THE EFFECT OF HIGH FREQUENCY WAVE IN VIBRO ACOUSTIC METHOD FOR CRACK DETECTION

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in fulfillment of the requirement for the degree of
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DECLARATION

I declare that this project report entitled “The Effect Of High Frequency Wave In Vibro Acoustic Method For Crack Detection” is the result of my own work except as cited in the references

Signature	:	....
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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 : Dr. Ruztamreen Bin Jenal

Date : ....

DEDICATION

To my beloved family for the endless support they had gave

ABSTRACT

The most common structural defect is the existence of fatigue crack. Fatigue cracks can present in the structures due to various reasons. The presence of cracks is hazardous as it can affect the mechanical behaviour of the entire structure to a considerable extent, thus a non-linear vibro-acoustic approach suitable for detecting the presence of fatigue crack as they are very sensitive even to a small damage severities or cracks and highly reliable method. This study is carried out to study about crack detection on a structure by using a non-linear vibro-acoustic technique. Vibro-acoustic method is a method based on propagation of high frequency acoustic waves in solid structures with low-frequency excitation. The interaction occur between the acoustic waves with material changes will cause wave distortion effects. The main objective of this study to find effects of high frequencies against the non-linear effects sensitivity using variation of high frequency wave in vibro-acoustic method to detect the fatigue crack. The test specimen that will be used in this study is a 150 mm x 400 mm x 2 mm aluminium plate (AL-2024). The plate will undergo some modal analysis to determine the dynamic response of a material and followed by the vibro-acoustic test. In addition, this study also will provide analysis on the relation of high frequency effect and the amplitude modulation intensity (R-value). The findings show that crack exhibited in a power spectra signal of the acoustic response by a pattern of sidebands around the ultrasonic signal and explains that the high frequencies excitation does not give significant change on the modulation intensity but proper selection of the high frequency excitation value and also its location is important to obtain a good result.

ABSTRAK

Kecacatan struktur yang paling biasa ialah retak lesu. Retak lesu boleh hadir dalam struktur disebabkan oleh pelbagai sebab. Kehadiran retak adalah berbahaya kerana ia boleh mempengaruhi tingkah laku mekanikal struktur keseluruhan ke tahap yang besar, oleh itu suatu pendekatan bukan sekata vibro-akustik sesuai untuk mengesan kehadiran retak kerana ia sangat sensitif walaupun untuk kerosakan kecil atau retak dan kaedah yang boleh dipercayai. Kajian ini dijalankan untuk mengkaji mengenai pengesanan retak pada struktur dengan menggunakan teknik vibro-akustik bukan sekata. Vibro-akustik adalah satu kaedah berdasarkan pengujaan gelombang akustik frekuensi tinggi dan rendah secara serentak kedalam struktur yang kukuh. Interaksi yang berlaku antara gelombang akustik dengan perubahan bahan akan menyebabkan kesan gelombang herotan. Objektif utama kajian ini untuk mencari kesan frekuensi tinggi terhadap sensitiviti kesan bukan sekata menggunakan variasi gelombang frekuensi tinggi dalam kaedah vibro-akustik untuk mengesan keretakan. Spesimen ujian yang akan digunakan dalam kajian ini ialah 150 mm x 400 mm x 2 mm plat aluminium (AL-2024). Plat akan menjalani beberapa analisis modal untuk menentukan gerak balas dinamik yang penting dan diikuti dengan ujian vibro-akustik. Di samping itu, kajian ini juga akan menyediakan analisis mengenai hubungan kesan frekuensi tinggi dan keamatan modulasi amplitud (nilai R). Keputusan menunjukkan bahawa retak dipamerkan di isyarat kuasa spektrum sambutan akustik oleh corak jalursisi sekitar isyarat ultrasonik dan menjelaskan bahawa frekuensi pengujaan tinggi tidak memberi perubahan yang besar ke atas keamatan modulasi tetapi pemilihan yang sepatutnya bagi nilai pengujaan frekuensi tinggi dan juga lokasi adalah penting untuk mendapatkan hasil yang baik.

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LIST OF ABBEREVATIONS

SHM	Structural Health Monitoring
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
AE	Acoustic Emission
UT	Ultrasonic Testing
RT	Radiography Technique
IT	Infrared Thermography
EDM	Electronic Discharge Machine
UTM	Universal Testing Machine
PSB	Persistent Slip Bands
VAM	Vibro-Acoustic Modulation
FEM	Finite Element Method
FE	Finite Element
IM	Impact Modulation
SLDV	Scanning Laser Doppler Vibrometer
PZT	Piezoceramic Transducer
HF	High Frequency
LF	Low Frequency
FRF	Frequency Response Function

CHAPTER 1

INTRODUCTION

1.1 Background

Structural health monitoring (SHM) is one of the common approach which being explored as techniques in assessing the integrity of mechanical, civil, and aerospace structures. SHM is the process of damage detection and characterization of the damage for further maintenance strategies. Yu, L. and V. Giurgiutiu (2009) claim that, various SHM methods can be used for crack detection by utilizing piezoelectric sensors. SHM can detect or quantify damage by comparing current structural state measurements to measurements collected from an undamaged structure (Raghavan et al., 2007).

SHM techniques can reduce cost and increase availability by eliminating unnecessary structural inspections. Previous study by Hamey et al (2004) found that SHM also provide a better understanding of the current operational state of the structure thus reducing the probability of catastrophic failures. SHM and Non-Destructive Evaluation (NDE) utilize similar methods and techniques but with several notable differences. For instance, SHM systems typically utilize sensors which are permanently bonded to the structure of interest but unlike NDE. In general, the process of SHM is started by exciting the structure using actuators or operational loading. Then, the response to the excitation will be sensed at various locations throughout the structure. The response signals are collected and processed, and based on the processed data, the state of the structure is diagnosed.

Non-Destructive Testing/Evaluation (NDT/NDE) is a method that evaluates the structure properties without causing damage. There are several of damage detection methods or damage monitoring systems which can be used to measure structural damage such as dye penetrant, Acoustic Emission (AE), Ultrasonic Testing (UT), Radiography Technique (RT), Vibro-acoustic and also Infrared Thermography (IT). However, all these techniques have limitations and are not possible in some situations.

Wevers (1997) described AE as a method to measure the mechanical stress waves that result when strain energy is released due to micro-structural changes in a material. The ultrasonic stress waves will propagate through the structural component and sensed by piezoelectric sensors. Measured data from AE method is often difficult to interpret due to the presence of ultrasonic energy with similar frequencies to those emitted by the release of strain energy. The AE method has found common use as an inspection method for pipelines, pressure vessels, and similar applications, where pressure sensitive structural components can be monitored without the presence of significant environmental noise (Aljets et al., 2012).

If the cracks are on the surface of non-porous materials, a dye penetrant can be done to reveal it. Dye penetrant testing can detect small cracks but only capable of detecting damages on the surface. Dye penetration works by applying colour or fluorescent dye into the surface flaws. After that a post-penetrant material was applied and the flaws will appear as coloured lines.

Infrared thermography is an application through the concept of energy emission. Every object that will be determined emits an amount of energy that will be detected by an infrared camera. Later, the energy emitted will be converted to temperature in form of a temperature distribution or so called "Thermogram". A red colour of distribution means temperature for that particular point is at low temperature while the red colour determines high temperature for that particular point.

Another method is by using the Lamb wave. Lamb wave is a special kind of guided wave which can be travel over a long distance. The sensitivity of lamb wave to defects is greater than common ultrasonic method. Lamb wave inspection is fast and its cost is so lower than common ultrasonic techniques or other inspection methods. There are two techniques in lamb wave testing which are pulse-echo and emission with different lamb modes as transmitter and receiver.

1.2 Problem Statement

The most common structural defect is the existence of fatigue crack. Fatigue cracks can present in the structures due to various reasons. The presence of cracks will cause a local variation in the stiffness and can affect the mechanical behaviour of the entire structure to a considerable extent. Thus, a non-linear vibro-acoustic approaches are especially well suited for detecting the presence of fatigue crack as they are very sensitive even to a small damage severities and this approach do not require dense sensor networks. However, there are no thorough studies on investigating the effects of high frequencies against the non-linear effects sensitivity, thus this study is carried out to investigate the effect of using variation of high frequency wave in vibro-acoustic method to detect the fatigue crack.

1.3 Objectives

The objectives of this project are as follows:

1. To conduct experiment in detecting fatigue crack, by using the effect of high frequency wave in vibro-acoustic method.
2. To provide analysis on the relation of increasing high frequency value and the effect on the sideband intensity.

1.4 Scope of Project

The scopes need to be cover in this project include:

a. The preparation of the test specimen notch (3 mm) by using Electronic Discharge Machine (EDM).

b. The preparation of the test specimen dynamic fatigue crack by using Universal Testing Machine (UTM).

c. Perform the experimental setup for Modal Analysis to obtain test specimen (aluminium plate) mode shapes and resonant frequencies.

d. Perform the non-linear vibro-acoustic test on the specimen to investigate the effect of using variation of high frequency wave in vibro-acoustic method to detect the fatigue crack.

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

CHAPTER 2

LITERATURE REVIEW

2.1 Damage in Structures

Many different methods have been developed for detecting damages in the structures. Damage was defined by Jean Lemaître (2005) as the creation and growth of microvoids or microcracks which will create discontinuities in a homogeneous material. Besides that, damage was also known as structural changes on the material geometric properties of a structural or mechanical system (Sohn et al., 2003). Damage can occur in many ways, such as when the stress applied exceeding the yield stress which resulting changes in the material property (Fatigue Properties, n.d.). One of the primary damages types occur in a structure material is fatigue cracking as illustrated in Figure 2.1. Fatigue crack occur when the structure burdened with cyclic loading that are lower than the ultimate tensile stress, or even the yield stress of the material. The most common form of fatigue crack is probably the fatigue crack that opens and closes under dynamic loading. Fatigue crack life is divided into parts, initiation and propagation. In initiation phase, large number dislocations will pile up and form structures called persistent slip bands (PSB). Budynas et al. (2014) claimed that PSB happened due to movement of material along slip planes. In this period there will be some microcrack growth, but the fatigue cracks are still too small to be visible. In the second period, the crack will be growing until complete failure.

Figure 2.1: Fatigue crack in structure.

The formation of crack can be divided into three distinct modes as shown in Figure 2.2 (Johnson P., 1999). Mode I, the opening crack propagation mode due to the tensile stress. Mode II, sliding mode due to the in-plane shear and Mode III, the tearing mode which arises from out-of-plane shear (Johnson P., 1999).

