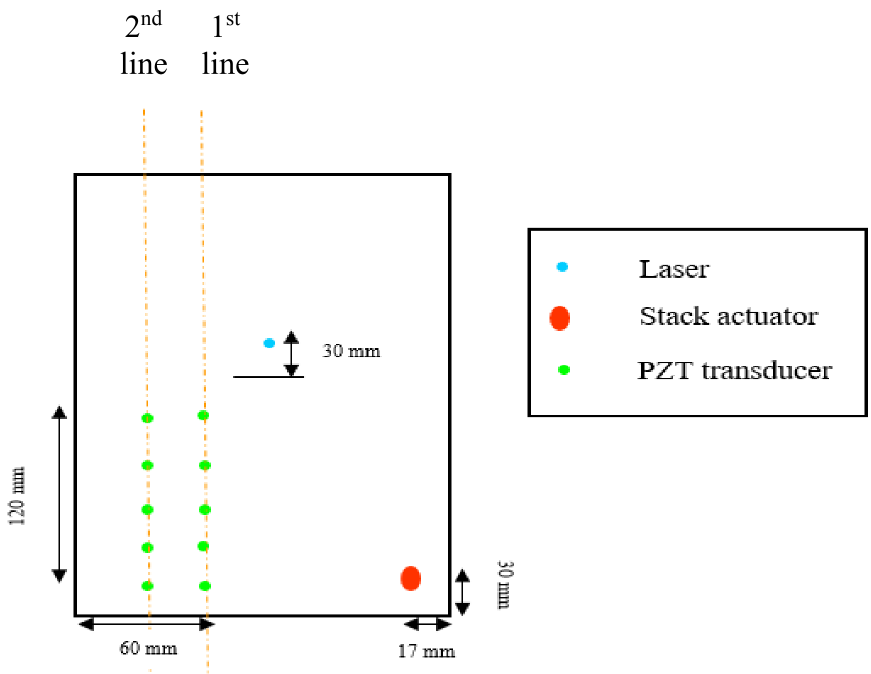

Figure 3.7: Layout of laser, stack actuator and PZT transducer on the aluminium plate.

Table 3.4: Points Location of PZT Transducer at y-axis.

Location	Point	Width * Length (mm)
At the right of the front surface of plate	1	51*235
	2	51*265
	3	51*295
	4	51*325
	5	51*355
	6	26*235
	7	26*265
	8	26*295
	9	26*325
	10	26*355

During the experiment, the plate will be hanged using a rope yarn and attached to stack actuator. The stack actuator function as for plate excitation at low harmonic frequency. Meanwhile, the transducer is used to acquire the plate vibration response. The 1st, 2nd and 3rd vibration mode frequencies were used for low-frequency vibration excitation and a fixed of 60 kHz ultrasonic wave was used by using a PZT transducer (high frequency input). Next, the vibration response is obtained using oscilloscope which the excitation signal have been generated using a waveform generator. The experiment setup can be seen in Figure 3.8.

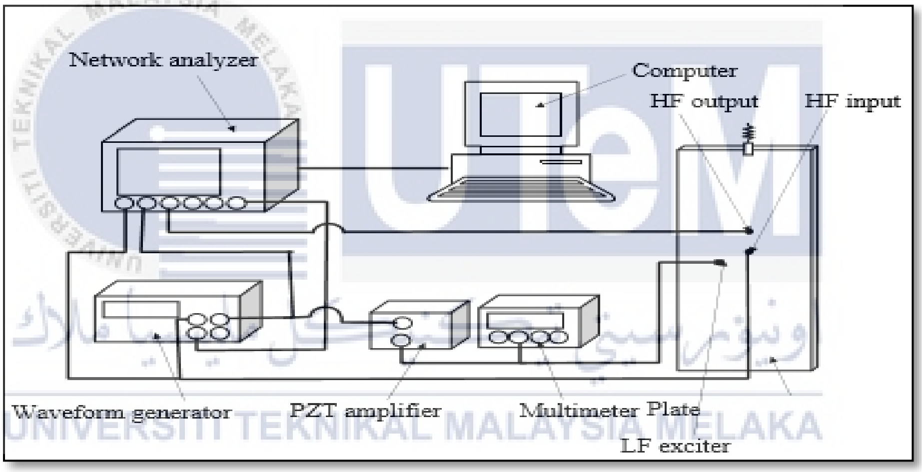

Figure 3.8: Experimental setup for vibro-acoustic test.

CHAPTER 4

DATA AND RESULT

4.1 Tensile Test

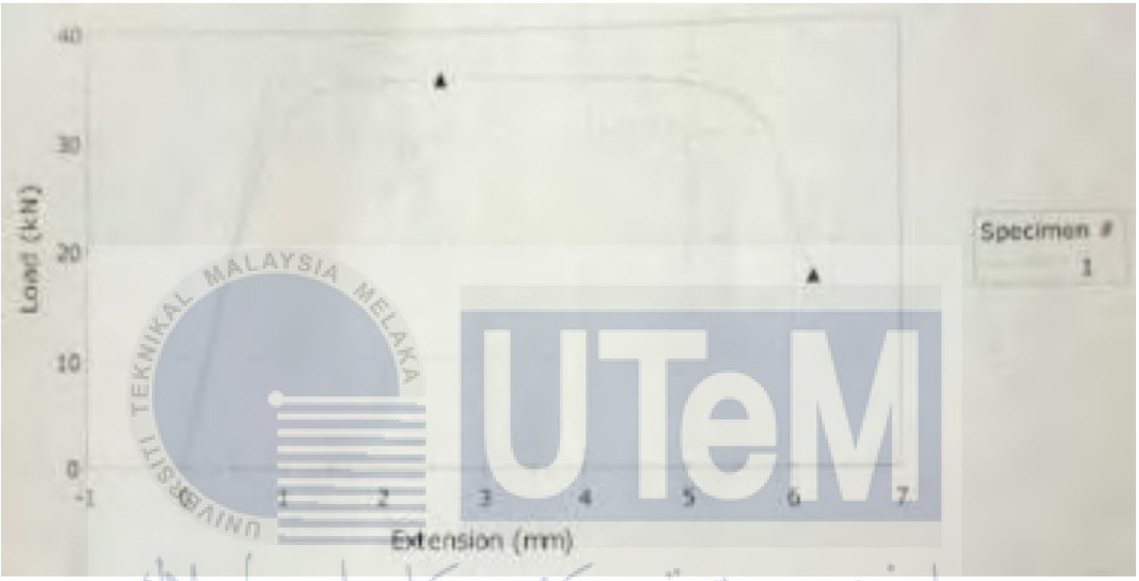

Figure 4.1: Graph of load (kN) and extension (mm).

Figure 4.1 shows the graph of applied load (kN) and extension (mm) for calculation of stress and strain. Next, Table 4.1 shows the data that is obtained from the tensile test.

Table 4.1: Data obtained from tensile test.

	Yield load (kN)	Tensile stress at yield load (MPa)	Maximum load (kN)	Tensile stress at maximum load (MPa)	Tensile stress at break (standard) (mm)
1.	35.62	118.73	35.62	118.73	6.28

Calculation involve in finding the value of maximum load, minimum load, mean load and amplitude load:

Maximum load = 75% of yield load

= 35.62 * 75%

= 26.715 kN

Minimum load = 0.1 of maximum load

= 26.715 * 0.1

= 2.6715 kN

$$\text{Mean load} = \frac{\textit{maximum load} + \textit{minimum load}}{2}$$

$$= \frac{26.715 + 2.6715}{2}$$

= 14.693 kN

$$\text{Amplitude load} = \frac{\textit{maximum load} - \textit{minimum load}}{2}$$

$$= \frac{26.715 - 2.6715}{2}$$

= 12.022 kN

4.2 Crack formation

The crack of aluminium plate was obtained after achieved 88633 cycle load amplitude with the frequency used is 10 kHz. Figure 4.2 shows the picture of front and back surface of a crack plate. The target crack length is 20mm. The crack formed accordingly from the crack slot.

(a) (b)

Figure 4.2: Picture of (a) front and (b) back surface of a crack plate.

4.3 Modal Analysis Test

Modal analysis usually is used to calculate the structures linear response to dynamic loading. The structures response will form several vibration modes which defined by its frequency and shape. The vibration modes and its natural or resonant frequencies can be shown in Table 4.2. The mass and stiffness of the structure will determine the resonant frequency itself. This relation can be proved through following equation:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (4\text{-}1)$$

Where

f_n: resonant frequency at n-th mode

m: mass of structure

k: stiffness of structure

However, this equation can be complicated for a thin plate structure. This is because this equation usually applied on a single degree of freedom of a simple mechanical system.

The graph of Frequency Response Function (FRF) commonly used in modal analysis to identify the peak response of the structure's resonant frequency which is shown in Figure 4.3. The frequency domain measure the input excitation and output response synchronously.

Table 4.2: Several vibration modes and its natural frequencies of cracked aluminium late.

Vibration mode	Natural Frequency (Hz)
1	67
2	90.5
3	111.5
4	130
5	197
6	206.5

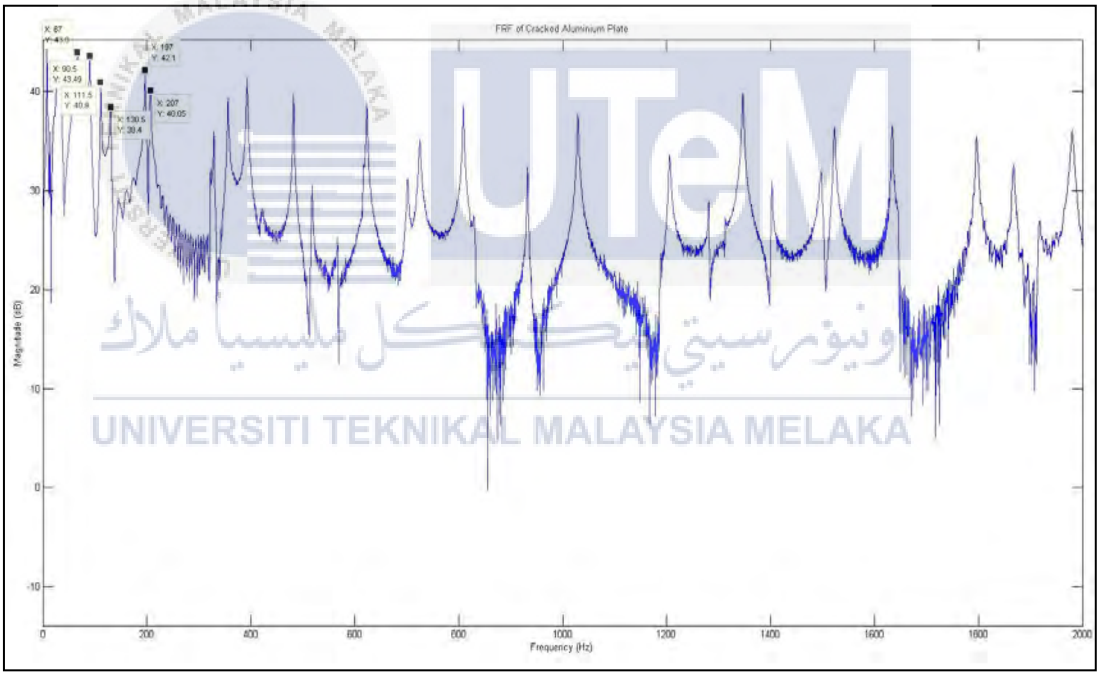

Figure 4.3: Graph of Frequency Response Function (FRF) of cracked aluminium plate.