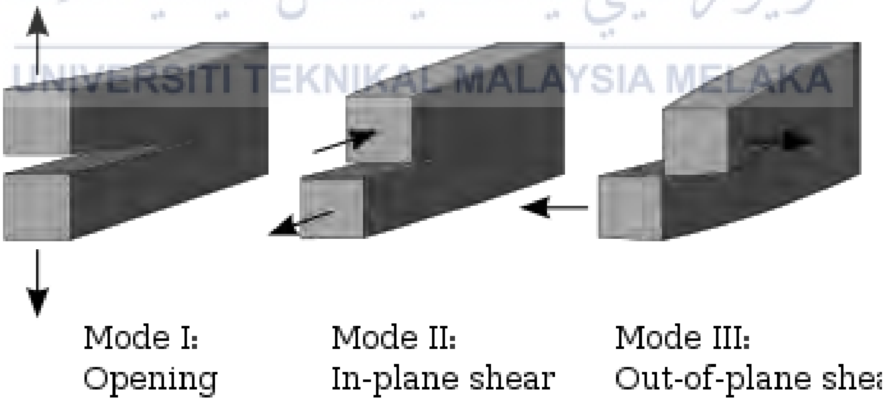


Figure 2.2: Three basic modes for fatigue crack.

2.2 Methods to Detect Fatigue Crack

In the past years, many researchers have shown interest in using non-linear vibration and acoustic phenomena in many research areas including damage detection (Donskoy and Sutin, 1999). Parsons et al. (2006) and Klepka et al. (2011) suggested many different methods have been developed for damage detection in composite structures. Part of the methods are dye penetration, acoustic emission, visual inspection, ultrasonic signals, vibro-acoustic, radiographic methods and also thermography methods. Non-linear acoustic can detect micro damage and early signs of damage. As state in its name, the non-linear is completely the opposite of linear analysis, non-linear technique analyse wave signal output which is unrelated to the signal inputs (Sutin, A.M. and V.E. Nazarov, 1995).

The most common findings from the non-linear effects, which correlated with defects from the non-linear effects, are the side bands generation, amplitude dissipation, harmonics generation and also resonant waves shifting. Some past application of the non-linear acoustics such as, in monitoring the development of fatigue crack by using the second harmonic generation, (Morris et al. 1979); evaluation of concrete material properties by using non-linear ultrasonic parameters, (Korotkov et al. 1994); evaluation of material disruption due to the asymmetry of a lattice structure and dislocation in crystals by using the non-linear acoustic imaging, (Zheng et al. 1999).

2.3 Vibro-acoustic Method

Non-linear vibro-acoustic method is very fast and sensitive in the detecting the cracks. Vibro-acoustic method is a technique which combined the interaction of high frequency wave and low frequency vibration excitation. The two excitations will be induced to the specimen simultaneously as illustrated in Figure 2.3 (L. Pieczonka et al.). The high frequency wave propagated in the specimen is modulated by the low frequency vibration. If there is a presence of crack in the plate, modulation is generated by the non-linear interaction of waves. Frequency sidebands can be observed around the high frequency excitation. In addition to that vibro-acoustic method able to detect structure damaged by measuring the vibration response signal. If the investigated structure is damaged, the spectrum of the response signal will show additional components which are a higher harmonic (K. Dziedziech, 2016). Besides that, previous research done also found that the modulation sidebands obtained from the nonlinear vibro-acoustic can locate the damage (L. Pieczonka et al., 2012) and can obtain the amplitude modulation intensity (R-value) (Klepka, A. et al., 2016). Klepka et al. (2016) claimed that R-value was obtained from the amplitudes of major sidebands obtained from the test and the high frequency component.

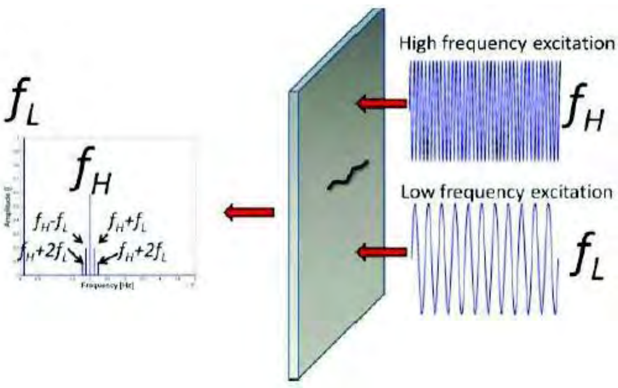


Figure 2.3: The principle of vibro-acoustic modulation (VAM).

Previous researched by Zeng. Chunhua and Zheng. Shijian (1992) state that there are two methods in analysing the structure fatigue under vibration loading. The two methods are time domain method based on the data statistics and the frequency domain method based on the power spectrum density. Yoder (2010) said that VAM is the applying of a lower frequency “pumping” excitation signal and a higher frequency “probing” excitation signal into the structure as shown in Figure 2.4 Yoder (2010). If the structures undamaged it will return a response with energy only at the pumping and probing frequencies. However, in the structure is damaged, additional nonlinear components are created due to nonlinear effects leading to mixing of the two input signals. Yoder also demonstrated that when the ultrasonic signal coincides with the resonant frequencies of the structure, amplitude of the power spectra is magnified (Yoder and Adam, 2010).

Figure 2.4: Schematic figure of cross modulation between pump wave and probe wave.

There are some previous experimental works for the non-linear vibro-acoustic method. The non-linear experimental works setup used by Donskoy et al. (2001) shown in Figure 2.5. In the experiment setup, low frequency signals introduced by using an impact hammer and the output were received and transmitted by using the piezo-ceramic transducer. Mordini et al. (2005) also use similar apparatus set up as shown in Figure 2.6. The different between two setups is the location of signal receiving transducer, in Mordini et al. case the signal will be transmitted through the crack but for Donskoy et al. case reflective signals is used. In both cases they used the first sideband effect in evaluating the effect of sensitivity against the defects sizes. Donskoy et al. method is capable in distinguishing between integrity reducing defects and other structural inhomogeneity while Mordini et al. (2005) found that this method can become one of the NDT damage detection when there are appropriate combination of low and high frequency vibration and a narrow frequency range of ultrasonic signal. Mordini et al. (2005) also found that controlled shaker is more reliable and stable to introduce low frequency signal. So it can replace the use of impact hammer to vibrate the specimen as shown in Figure 2.7.

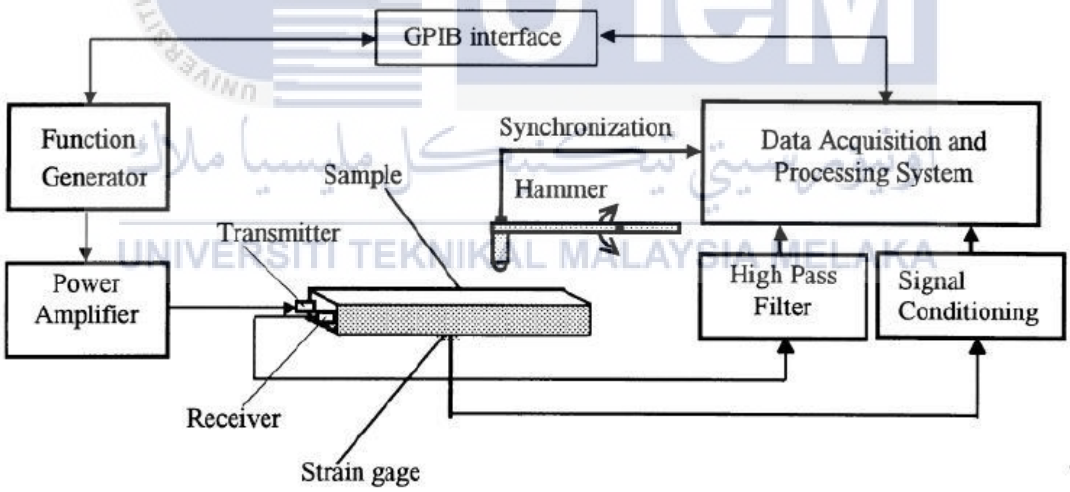


Figure 2.5: Setup of Impact Modulation (IM) technique on a beam (Donskoy et al., 2001)

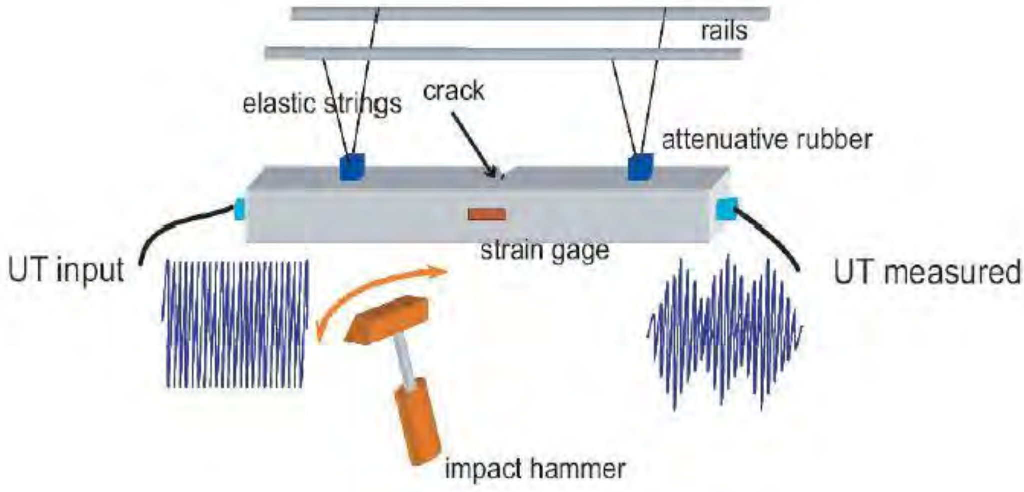


Figure 2.6: Setup of the Vibro-acoustic Method (VAM) testing using impact hammer (Mordini et al., 2005)

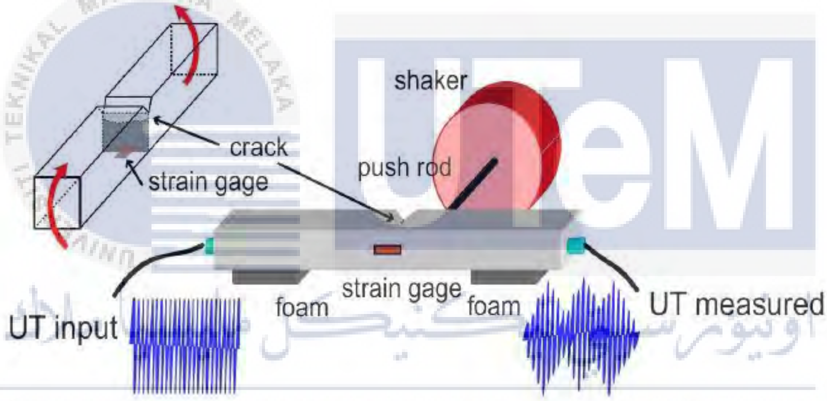


Figure 2.7: Setup of vibro-acoustic method (VAM) by using a shaker as exciter on a steel beam (Mordini et al., 2005)

The best method was introduced by Parson et al. (2006) which incorporated the advance in smart material technologies. Piezo-ceramic stack actuator will be used to excite specimen and the specimen will be hang on elastic string and having a smaller size compared to the actuator as shown in Figure 2.8. Even though, the maximum excitation level from the piezo-ceramic stack actuator is lower compared to the shaker but the result shows a good signature of the sideband effect against the defects.

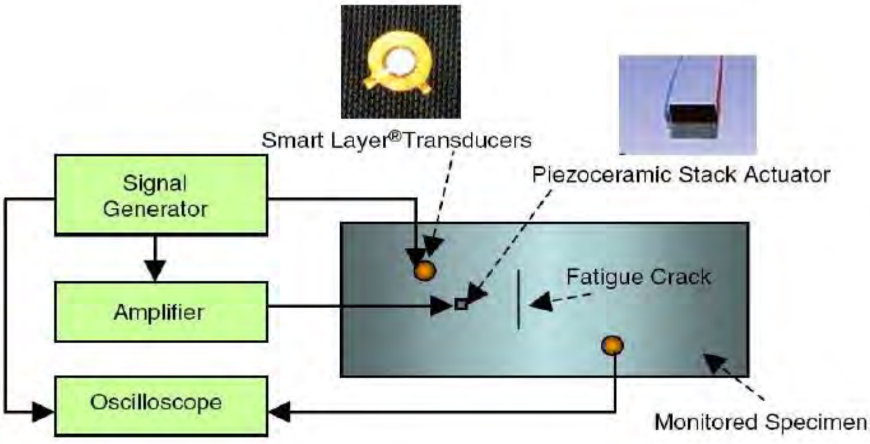


Figure 2.8: Experimental arrangement by using PZT transducer and stack actuator on an aluminium plate (Parson et al., 2006)

CHAPTER 3

METHODOLOGY

This chapter describes the methodology used in this project to obtain the effect of using variation of high frequency wave in vibro-acoustic method to detect the fatigue crack. Firstly, this chapter will present the test specimen preparation for the experimental tests and procedures for the modal analysis and non-linear vibro-acoustic test. At the end of the test, the relation or effect of using variation of high frequency wave in vibro-acoustic method to detect the fatigue crack can be determined. The methodology of this study is summarized in the flow chart as shown in Figure 3.1. The project started by preparation of the test specimen and studying the theory, strategy and approach of vibro-acoustic method. After the preparation of test specimen is completed, modal analysis will be before conducting the non-linear vibro-acoustic test for the crack detection. If the data analysis obtained from the non-linear vibro-acoustic test shows significant result, the effect of using variation of high frequency wave in vibro-acoustic method can be obtained. Otherwise the non-linear vibro-acoustic test should be retaken.

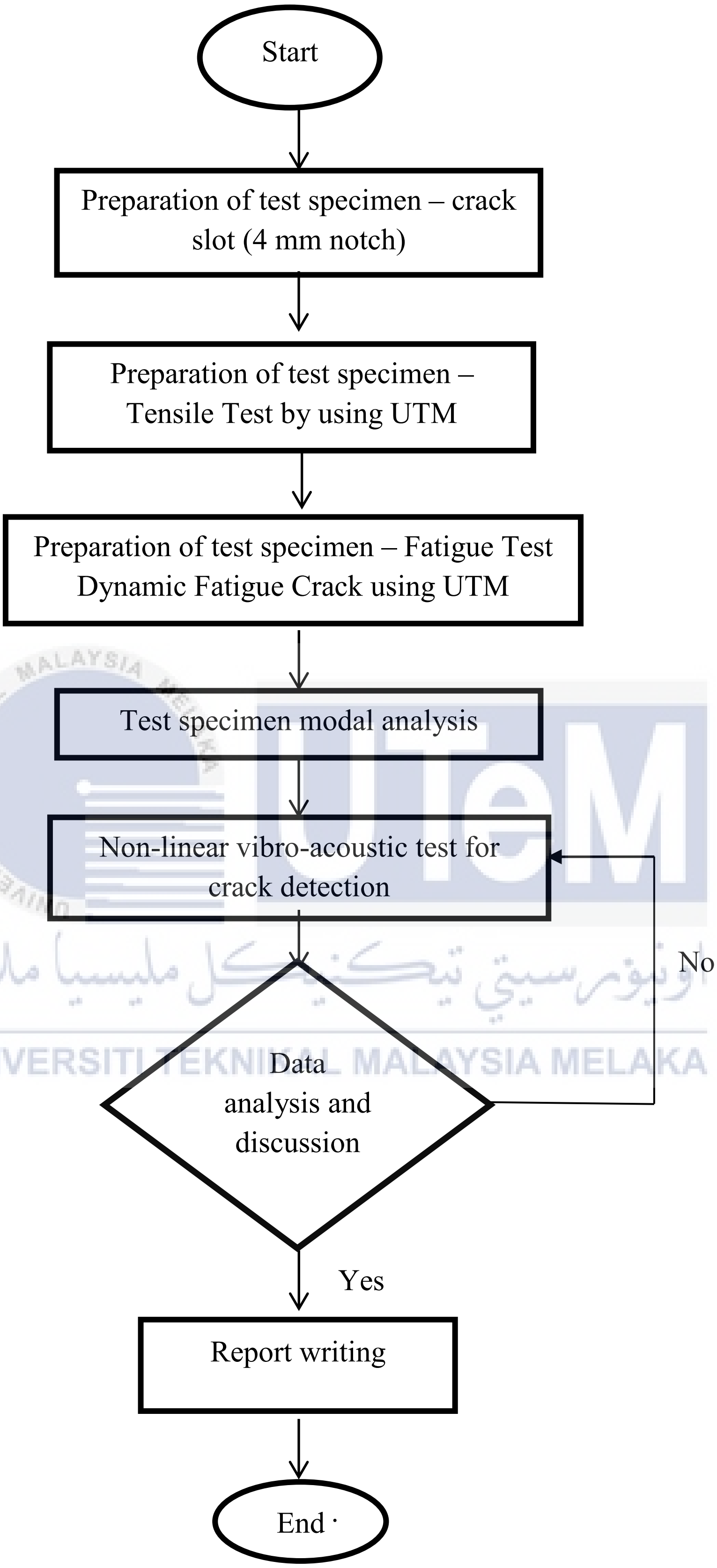


Figure 3.1: Experiment flow chart.

3.1 Test Specimen Preparation

In order to perform the non-linear vibro-acoustic, a test specimen with the present of fatigue crack is needed. The type plate used in the experimental test is 150 mm x 400 mm x 2 mm aluminium plate (AL-2024). The material properties of the aluminium plate used in the test as shown in Table 3.1. AL-2024 is a high strength aluminium alloys and an excellence fatigue resistance. It is usually used in aircraft structural components and fittings, hardware and some parts of the transportation industry.

Table 3.1: Material properties of the aluminium plate.

Property name		Details
Material	Name	Aluminium Al-2024
	Density	2 780 kg/m^3
	Young’s Modulus	72 400 MPa
	Poisson’s ratio	0.33

3.1.1 Crack Slot Preparation

The process of crack creation is initiated by a 3-mm notch in the middle of the plate as shown in Figure 3.2. Then a very small notch was created by using Electrical Discharge Machining (EDM) Drilling Hole and EDM Wire Cut as shown in Figure 3.3 and Figure 3.4. EDM is a manufacturing process by using electrical discharges or sparks. By using EDM, tolerances of +/- 0.005 can be achieved and complex shapes and thin walled configurations without distortion. The finished 3 mm notch on the aluminium plate is shown in Figure 3.5. The notch diameter is 1.5 mm while the slot is 1.5 mm in length and having a 0.2 mm loop for both sides.

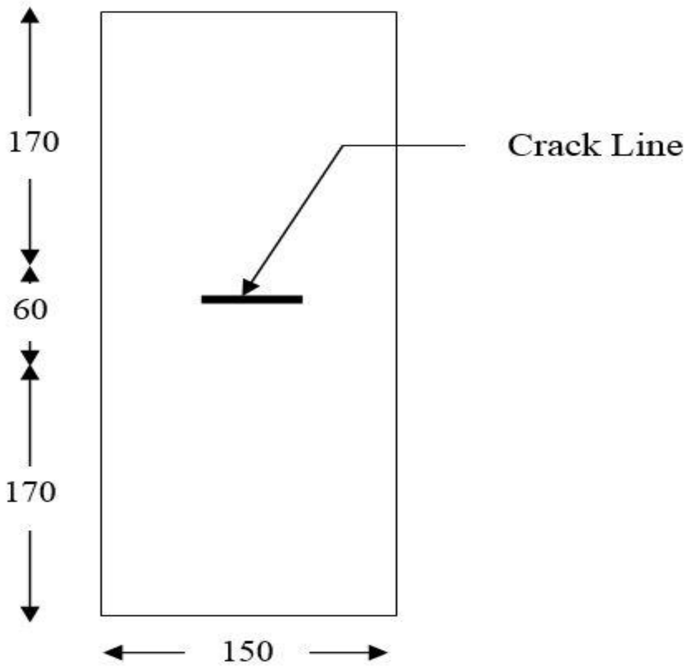


Figure 3.2: Schematic drawing of the aluminium plate.

Figure 3.3: EDM drilling hole machine.

Figure 3.4: EDM wire cut machine.

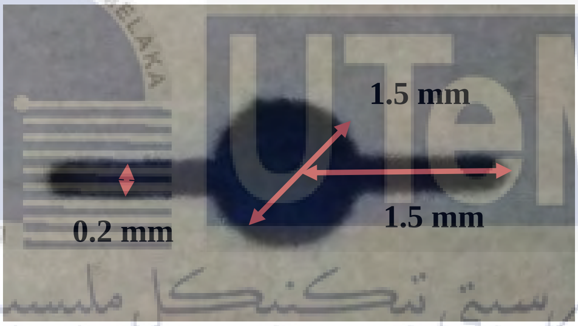


Figure 3.5: 3-mm notch on the aluminium plate.

3.1.2 Tensile Test

Before the crack was initiated on the plate, a tensile test was done to measures the resistance of the plate to a static or slowly applied force. The Tensile Test was done by using INSTRON Universal Testing Machine (UTM). In order to place the plate, align with the UTM jigs; gridlines was drawn as shown in Figure 3.6 as guidance to place the plate accordingly later on.