4.4 Vibro-cosutic Test

The aim of this vibro-acoustic test is to find the effects of high frequency excitation location in crack detection. The first three of vibration modes (67Hz, 90.5Hz and 111.5 Hz) is used as excitation of low frequencies and 60 kHz as ultrasonic signal. Each vibration modes will be performed at each 10 points selected of high frequency input. Therefore, there will 30 data needed in this experiment. The output signal response will be transformed into a graph of amplitude against frequency through a MATLAB software. The sideband of the spectrum is specifically identified for existence of a crack's plate. The peak domain (A_0) of the spectrum is refer as 60 kHz. The value differences of first and second sideband amplitude ($A_{1,2}$) with the peak domain amplitude need to be same as the value of low frequency excitation. Thus, the signal will be accepted as the correct data. Figure 4.5, 4.6 and 4.7 shows the graph of FRF of the cracked aluminium plate for each vibration modes excitation at point 1 of PZT transducer. Meanwhile Table 4.3, 4.4, and 4.5 shows value amplitude obtained from Figure 4.4, 4.5 and 4.6 of the low frequency excitation value at point 1 of PZT transducer.

- Point 1

i. 67 Hz (1st mode)

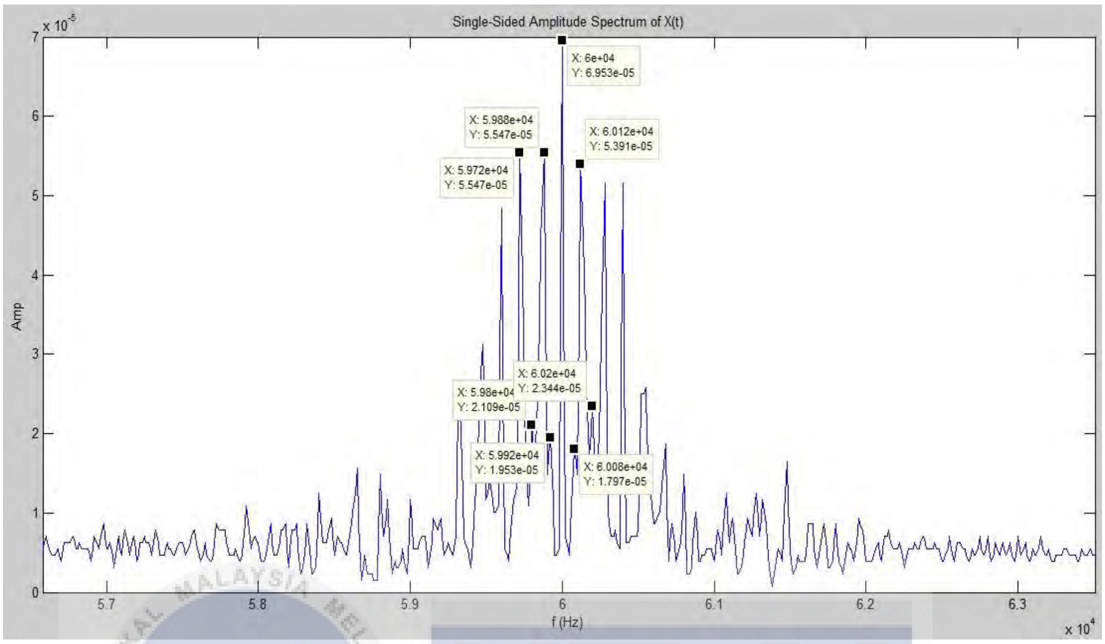

Figure 4.4: Graph of FRF of Cracked Aluminium Plate with low frequency of 67Hz at point 1 for PZT transducer.

Table 4.3: Value amplitude at Graph of FRF of Cracked Aluminium Plate with low frequency of 67Hz at point 1 for PZT transducer.

Peak No.	Amplitude value
A_0	$6.953\text{x}10^{-5}$
A_1	$1.953\text{x}10^{-5}$
A_2	$1.797\ \text{x}10^{-5}$
A_3	$5.547\ \text{x}10^{-5}$
A_4	$5.391\ \text{x}10^{-5}$

ii. 90.5 Hz (2nd mode)

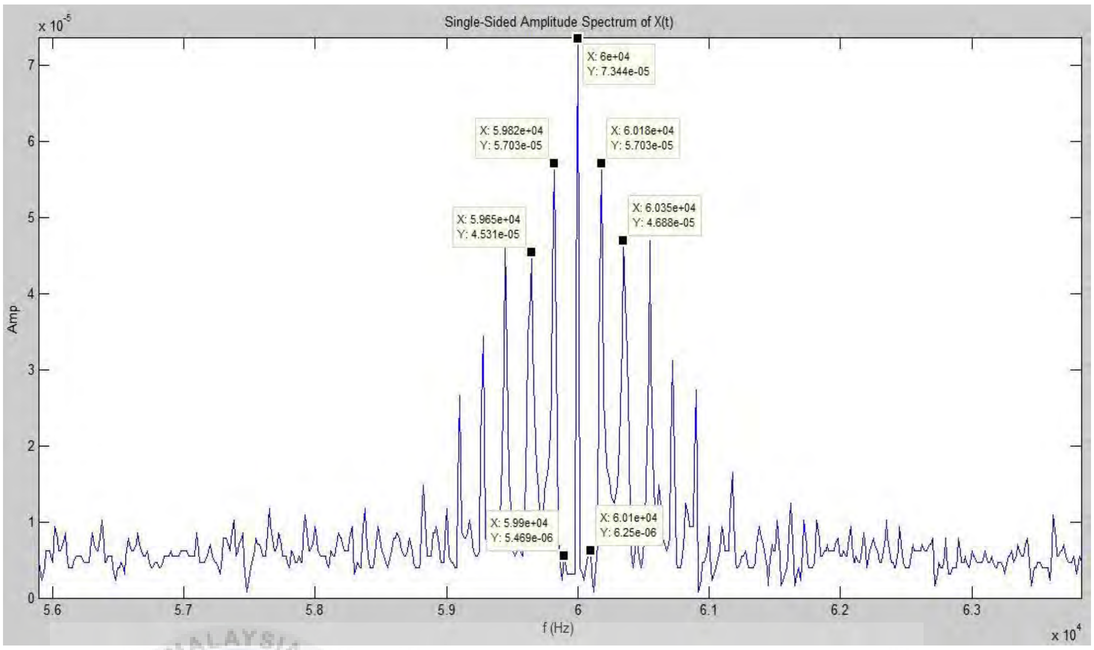

Figure 4.5: Graph of FRF of Cracked Aluminium Plate with low frequency of 90.5Hz at point 1 for PZT transducer.

Table 4.4: Value amplitude at Graph of FRF of Cracked Aluminium Plate with low frequency of 90.5Hz at point 1 for PZT transducer.

Peak No.	Amplitude value
A_0	$7.344 \text{ x}10^{-5}$
A_1	$5.469 \text{ x}10^{-5}$
A_2	$6.25 \text{ x}10^{-5}$
A_3	$5.703 \text{ x}10^{-5}$
A_4	$5.703 \text{ x}10^{-5}$

iii.111.5Hz (3rd mode)

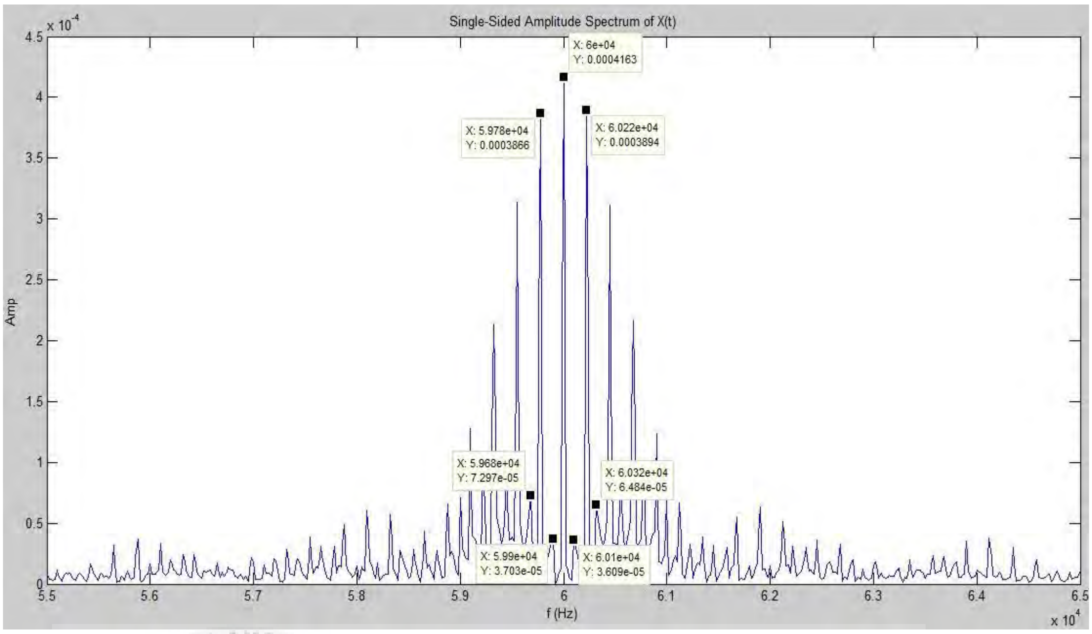

Figure 4.6: Graph of FRF of Cracked Aluminium Plate with low frequency of 111.5Hz at point 1 for PZT transducer.

Table 4.5: Value amplitude at Graph of FRF of Cracked Aluminium Plate with low frequency of 111.5Hz at point 1 for PZT transducer.

Peak No.	Amplitude Value
A_0	0.0004163
A_1	$3.703\text{x}10^{-5}$
A_2	$3.609\text{x}10^{-5}$
A_3	0.0003866
A_4	0.0003894

CHAPTER 5

DISCUSSION AND ANALYSIS

An experimental of vibro-acoustic test was performed to evaluate the importance of high frequency input excitation position. Therefore, several points of PZT transducer have been selected which was previously mentioned in methodology. The PZT transducer with 1mm thickness is chosen because of it is a small size and lightweight. The measurement point for each PZT transducer position can be seen in Table 3.4. In this vibro-acoustic test, the first three vibration modes (67 Hz, 90.5 Hz and 111.5 Hz) act as low frequency excitation which have been extracted from the experimental modal test. Meanwhile, 60 kHz was excite as high frequency ultrasonic signal. This frequency have good sensitivity for small and large crack values.