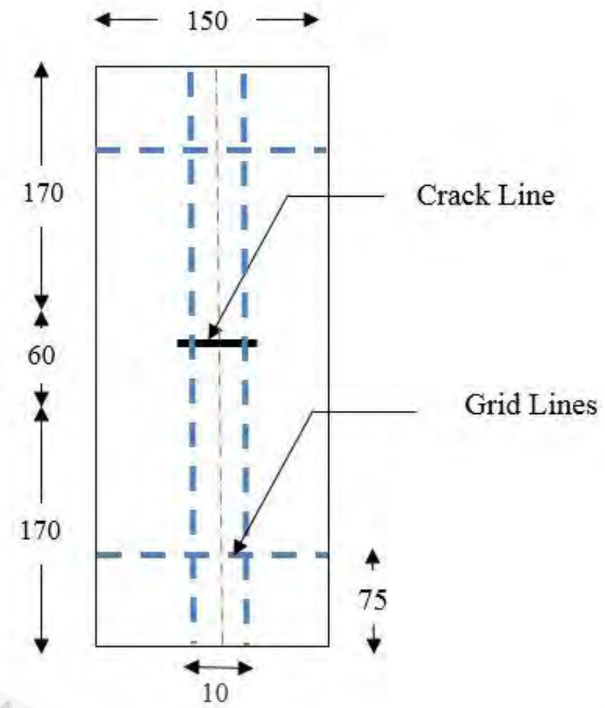


Figure 3.6: Schematic drawing of the aluminium plate with gridlines.

Figure 3.7: INSTRON Universal Testing Machine (UTM).

3.1.3 Fatigue Test

A fatigue test was performed against the aluminium plate to produce fatigue crack. Fatigue crack formation was initiated by applying cyclic load on the plate by using the UTM. The maximum, minimum, mean and amplitude load obtained earlier from the tensile test is test into the UTM system. The desired fatigue crack length is 20 mm. The procedure was started by set-up the obtained parameter of the mechanical properties of the plate i.e. the maximum, minimum, mean, amplitude load and frequency in the UTM. The specimen was clamped onto the UTM jigs. Then control by load and cyclic waveform was selected for the system. After that, set the maximum and minimum loading limit were set for the operating system and the machine operation was started. Setting up the limits is necessary for safety precaution. After 20 cycles, press the amplitude control button and when the operation was finished, press the hold button followed by finish and then stop. Reset all the button and unclamp the test specimen. Constant monitoring is needed during the process; it is because when the fatigue crack start to initiate, the propagation of the crack become very fast.

Figure 3.8: Aluminium plate was clamped into the UTM jigs.

3.2 Modal Analysis

Experimental modal test was performed to determine the natural acoustic characteristics or dynamic response of a material, vibration mode and mode shape for each vibration mode. Modal analysis involves imposing an excitation into the structure and finding the frequencies the structure resonates (Sohn et al., 2003). A system setup for modal analysis includes several measurement and test components around the test structure itself as shown in Figure 3.9. Typically, one or more electrodynamics shakers (also called modal exciters) are employed to provide a known excitation input force to the structure. Scanning Laser Doppler Vibrometer (SLDV) is used to measure the resulting vibration responses.

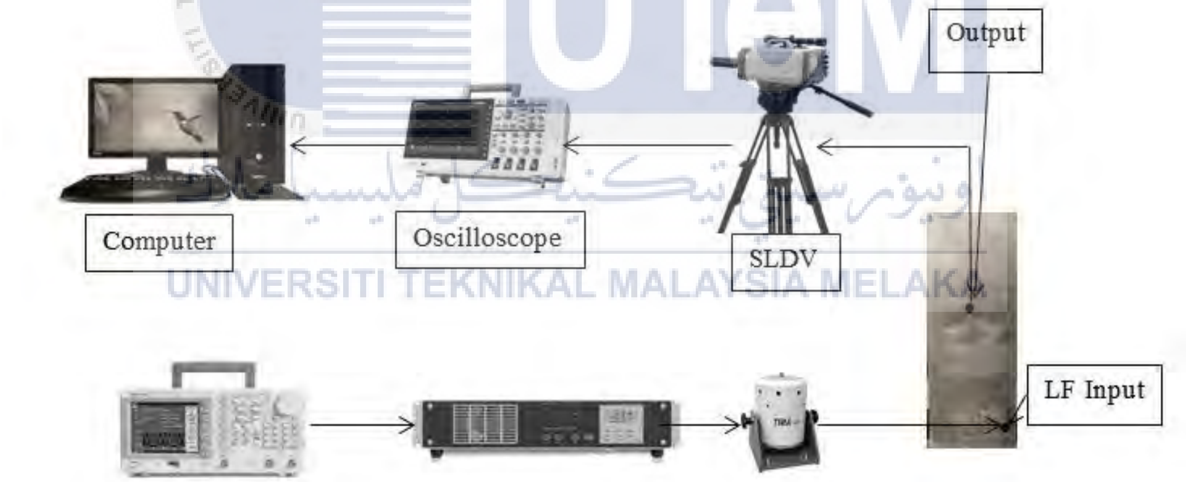


Figure 3.9: Schematic diagram of modal analysis experimental setup.

In order to select the low frequency excitation value for the non-linear vibro-acoustic test, experimental modal analysis was performed. The experiment was performed on 150 mm x 400 mm x 2 mm aluminium Al-2024 plate. Figure 3.10 shows the experimental arrangement of modal analysis experiment by using the SLDV. The aluminium plate will be suspended by using a thread and the distance between the SLDV and the plate was about 1395 mm.

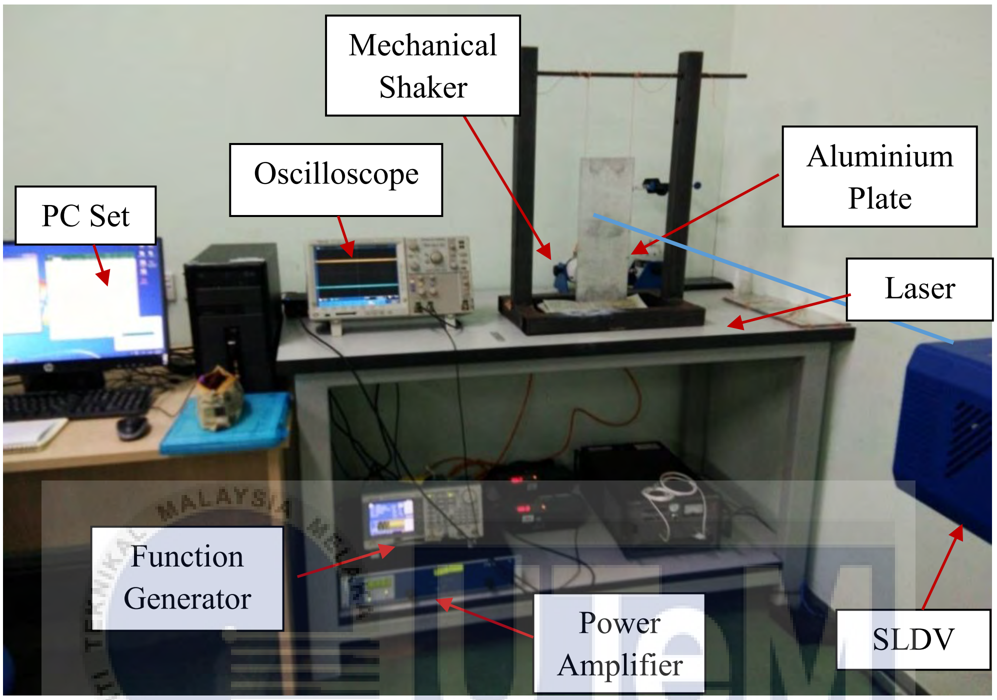


Figure 3.10: Modal analysis experiment setup by using SLDV.

As illustrated in Figure 3.11 the laser beam from the SLDV (SWIR OptoMET) was point 30 mm above the crack line to measure the output signal from the excitation. Function generator (Tektronix AFG 3022) controlled the low frequency signal. While a mechanical shaker (TIRA GmbH type S 50018) to induce low frequency signal which amplified by a power amplifier (TIRA type BAA 60), was attached at 25 mm x 25 mm on the bottom right corner edge of the plate. The vibration response was captured and recorded by SLDV. The parameter configuration for the function generator, SLDV and power amplifier were provided in Table 3.2, Table 3.3 and Table 3.4 respectively.

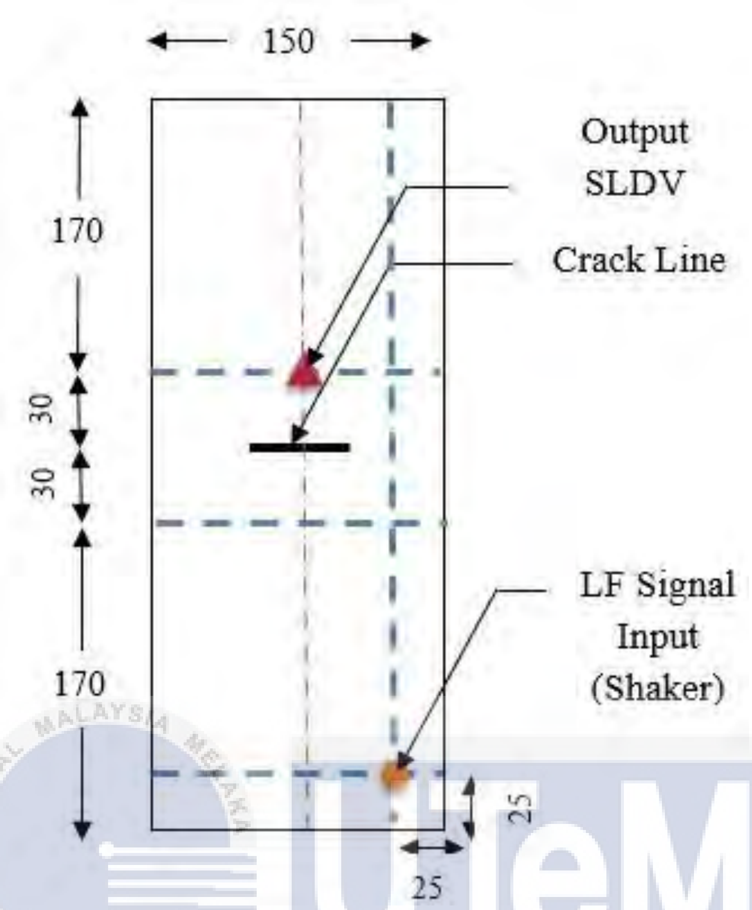


Figure 3.11: Schematic drawing of plate during modal analysis experiment.

Notes: All the dimensions in mm

Table 3.2: Function generator parameter and configuration for modal analysis.

Item	**Parameter**
Sweep frequency	1-2000 Hz
Sweep Time	2 s
Amplitude	2 vpp
Sampling Size	100k/sample

Table 3.3: SLDV parameter and configuration for modal analysis.

Item	Parameter
Displacement	$\pm$ 122.5 um
Velocity	$\pm$ 490 mm/s
Acceleration	$\pm$ 156 000 g
Max. Frequency	500kHz
Filter	Off

Table 3.4: Power amplifier parameter and configuration for modal analysis.