The output signal data will be plotted through MATLAB software. It will form a graph of an amplitude and low frequency (Hz). The amplitude of the peak response from the sideband of the spectrum will be used to calculate the R-index value. The index which called R modulation coefficient, which can defined by the equation 5.1, was used to detect the level of a crack on the plate (Simondi et al., 2009) (Duffour et al., 2005) (Morbidini et al., 2005).

$$R = \frac{A_1 + A_2}{A_0} \tag{5-1}$$

Where A_0 is an ultrasonic amplitude and A_1 and A_2 are first sideband amplitude on the left and right of the ultrasonic spectrum. However, in this result, R index is calculated using value of A_3 and A_4 second sideband amplitude of left and right of spectrum and ultrasonic amplitude as shown in equation 5.2.

$$R = \frac{A_3 + A_4}{A_0} \tag{5-2}$$

The Figure 5. 1 and 5.2 shows the graph of R-index against the distance of high frequency input position from crack line at y-axis for at centre and side of the plate which consisting of 10 points. The Figure 5.1 and 5.2 basically show how different of high frequency excitation positions affect the crack mode behaviour. In Figure 5.1, the 1^{st} and 2^{nd} vibration modes have slightly difference of R values against the first five of high frequency input positions. But, the 2^{nd} vibration mode have a consistent increasing trend. Meanwhile, the 3^{rd} vibration mode trend fluctuated up and down. This is maybe because the 3^{rd} vibration mode have slightly impacted from the vibration response.

In Figure 5.2, the 1^{st} and 3^{rd} vibration modes have stabilized trends. However, for 2^{nd} vibration modes, the R-index value increasing at point 6 (235mm, y-axis) and decreasing starting from point 7 (265 mm, y-axis). But, in comparison for all vibration modes, there is only a slightly difference of R-index value. This is maybe because of position of the PZT transducer which at the side of the plane

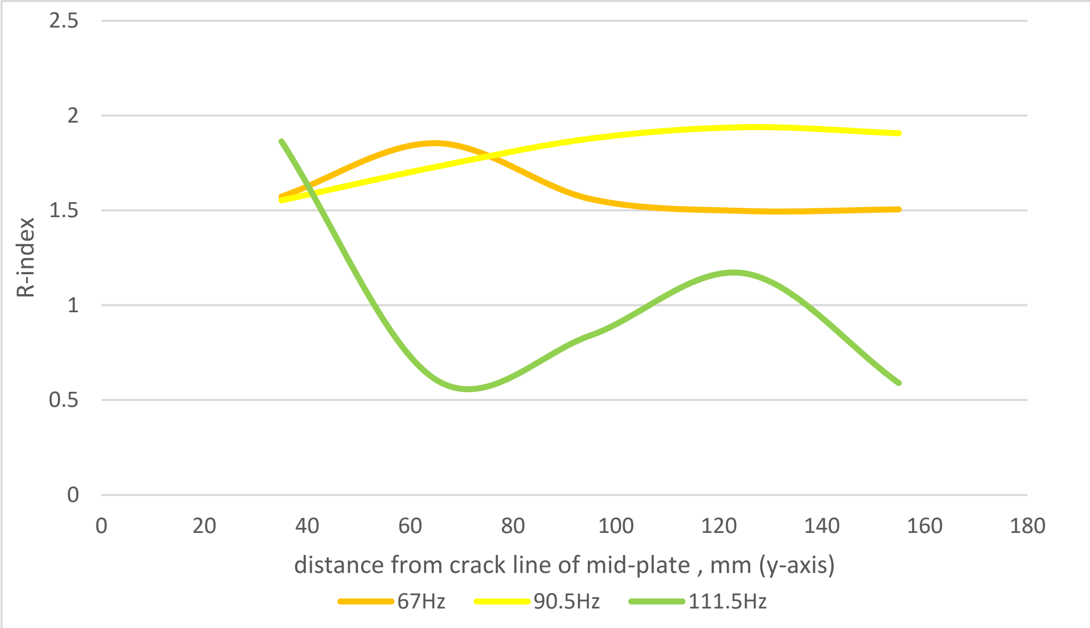

Figure 5.1: Graph of R-index against distance of high frequency input from crack line at y-axis for first line column (centre of the plate); consisting point 1,2,3,4 and 5.

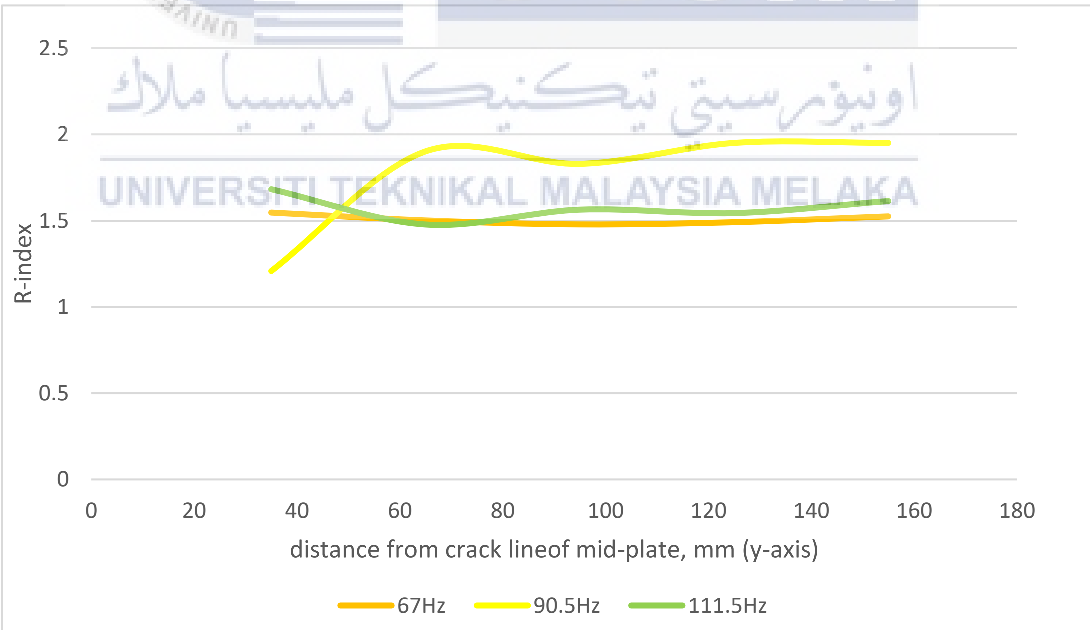

Figure 5.2: Graph of R-index against distance of high frequency input from crack line at y-axis for second line column (side of the plate); consisting of point 6,7,8,9 and 10.

Table 5.1: Average value of R-index for each vibration mode excitation on 10 points of high frequency input.

Vibration mode	Average value of R-index
1	1.5535
2	1.7849
3	1.2953

Table 5.1 shows the average value of R-index for each vibration mode excitation on 10 points of high frequency input. The 2nd vibration mode had the highest value of R-index at 1.7849; which is followed by the 1st vibration mode at 1.7849. Lastly, the 3rd vibration mode had the lowest value of R-index at 1.2953. It can be result as 2nd vibration mode has the highest R-index value among all because of its mode shape (twisting). In addition, the R- index that have largest value can be marked as crack.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The aim of this project is to determine the effect of high frequency excitation location in crack detection by using vibro-acoustic method. The experimental results showed that the location of high frequency excitation does not affect the detection of the crack's plate in vibro-acoustic method. The trend result generally showed that there is only slightly difference of R-index value at the selected points of high frequency input.

As a conclusion, vibro-acoustic method can be used for crack detection because it has high sensitivity compared to the other methods. The presence of crack can be deeply detect if proper excitation frequencies and others parameters is selected. In addition, the vibration modes required at least 3 to study on the physical mechanisms of the nonlinear acoustic effect.

6.2 Recommendations

After completing the current research, a few recommendations can be appointed for future work. This research is basically tested only on one crack's plate model which have a certain size of crack. Therefore, for better comparison and convincing research result. It is recommended to carry the experiment on several difference of crack size on the same type of material used. This means have several crack's plate model with difference size of crack. This research is mainly an experimental work. In order to get a more detail on this research, it is recommended to do a simulation analysis.

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APPENDIXES

APPENDIX A

MATLAB Software Coding

A.1 FRF coding for modal analysis test

```
clc;
data = csvread('out') ;
t = data(:,1) ;
amp = data(:,2) ;
L = length(t) ;
N = length(amp);
dt = max(diff(t)) ;
Fs = 1/dt ;
X_mags = abs(fft(amp));
bin_vals = [0 : N-1];
fax_Hz = bin_vals*Fs/N;
N_2 = ceil(N/2);
plot(fax_Hz(1:N_2), 10*log10(X_mags(1:N_2)))
xlabel('Frequency (Hz)')
ylabel('Magnitude (dB)');
title('FRF of Cracked Aluminium Plate');
axis tight
xlim([0 2000])
```

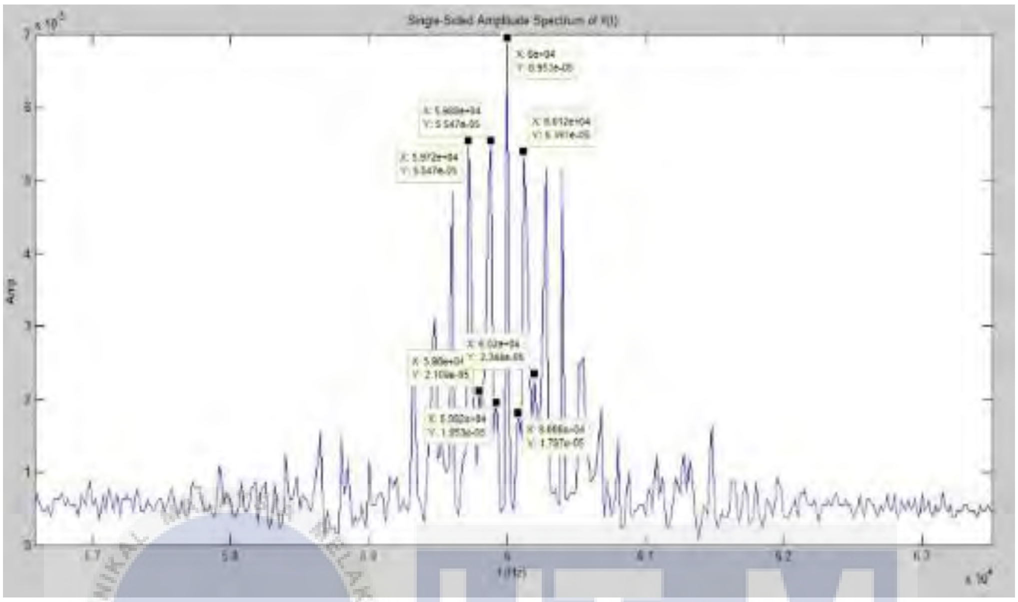
A.2 FRF coding for vibro-acoustic test

```
clear all;
data1 = csvread('tek00001.csv');
f1 = data1(:,1);
amp1 = data1(:,2);
plot(f1,amp1)
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('Amp')
xlim([55000 65000])
```

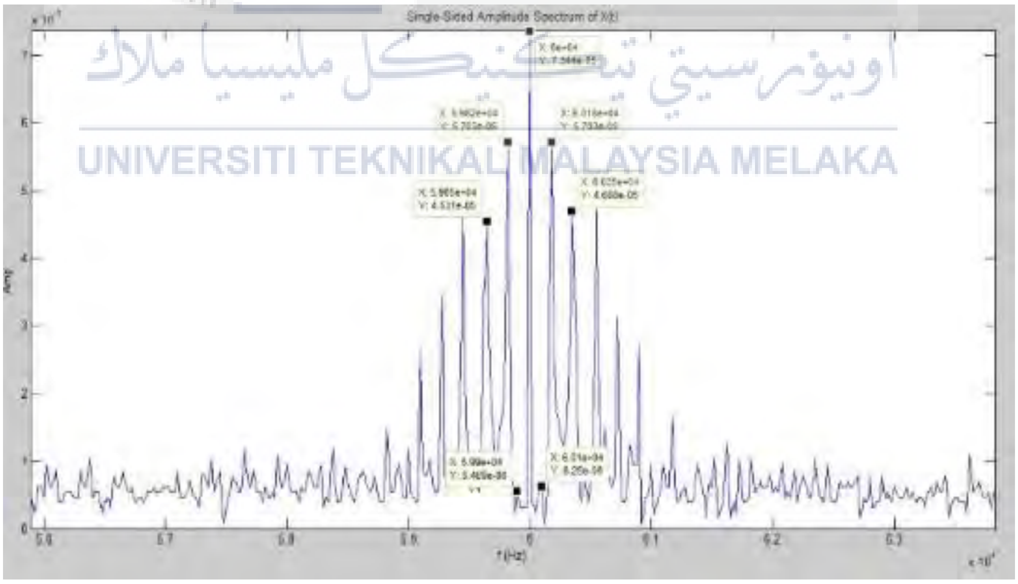
APPENDIX B

Data Collected For Vibro-Acoustic Modulation (VAM) Test

(a)



(b)



(c)

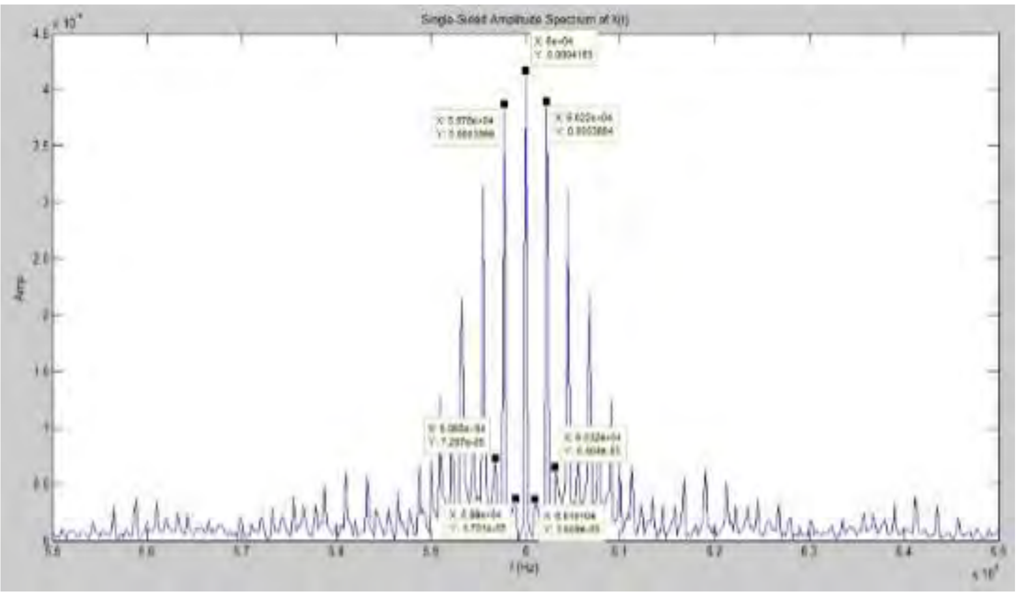
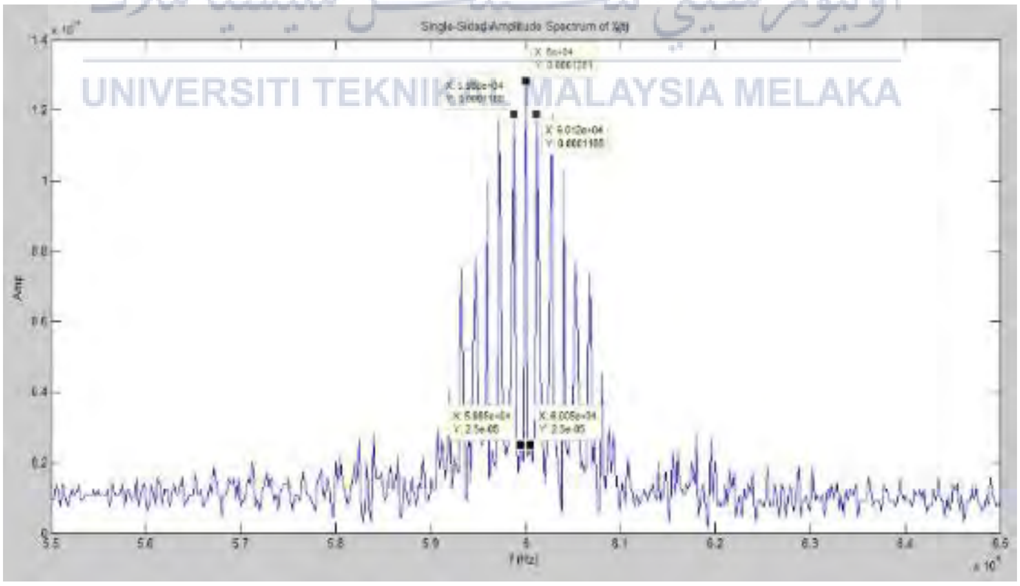
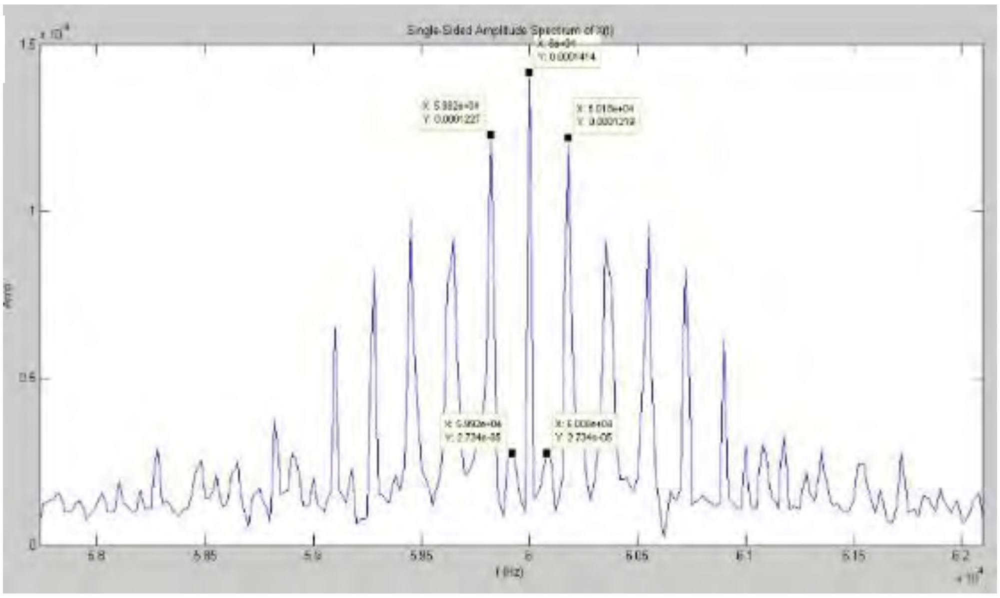


Figure B.1: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1^{st}; 67Hz, (b) 2^{nd}; 90.5 Hz, and (c) 3^{rd}; 111.5Hz vibration modes for point 1 in VAM test

(a)



(b)



(c)

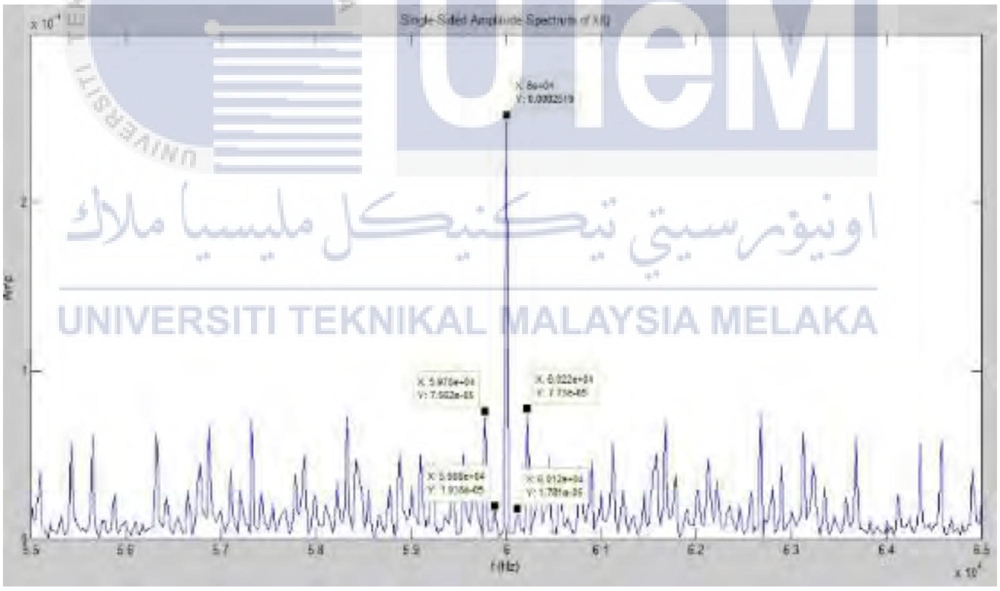
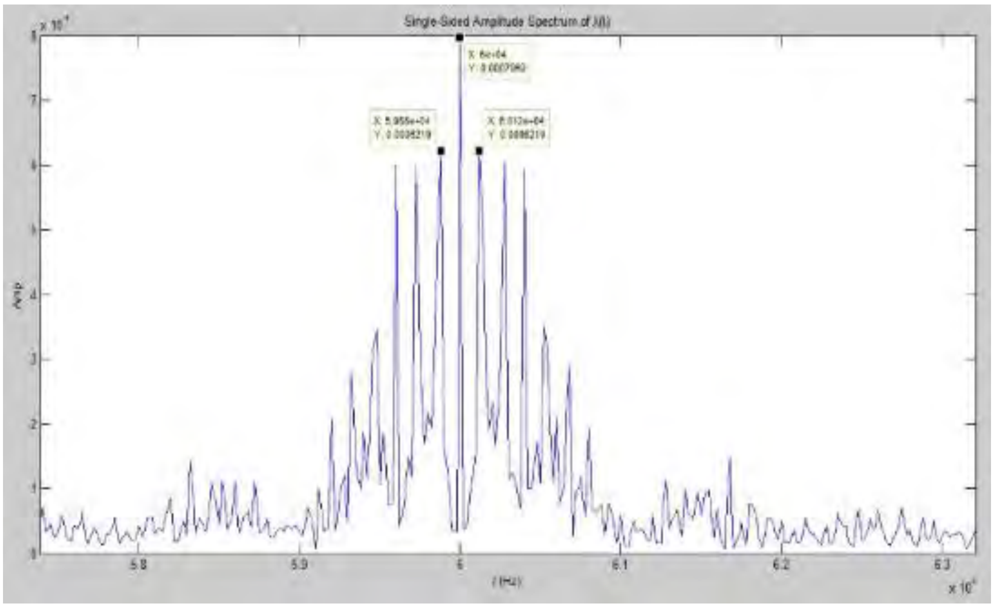
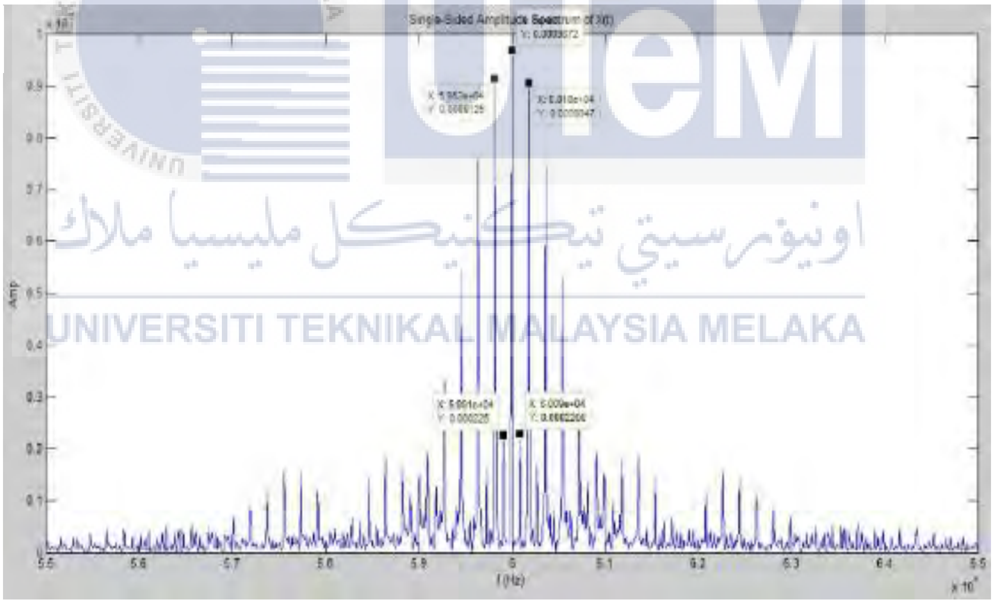