Item	Parameter
Amplifier power	1V

3.3 Vibro-acoustic Method and Analysis

Next procedure is to perform a non-linear vibro-acoustic test on the cracked plate to investigate the present of the crack on the plate. Non-linear vibro-acoustic is a combination of vibro-acoustic modulation of an intensive low frequency (modal) vibration and weaker high-frequency ultrasonic wave. The plate will be suspended using a thick thread/spring. A mechanical shaker is used as a low frequency exciter while a piezoceramic transducer is used as the high frequency input. The excitation waveform will be generated by a function generator and a power amplifier was used to amplify the signal from the shaker. A schematic diagram that illustrates the experimental set-up is shown in Figure 3.12**.**

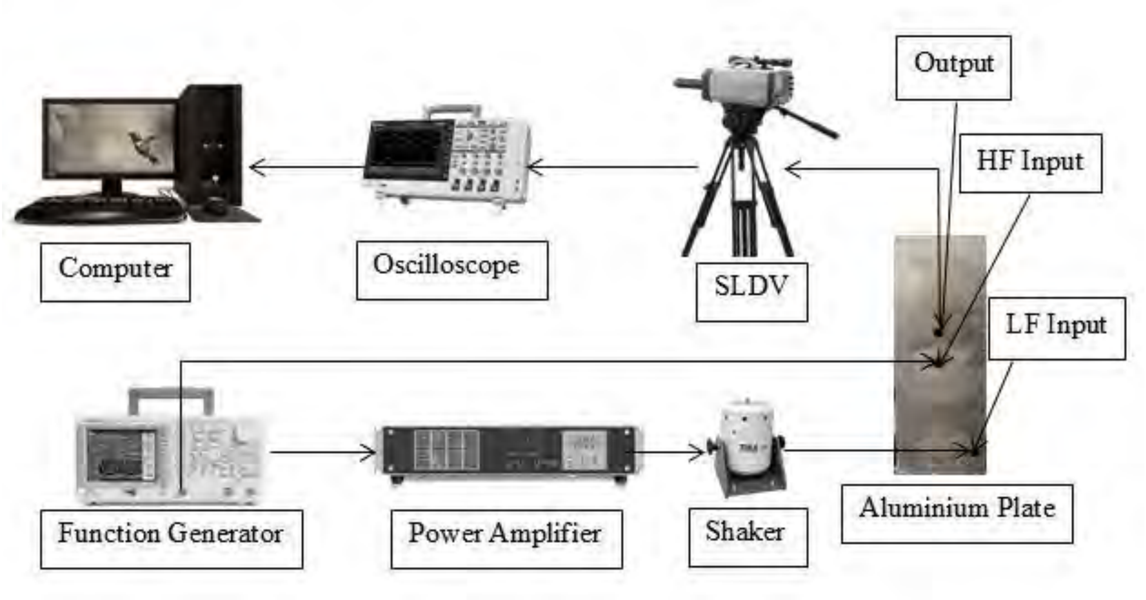
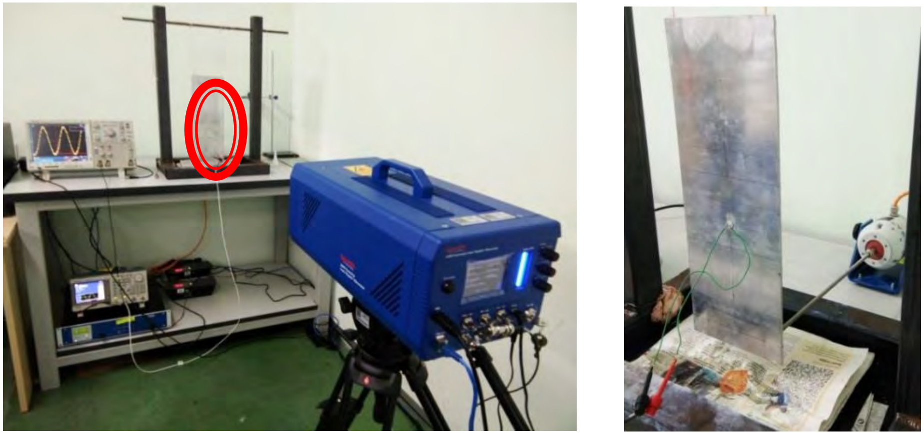


Figure 3.12: Schematic diagram of vibro-acoustic test.

The non-linear vibro-acoustic experimental arrangement and equipment was quite similar with modal analysis as shown in Figure 3.13. But in the vibro-acoustic test, a piezoceramic transducer (PZT) was attached to the plate to induce the high frequency (HF) signal excitation as illustrated in Figure 3.14. The HF excitation signals used are 60, 100, 150, 200, 250 and 300 kHz. The LF (66 Hz, 88.5 Hz and 110.5 Hz) is excited at the lower corner of the plate by using a shaker. The output of the vibration response will be measured by the SLDV**.** The parameter configuration for the function generator, SLDV and power amplifier were provided in Table 3.5, Table 3.6 and Table 3.7 respectively.



(a) (b)

Figure 3.13: Vibro-acoustic (a) experimental arrangement (b) enlarged PZT location.

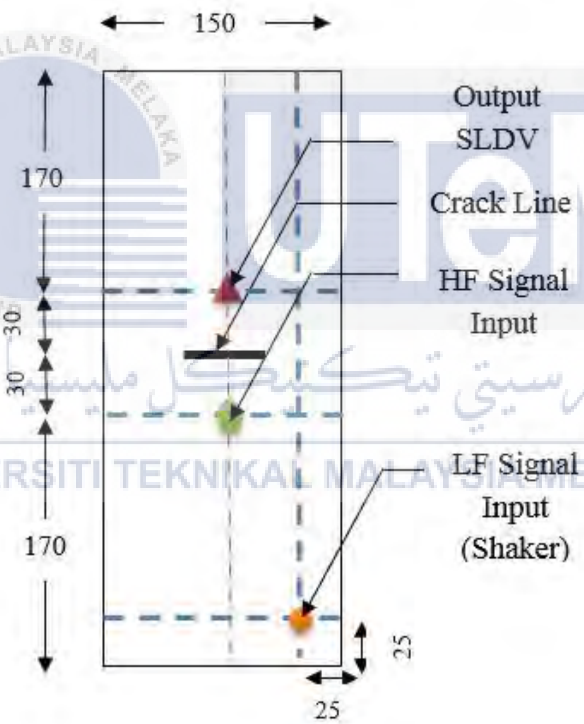


Figure 3.14: Schematic drawing of plate during vibro-acoustic test.

Notes: All the dimensions in mm.

Table 3.5: Function generator parameter and configuration for vibro-acoustic test.

Item	Parameter
Continuous frequency	66, 88.5 and 110.5 Hz
Amplitude level	2 vpp
Sampling Size	2.5 MS / sample
No of sample	100 k points

Table 3.6: SLDV parameter and configuration for vibro-acoustic test.

Item	Parameter
Displacement	$\pm$ 122.5 um
Velocity	$\pm$ 490 mm/s
Acceleration	$\pm$ 156 000 g
Max. Frequency	500kHz
Filter	Off

Table 3.7: Power amplifier parameter and configuration for vibro-acoustic test.

Item	Parameter
Amplifier power	2V

CHAPTER 4

RESULTS ANALYSIS AND DISCUSSION

4.1 Tensile Test

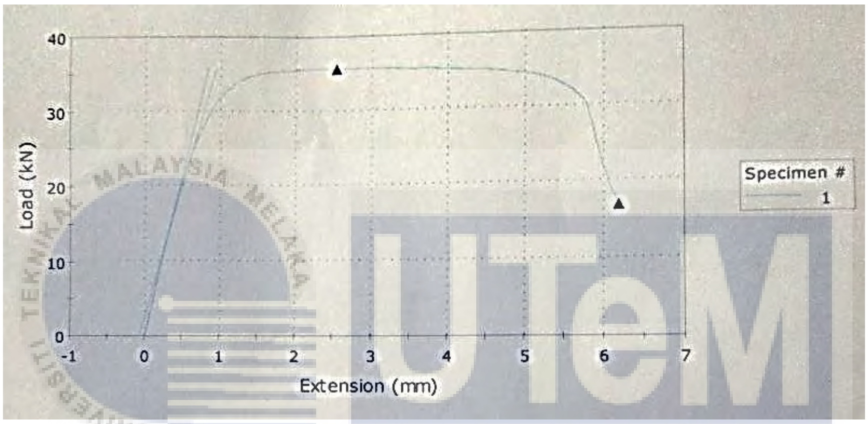


Figure 4.1: Tensile test graph of load vs extension.

The value of minimum, maximum mean and the amplitude load can be calculated from the data in Table 4.1.

Table 4.1: Parameter of the mechanical properties obtained from the tensile test.

No	Max load for yield (kN)	Tensile stress at maxi load for yield (MPa)	Maximum Load (kN)	Tensile stress at Maximum Load (MPa)	Modulus (E-modulus) (GPa)	Modulus (Chord - Cursor) (GPa)	Extension at Break (Standard) (mm)
1	> 35.62	> 118.73	35.62	118.73	29.22	-	6.28

$$\textbf{Maximum Load} = 75\% \text{ of Yield Load}$$

$$= (75/100) \times 35.62$$

$$= 26.7150 \text{ kN}$$

$$\textbf{Minimum Load} = 0.1 \text{ of Maximum Load}$$

$$= 0.1 \times 26.715 \text{ kN}$$

$$= 2.6715 \text{ kN}$$

$$\textbf{Mean Load} = \frac{\text{Maximum Load} + \text{Minimum Load}}{2}$$

$$= \frac{29.3865 \text{ kN}}{2}$$

$$= 14.6933 \text{ kN}$$

$$\textbf{Amplitude Load} = \frac{\text{Maximum Load} - \text{Minimum Load}}{2}$$

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

$$= 12.0218 \text{ kN}$$

The maximum load for the fatigue test is 75% of the yield load which is 26.715 kN. The minimum load is 0.1 of the maximum load value which is 2.6715 kN. The average number of maximum and minimum load is the mean load which is 14.6933 kN. While for the amplitude load is the average of different value of maximum and minimum load which is 12.0218 kN.

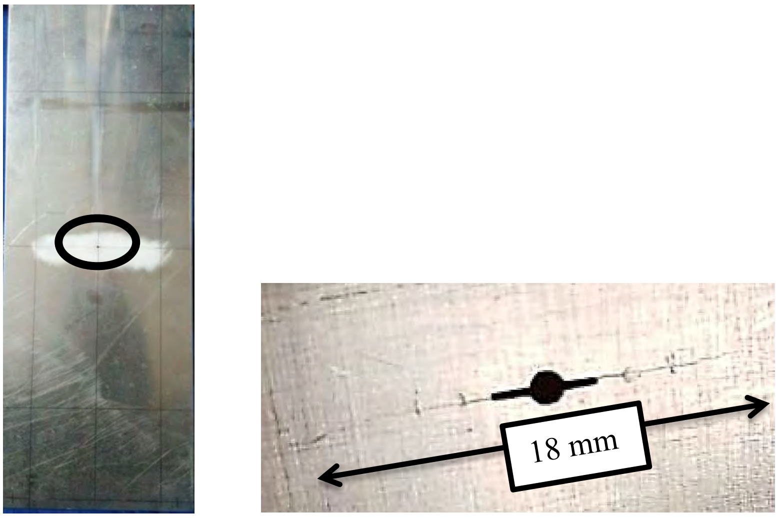
4.2 Fatigue Test

The 18-mm crack was obtained after 129 209 cycle amplitude load with the range of loading between 2.6715 kN and 26.715 kN and 7 Hz frequency. All the data were obtained from the UTM System Controller. The duration to produce fatigue crack on the aluminium plate is about 5 hours and 13 minutes. The time taken can be reduced by increasing the frequency value. Table 4.2 shows the number of test parameter i.e. maximum and minimum load, loading cycle and loading frequency, to obtain the desired crack length. The crack length obtained is not exactly symmetrical for both side due to the load distribution and the position of the plate during the test.

Table 4.2: Number of cycles, loads and loading frequency to create fatigue crack

Crack Length (mm)	No of cycle	Load (kN)		Loading Frequency
		Min	Max	
No crack	10 200	2.6715	26.715	7
No crack	20 000	2.6715	26.715	7
5	39 082	2.6715	26.715	7
9	60 800	2.6715	26.715	7
14	90 009	2.6715	26.715	7
18	129 209	2.6715	26.715	7

Figure 4.2: UTM machine control system.



(a) (b)

Figure 4.3: Dynamic fatigue crack on the (a) aluminium plate and (b) enlarged area.

4.3 Modal Analysis

In finding the resonant frequencies, the plate will be excites with varieties frequencies between 1 Hz to 2000 Hz (Sweep). Figure 4.4 shows the input signal and output signal in time domain. The vibration response was captured and recorded by SLDV. Recorded data as shown in Figure 4.4 will be converted to frequency domain by using transfer function in MATLAB software. From the analyses, frequency response function (FRF) was obtained as

$$T_{xy} = \text{tfestimate}\,(x,y) = P_{xx} / P_{xy} \tag{4.1}$$

The transfer function T_{xy} estimated by using the power spectral density of input signal vector P_{xx} and power spectral density of the output signal vector P_{xy}.

a)

b)

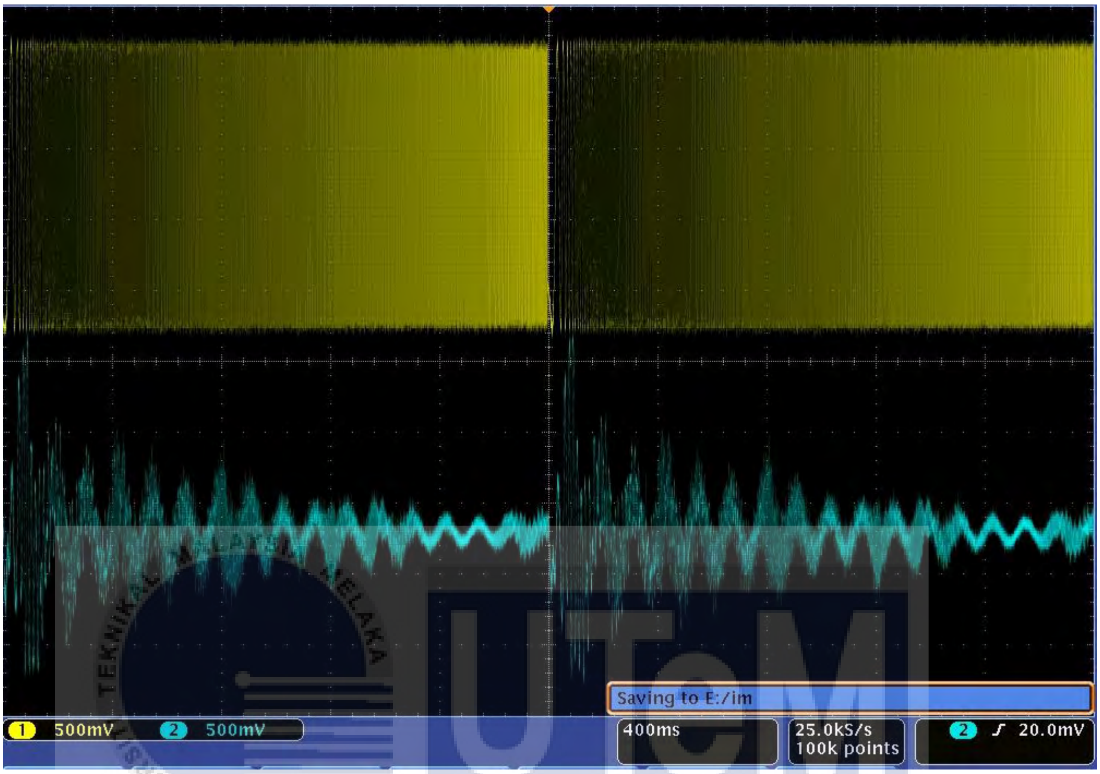


Figure 4.4 Input signal a) and output signal b) in time domain for modal analysis

Figure 4.5 shows the frequency response result for the aluminium plate where several vibration modes of the damaged plate can be observed. When a resonant frequency reached, there will be a peak. Generally, in modal analysis several resonant frequencies and displacement field also known as mode shape will be obtained.The first six peaks value for the plate are 66, 88.5, 110.5, 129, 201.1 and 325.7 Hz but only three modal frequencies were selected as listed in Table 4.3 for non-linear vibro-acoustic modulation tests for crack detection. These three frequencies will be used as the low frequency (LF) signal. One of the issue during the test is there is some external vibrations which can affect the resonant frequency such as room temperature and sound. A way suggested to fix this is by setting up the test in an enclosed space where no extra vibrations could affect the test. Other ways suggested are by doing the theoretical validation or simulation.

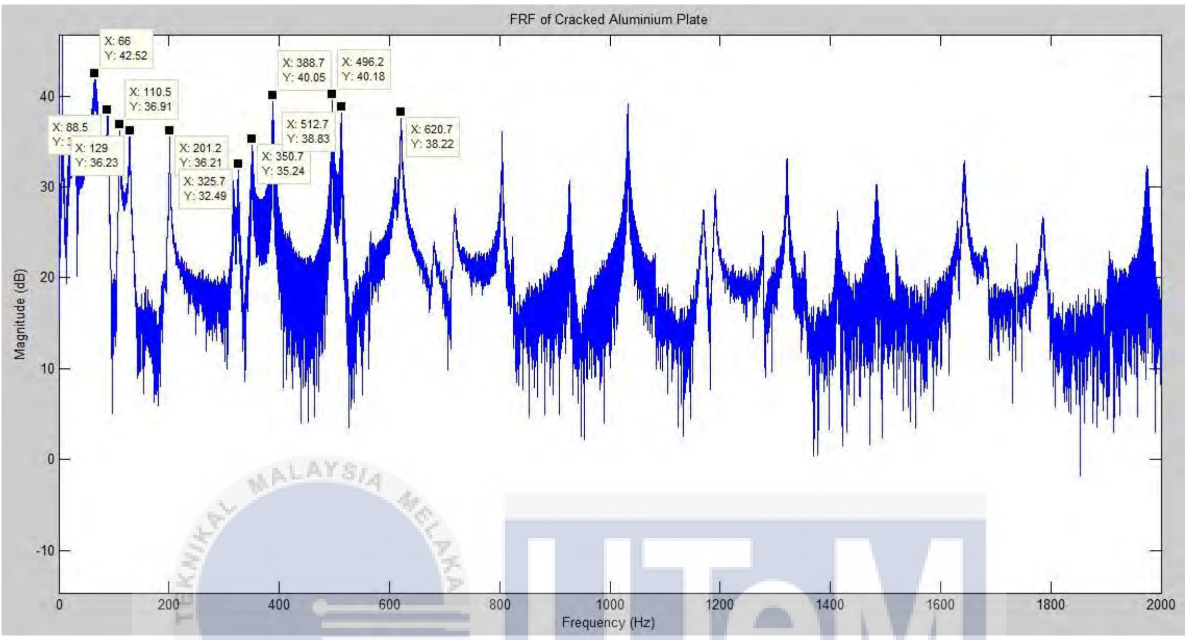


Figure 4.5: Modal analysis result for vibration Frequency Response Function of cracked aluminium plate.

Table 4.3: Peaks and frequency value for cracked aluminium plate FRF

No of peaks	Frequency (Hz)
1	66
2	88.5
3	110.5

4.4 Non-Linear Vibro-Acoustic Test

In order to determine the non-linear modulation intensity effect, the experimental methodology described earlier in section 3.3 was performed. The vibro-acoustic was performed on 18 mm cracked aluminium plate by using the three modal frequencies obtain in Section 4.3 along with 60, 100, 150, 200, 250 and 300 kHz ultrasonic frequencies.

Recorded data as shown in Figure 4.6 will be converted to frequency domain by using FFT function in MATLAB software. From the analyses, Power Spectra was obtained and were zoomed around the HF excitation value to reveal possible modulation sidebands (R-index) as shown in Figure 4.7 until Figure 4.9. Then, amplitude of all these sidebands will be analysed using

$$\text{R-value}_1 = \frac{A_1 + A_2}{A_0} \tag{4.2}$$

$$\text{R-value}_2 = \frac{A_3 + A_4}{A_0} \tag{4.3}$$

$$\text{R-value}_{avg} = \frac{A_1 + A_2 + A_3 + A_4}{A_0} \tag{4.4}$$

Where A_0 is the high frequency excitation value (probing wave), A_1 and A_2 are the amplitude of the first sideband components while A_3 and A_4 are the amplitude of the second sideband components.

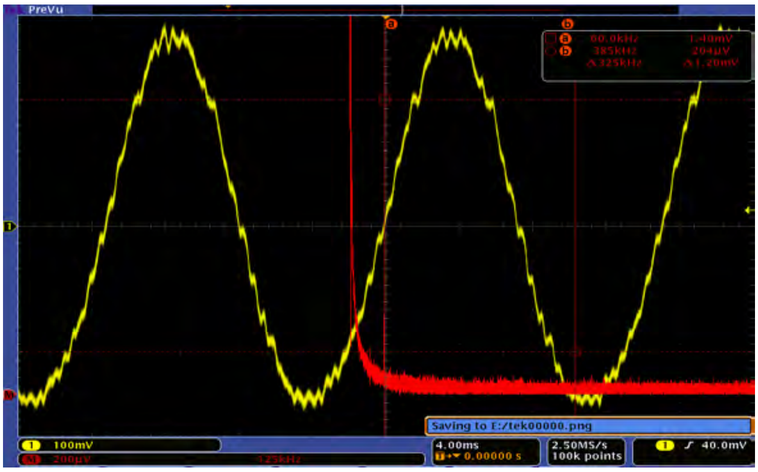


Figure 4.6 Input and FFT signal for non-linear vibro-acoustic test.