Figure B.2: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 2 in VAM test

(a)


Single-Sided Amplitude Spectrum of X(f)
Amp
f (Hz)

(b)


Single-Sided Amplitude Spectrum of X(f)
Amp
f (Hz)

(c)

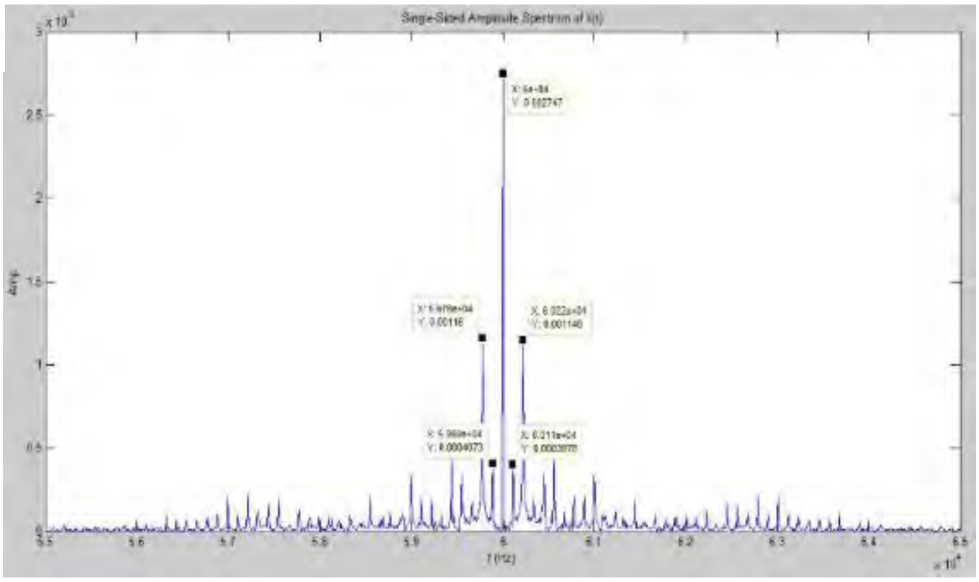
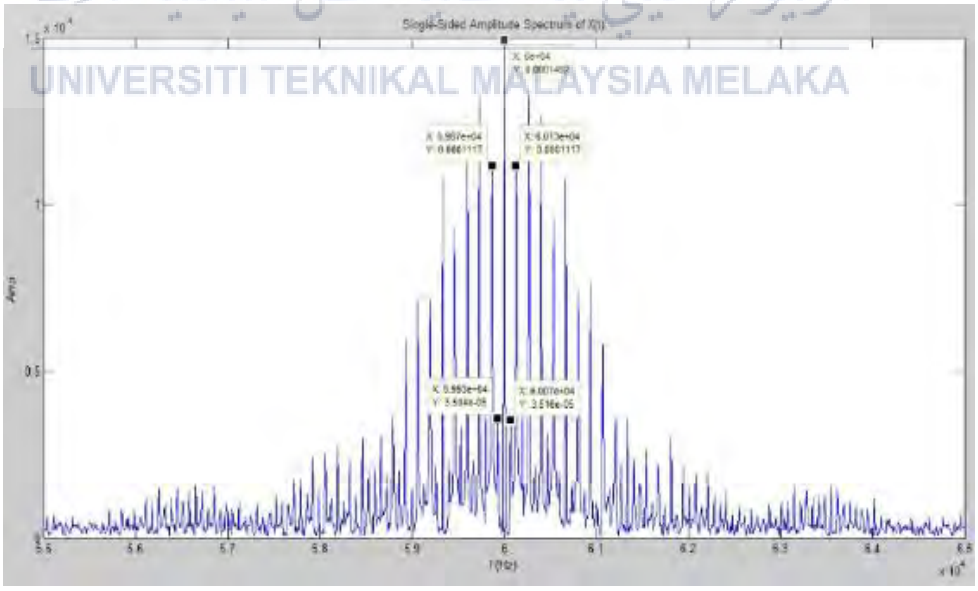
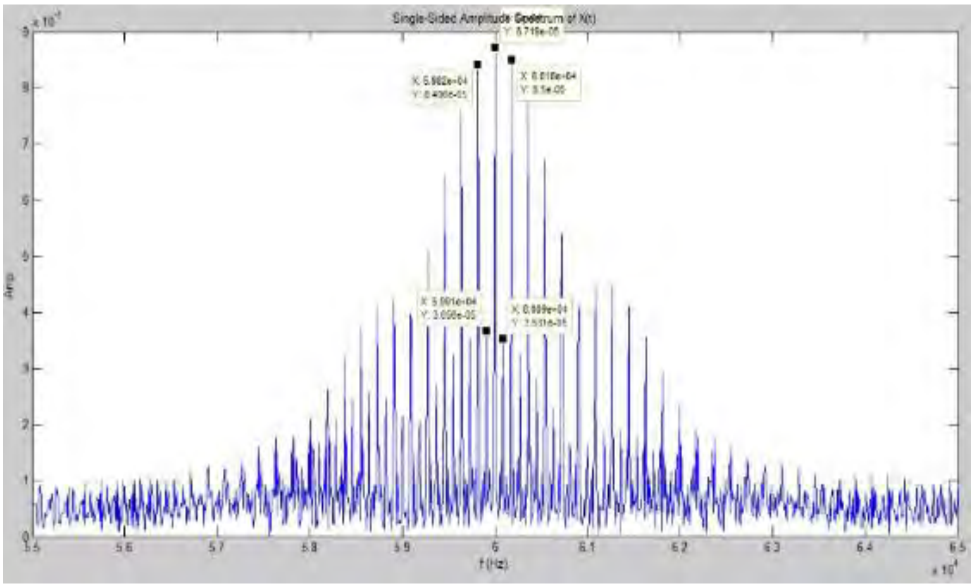


Figure B.3: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 3 in VAM test

(a)



(b)



(c)