The intensity of modulation (R-value) can be analysed using Eq. (4-2), (4-3), and (4-4). Eighteen values of modulation coefficient (R-value) will be obtained at the end of the test. The R-value for all the first sideband, second sideband and the average value are listed in Table 4.4, Table 4.5 and Table 4.6 respectively.

Table 4.4: First sideband value (R-value$_1$) for cracked aluminium plate

High frequency (kHz)	Modal frequency (Hz)		
	66	88.5	110.5
60	0.3267	0.6951	0.3421
100	0.345	0.5278	`0.7615
150	0.6923	1.4483	0.3387
200	0.1675	0.5955	0.1062
250	0.2095	0.2009	0.1412
300	0.6647	0.5274	0.2498

Table 4.5: Second sideband value (R-value$_2$) for cracked aluminium plate

High frequency (kHz)	Modal frequency (Hz)		
	66	88.5	110.5
60	1.8911	1.756	0.7476
100	1.78	1.722	1.2385
150	1.8154	1.6207	1.0933
200	1.823	1.2303	1.2346
250	1.7298	1.4081	1.2933
300	1.815	1.5691	1.0438

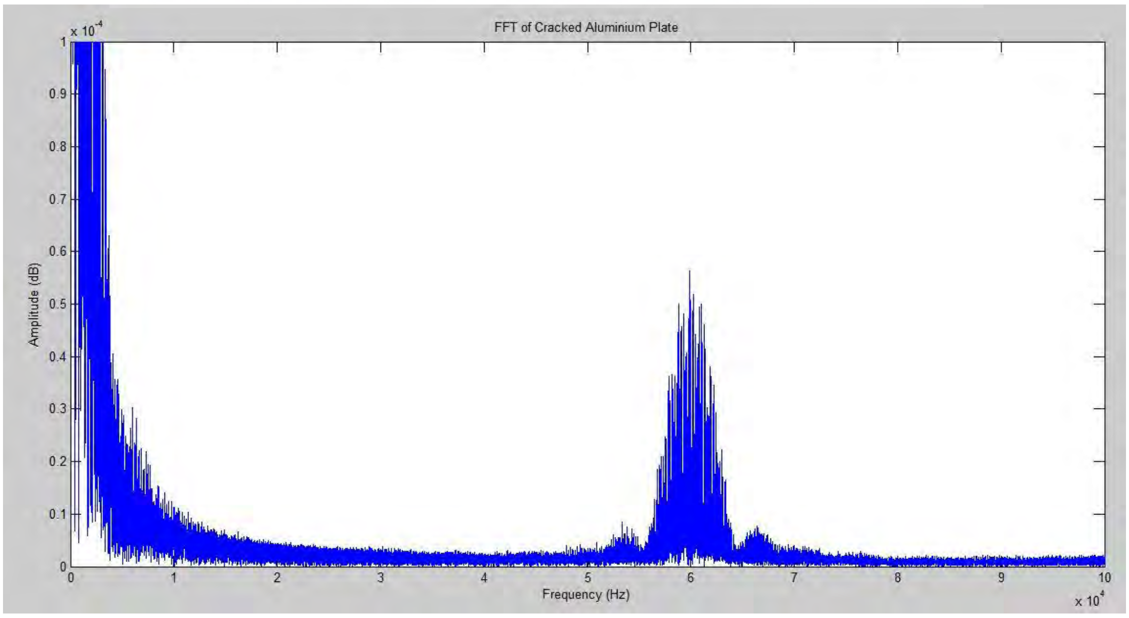
Table 4.6: Average of the sideband value (R-value$_{avg}$) for cracked aluminium plate

High frequency (kHz)	Modal frequency (Hz)		
	66	88.5	110.5
60	2.217841482	2.451196478	1.089665725
100	2.124966	2.25	1.999989474
150	2.507689884	3.068957907	1.432025652
200	1.990439735	1.825869663	1.340771507
250	1.939307073	1.608938641	1.434536579
300	2.47967594	2.141465263	1.293628276

4.5 Analysis of Non-Linear Vibro-Acoustic Test

Figure 4.7 until Figure 4.9 shows examples of the power spectra obtained from the vibro-acoustic test for the 60 kHz HF excitation with three different modal excitation frequencies. From the figures it can be observed that the cracked aluminium plate produced amplitude modulation due to the ultrasonic wave which is modulated by the low-frequency vibration wave. Theoretically as explained in Chapter 2, when there is no damage in the specimen, the spectrum of the measured vibration response signal exhibits only the major frequency components but when there are damages on the specimen additional components will produce such as higher harmonics and sidebands around the high frequency components.Figure 4.7 (b) clearly displays a clear pattern of the amplitude modulation around 60 kHz ultrasonic wave signal. The spacing between the ultrasonic frequency (HF) excitation and the sidebands corresponds to the modal frequency of LF excitation, i.e. 66 Hz. Similar sidebands spacing can be seen for other two LF excitation which are 88.5 Hz and 110.5 Hz as shown in Figure 4.8 and 4.9.

a)



b)

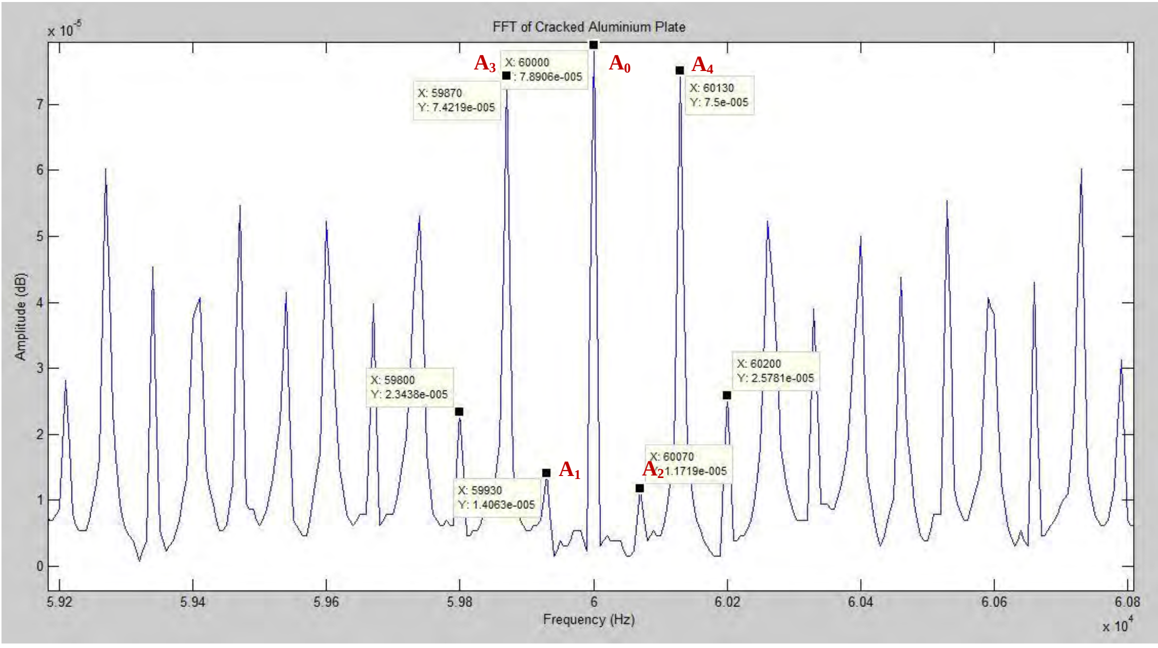


Figure 4.7 Power spectra signal for 60 kHz (HF) 66 Hz (LF) a) Overall b) zoomed around the HF excitation.

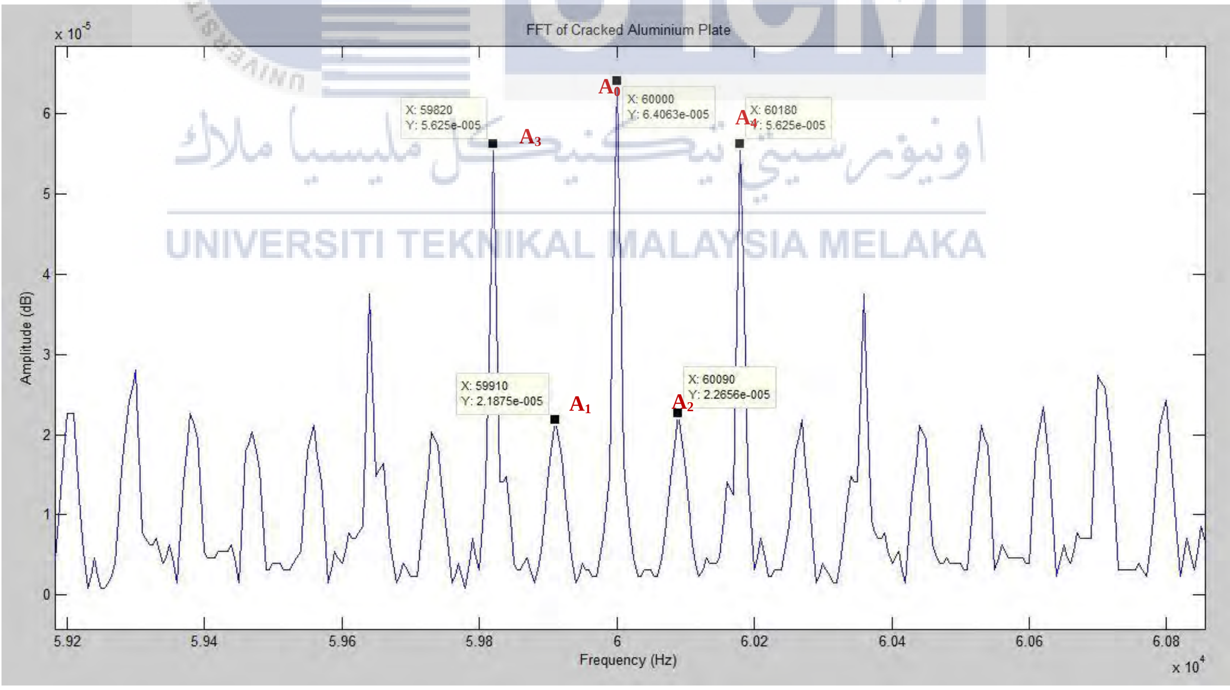


Figure 4.8 Power spectra signal for 60 kHz (HF) 88.5 Hz (LF).