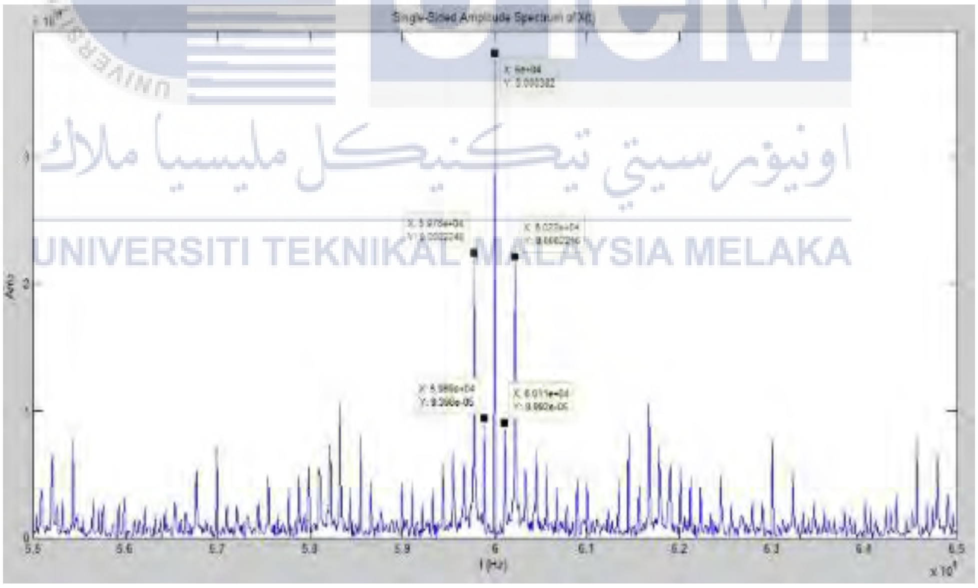
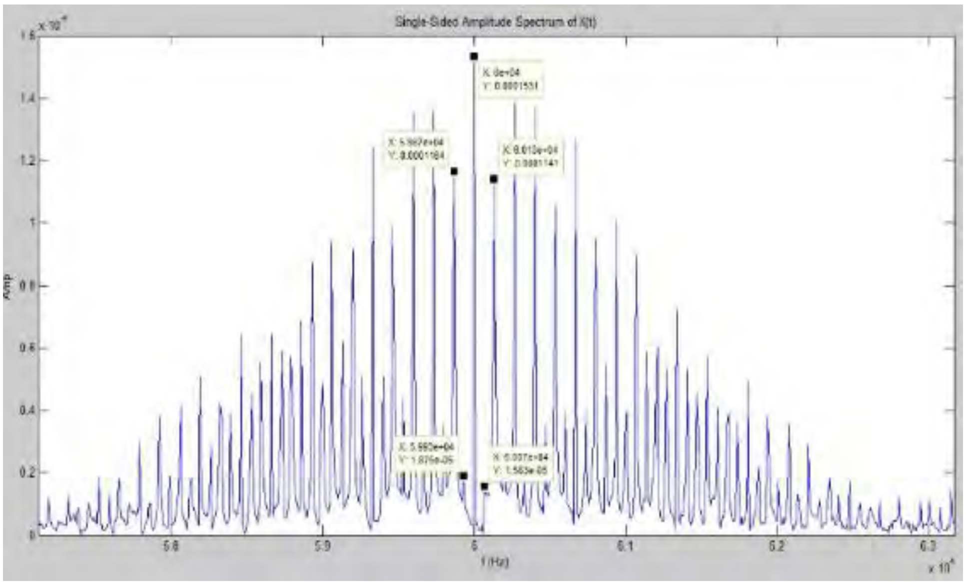
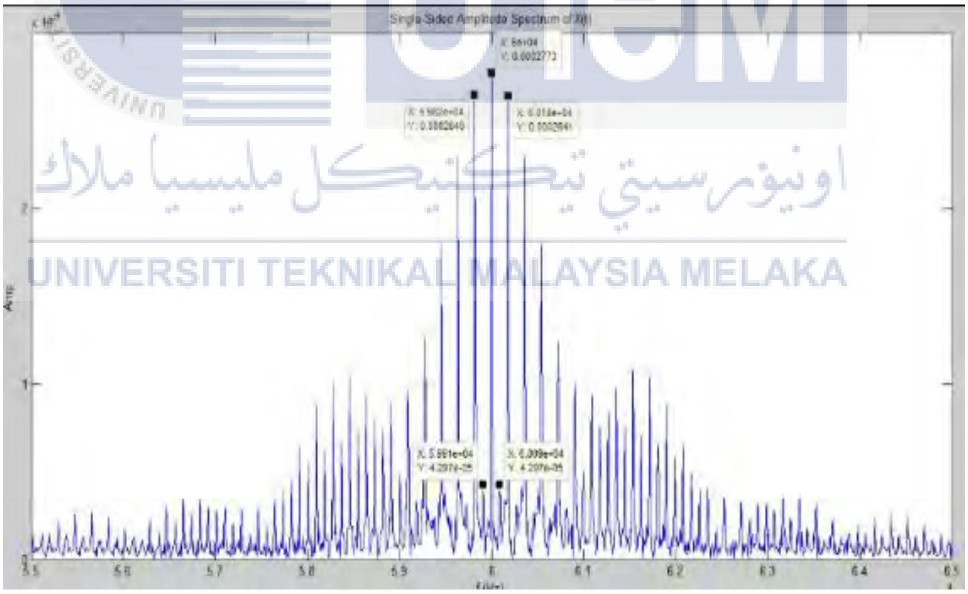


Figure B.4: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 4 in VAM test

(a)


Single-Sided Amplitude Spectrum of X(t)
X: 6e+04
Y: 0.0001531
f (Hz)
Amp

(b)


Single-Sided Amplitude Spectrum of X(t)
X: 6e+04
Y: 0.0002773
Amp

(c)

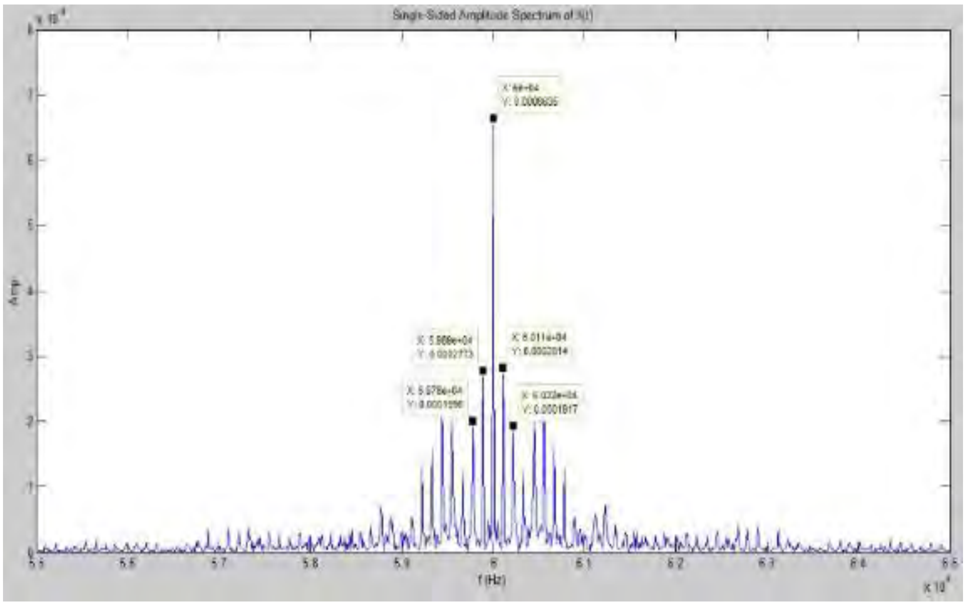
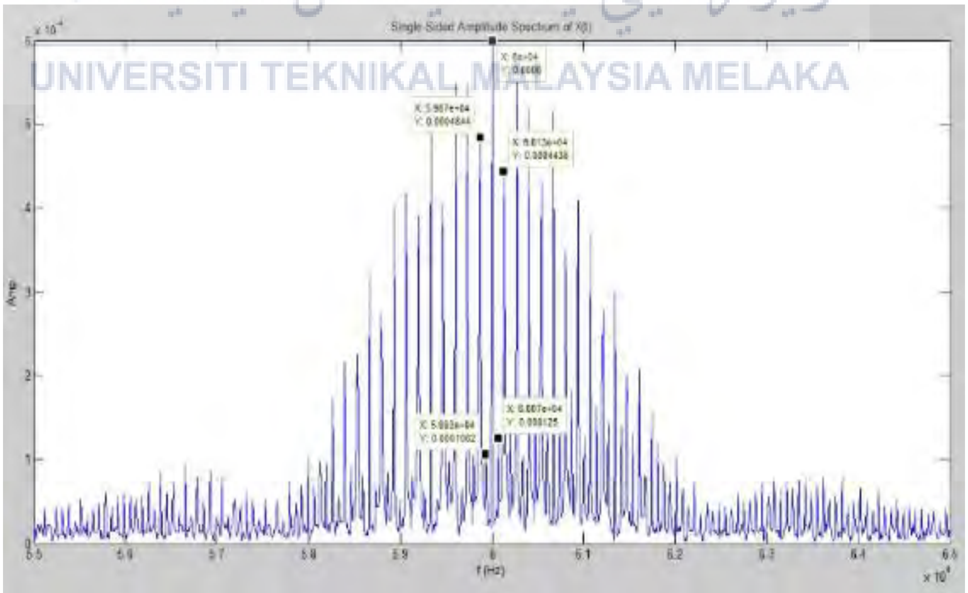
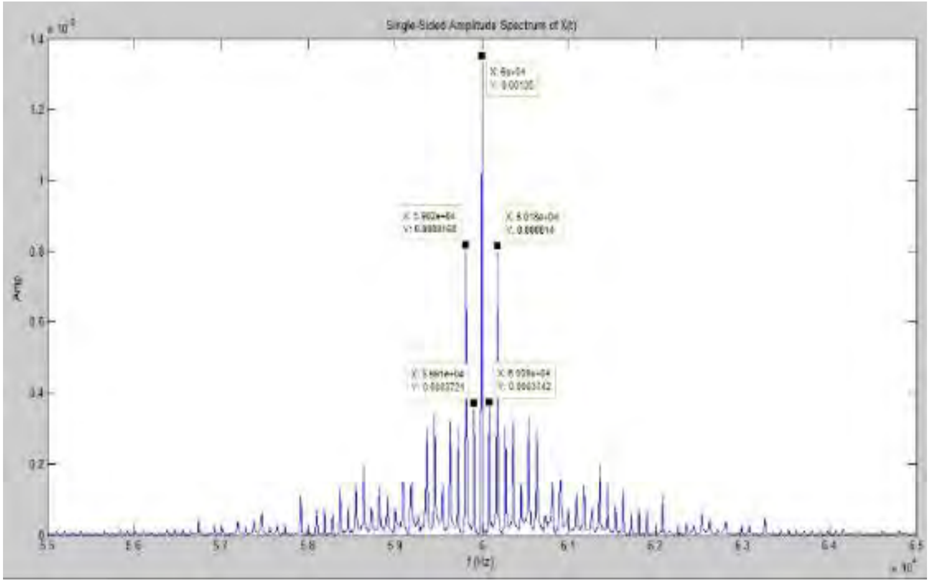


Figure B.5: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 5 in VAM test

(a)



(b)



(c)

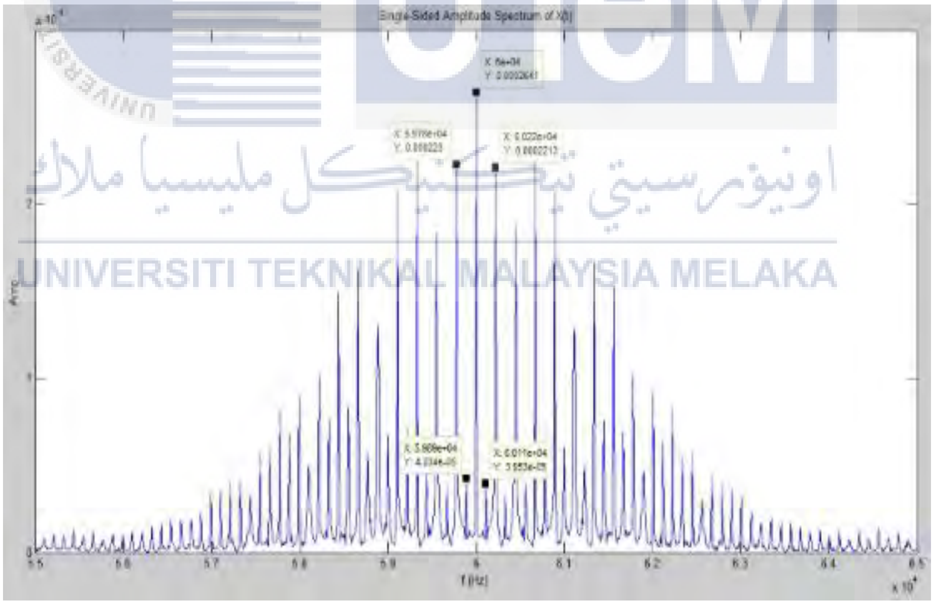
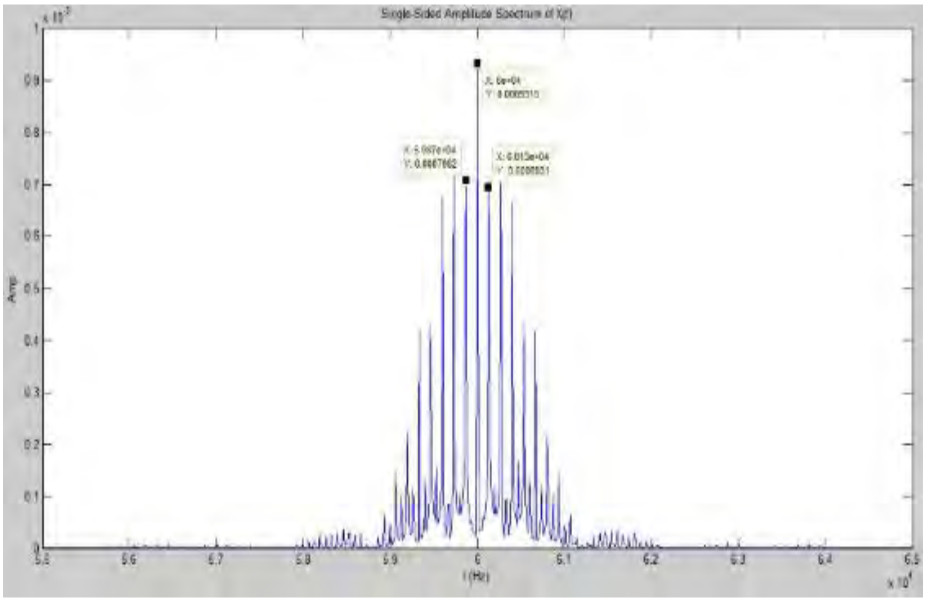
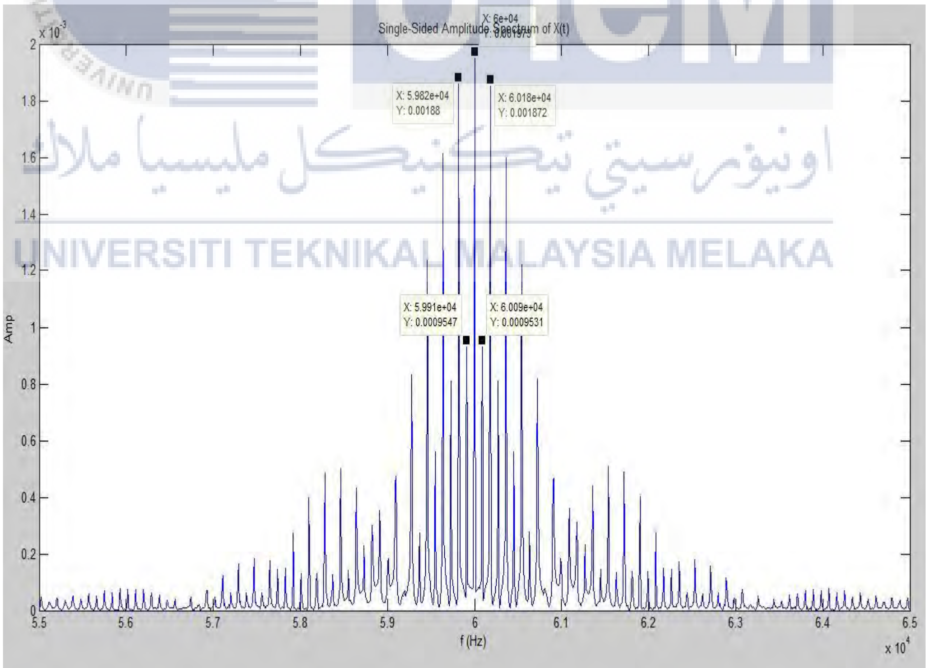


Figure B.6: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 6 in VAM test

(a)


Single-Sided Amplitude Spectrum of X(f)
Amp
f (Hz)
x 10^4

(b)


Single-Sided Amplitude Spectrum of X(t)
x 10^-3
X: 6e+04
X: 5.982e+04
Y: 0.00188
X: 6.018e+04
Y: 0.001872
X: 5.991e+04
Y: 0.0009547
X: 6.009e+04
Y: 0.0009531
Amp
f (Hz)
x 10^4

(c)

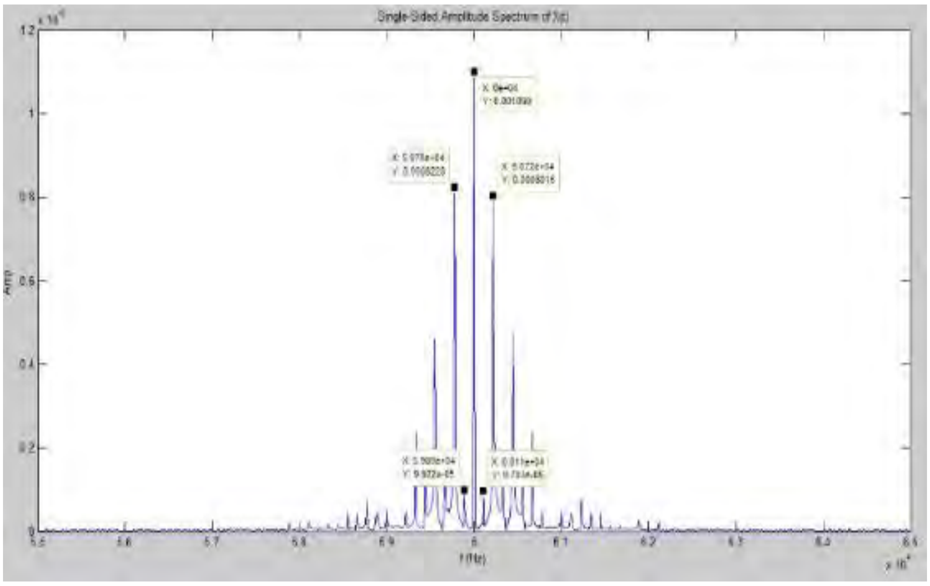
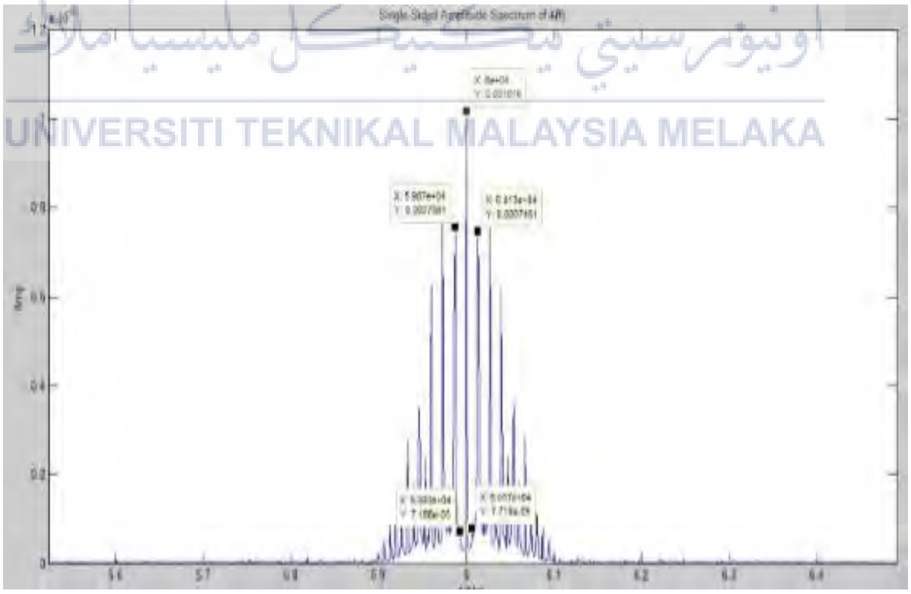
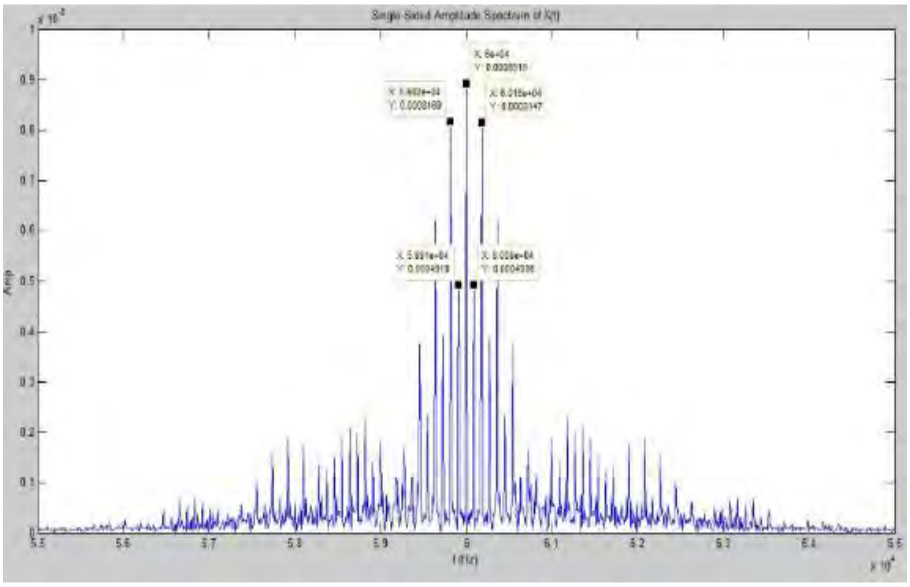


Figure B.7: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 7 in VAM test

(a)



(b)



(c)

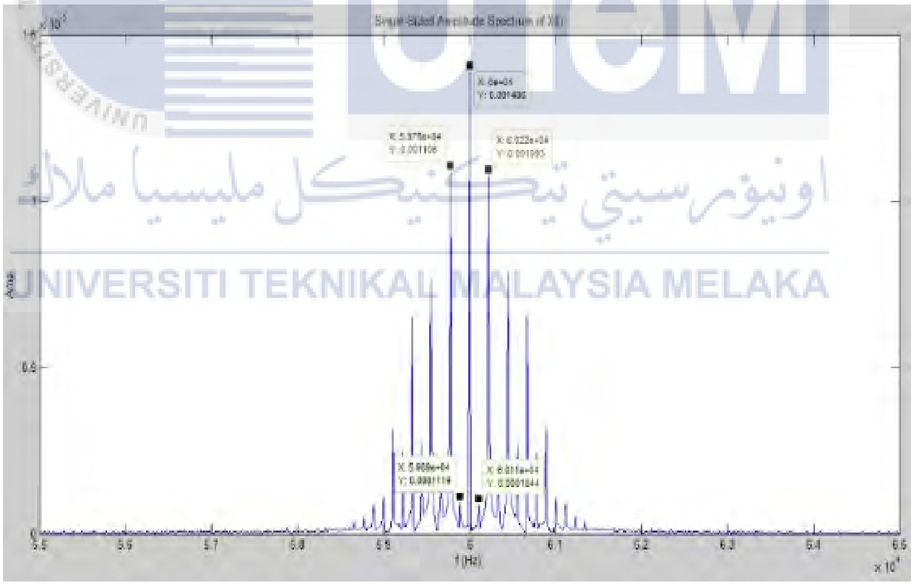
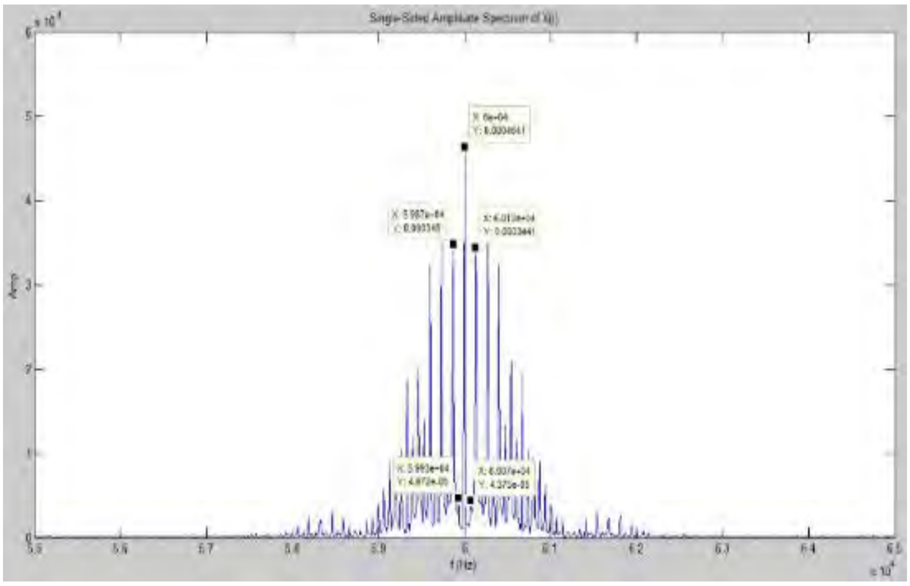
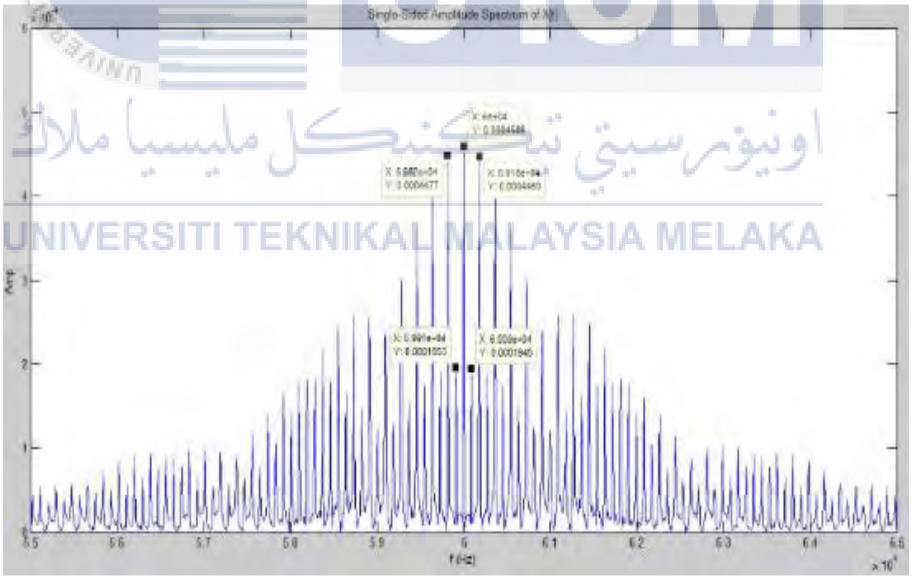


Figure B.8: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 8 in VAM test

(a)


Single-Sided Amplitude Spectrum of X(t)
Amp
f (Hz)

(b)


Single-Sided Amplitude Spectrum of X(t)
Amp
f (Hz)

(c)

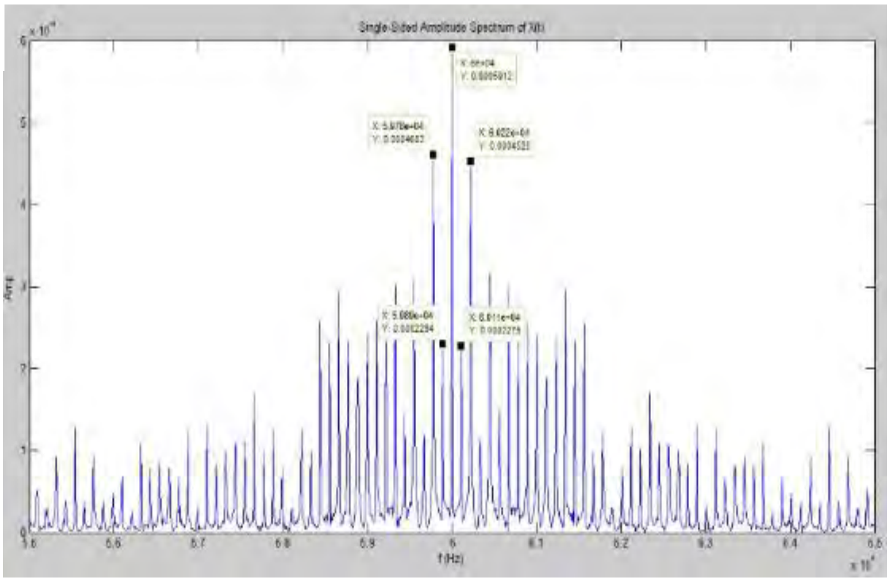
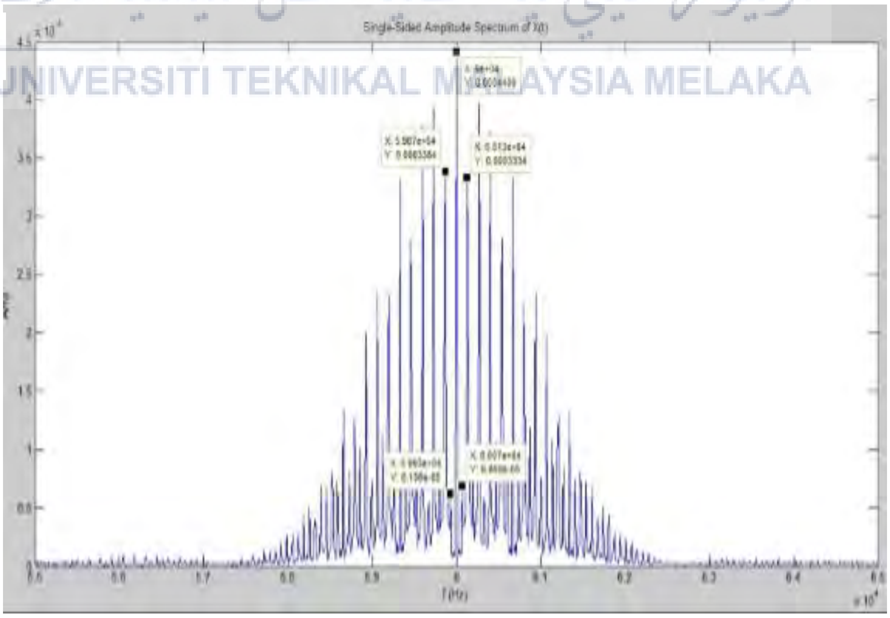
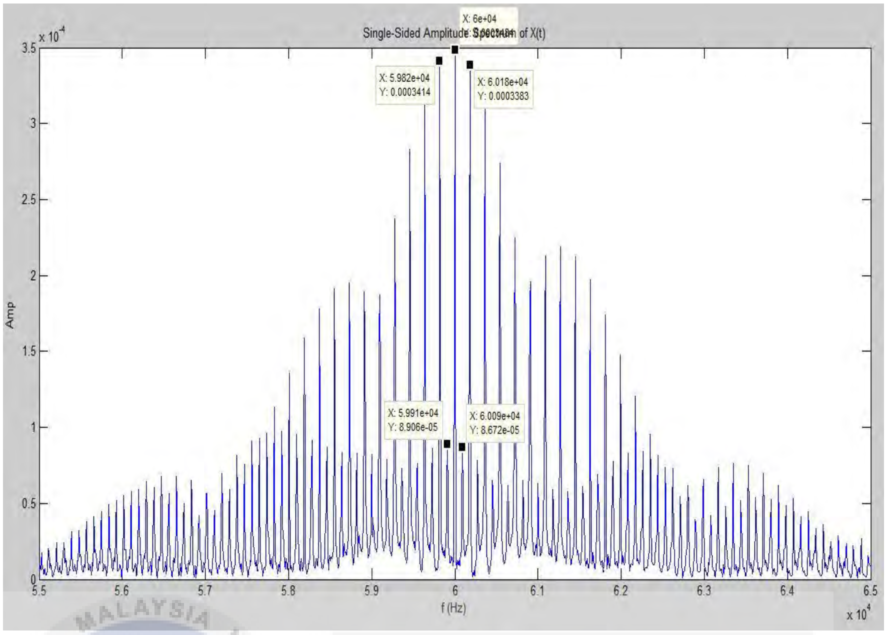


Figure B.9: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 9 in VAM test

(a)



(b)



(c)

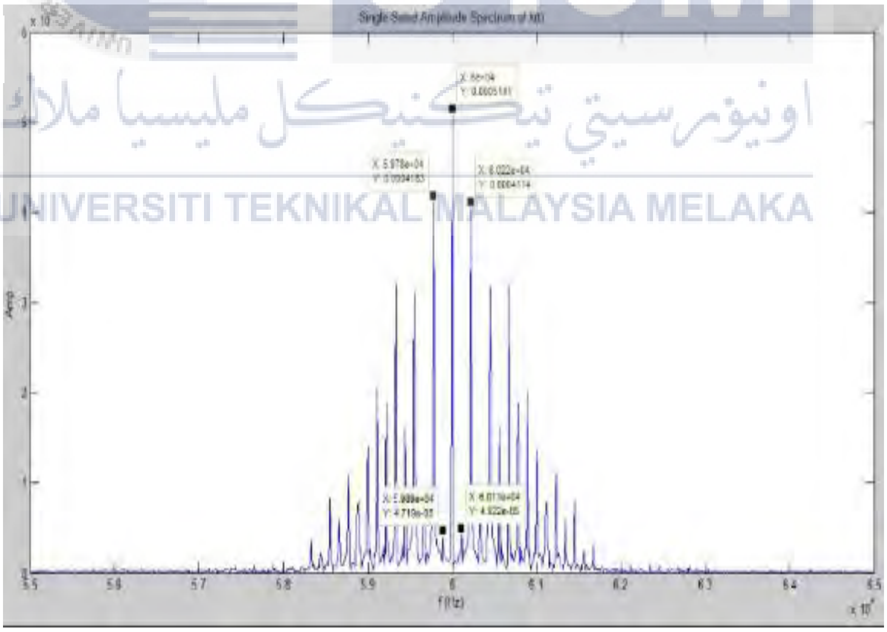


Figure B.10: Observation of sidebands for 20mm cracked aluminium plate excited by (a) 1st; 67Hz, (b) 2nd; 90.5 Hz, and (c) 3rd; 111.5Hz vibration modes for point 10 in VAM test