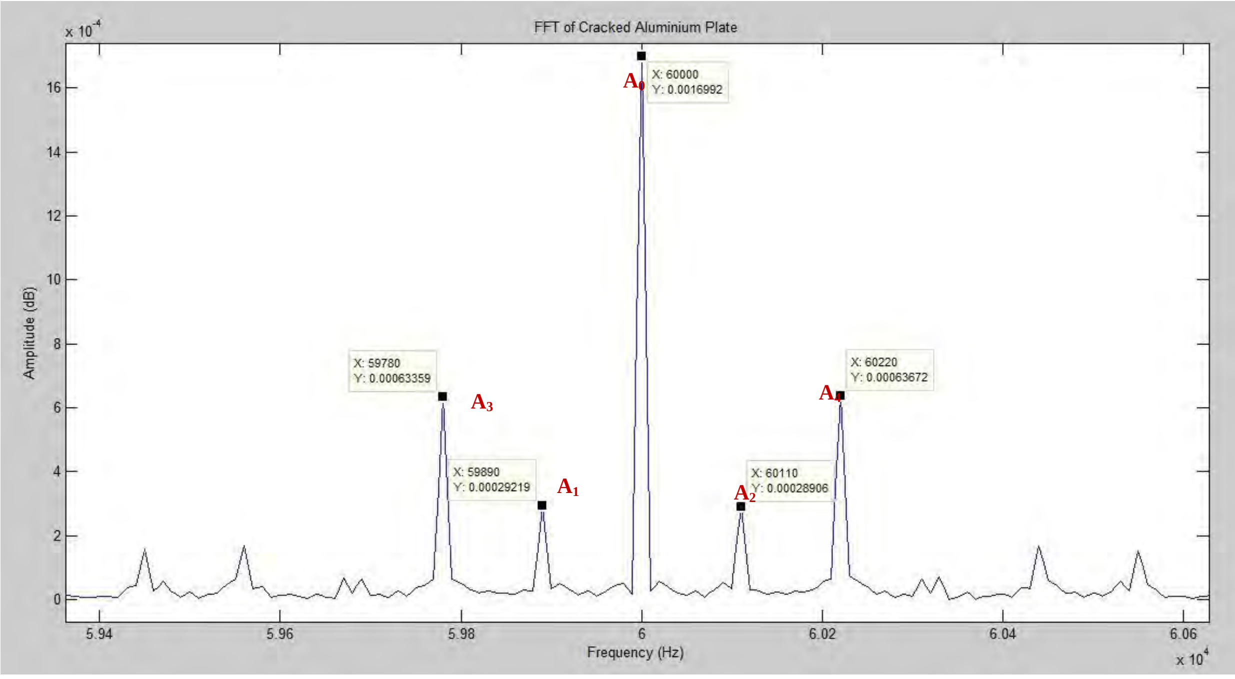


Figure 4.9 Power spectra signal for 60 kHz (HF) 110.5 Hz (LF).

4.6 Analysis of High-Frequency Dependence on Sideband

A series of test was performed to analyse the modulation intensity for different LF and HF excitation value. In order to verify the nonlinear modulation intensity effects, the findings from previous section will be validated. This section will presents the results for the ultrasonic wave modulation dependence against the HF excitations. The results are presented in Figure 4.10 for the different HF value and modal frequencies. Figure 4.10 (a) and (b) show result for the 1st and 2nd sideband amplitudes against the HF excitations for the cracked plate respectively.

Referring to Figure 4.10 (a), the first sidebands values is increasing during 150 kHz and 300 kHz for all three modal frequencies. While for the second sidebands values as shown in Figure 4.10 (b), for 66 Hz signal does not show any significant change, but for

88.5 Hz the value is slightly decrease during 200 kHz signal excitation. While for 110.5 Hz, the R-value increase during 100 kHz, 200 kHz and 250 kHz.

Referring to Figure 4.10 (c), the average value for both sidebands, the modulation intensity increase significantly for the damaged plate after the 60 kHz, but only for 110.5 Hz modal excitation. However for 88.5 Hz and 66 Hz the modulation intensity increase significantly for the damaged plate after the 100 kHz and 250 Hz. Based on the overall view on the illustrated figure, it can be seen that increasing the HF excitation value does not have much impact on the amplitude modulations. Besides that, it will difficult to distinguish the crack length based on the R-value because they have mostly a similar value within the range.

Previous research done by P. Duffour et al. (2006) suggested that 60 kHz of ultrasonic excitation signal. In the research 60 kHz demonstrated good sensitivity for both small and large crack. The finding also shows that the frequency at high range does not affect the sensitivity of R-value against the crack length. Other research done by Van et. al. (2000) also accepted that low frequency is the causes of wave distortion and high frequency does not leave much impact on the test. Modal frequencies value is more essential for the non-linear effects to appear due to the interaction of crack faces cause by the excitation. In summary, increasing the high frequency excitations value does not produce significant change on the amplitude modulations.

a)

b)

c)

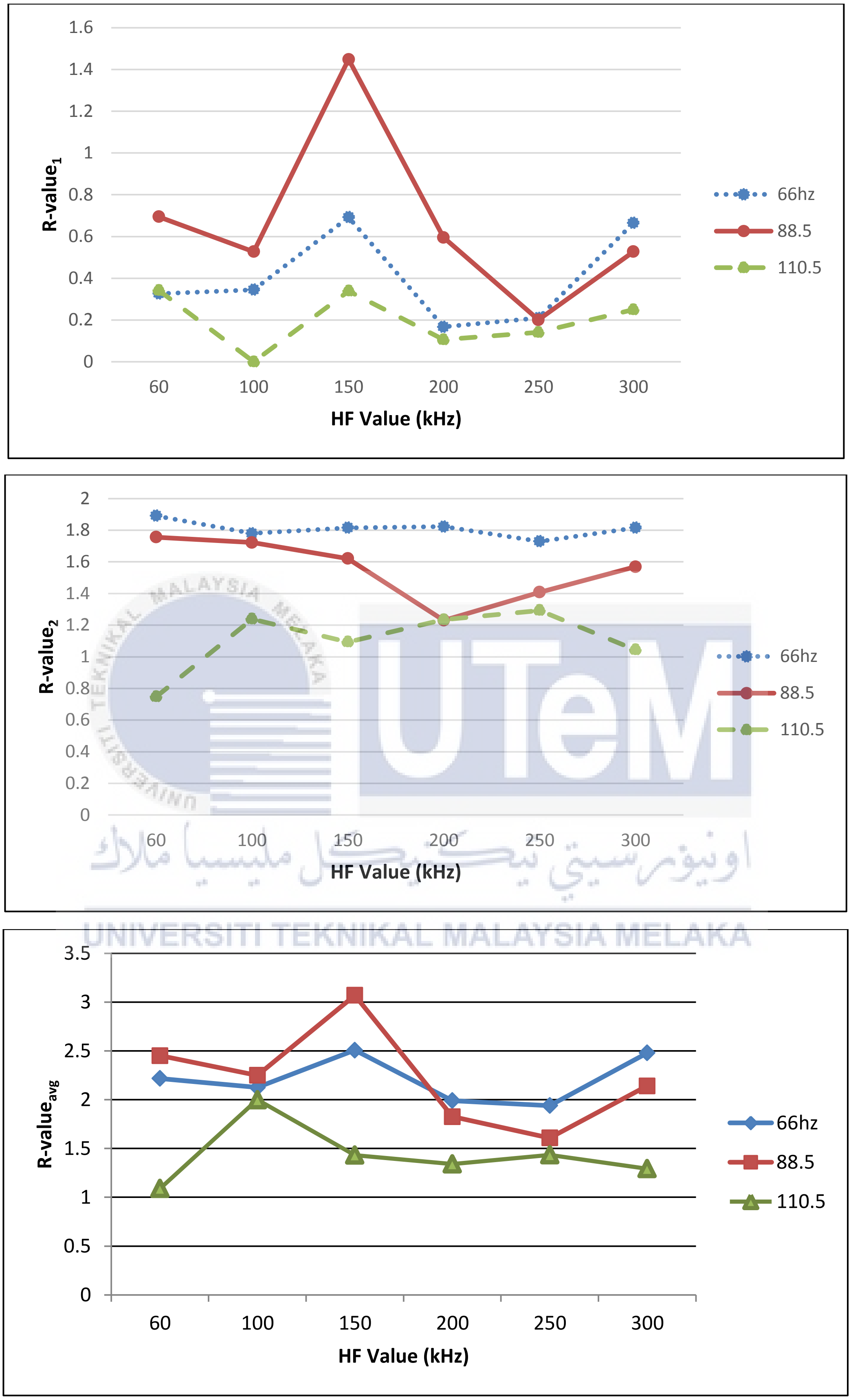


Figure 4.10 R-value for all the a) first sideband, b) second sideband and c) the average value of first and second sideband.

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

In summary, by using the non-linear vibro-acoustic as the analysis technique, undamaged structure can be represented by a linear system while damaged structure will include generation of sideband responses. This technique capable and showed that nonlinear effects can detect small fatigue crack in the aluminium plate. The results show the amplitude modulation effects around the ultrasonic frequency in the power spectra signal. The non-linear vibro-acoustic test also explains the amplitude modulation dependence of using variation of high frequency wave in vibro-acoustic method to detect the fatigue crack. The result of experimental studies shows that the high frequencies excitation does not give significant change on the modulation intensity but proper selection of the high frequency excitation value and also its location is important to obtain a good result. Besides that, the results are similar to previous research findings. However, further research work is required to confirm the findings and more understanding on the mechanisms behind this method could be studied and developed.

Some recommendations for future works are to do simulation work in order to analyse the mode shape, frequencies and the location to induce the excitation by using Finite Element (FE) modelling before running the experimental works. Further work related to the three fatigue crack modes against the resonance frequency also recommended to be study further. It is because each resonance frequency has its own deformation shape and may also contribute to the modulation effects. Future works also need to use varieties of excitation frequencies, location and also few other crack sizes in order to study the modulation intensity at different parameter. The modulation effect also should be investigated on undamaged specimens in order to study the nonlinearities caused by material, boundary effects or the instrumentation itself.

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APPENDIXES

Appendix A - 1

MATLAB code for determining modal analysis of the aluminium plate

```
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])
```

Appendix A - 2

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

```
clear all;

data1 = csvread ('tek00000.csv');

f1 = data1 (:,1);

amp1 = data1 (:,2);

plot (f1,amp1)

title ('FFT of Cracked Aluminium Plate')

xlabel ('Frequency (Hz)')

ylabel ('Amplitude (dB)')

xlim ([0 65000])


dcmObj=datacursormode;

set (dcmObj,'UpdateFcn',@updateFcn);
```

Appendix B

Power spectra signal zoomed around the HF excitation.

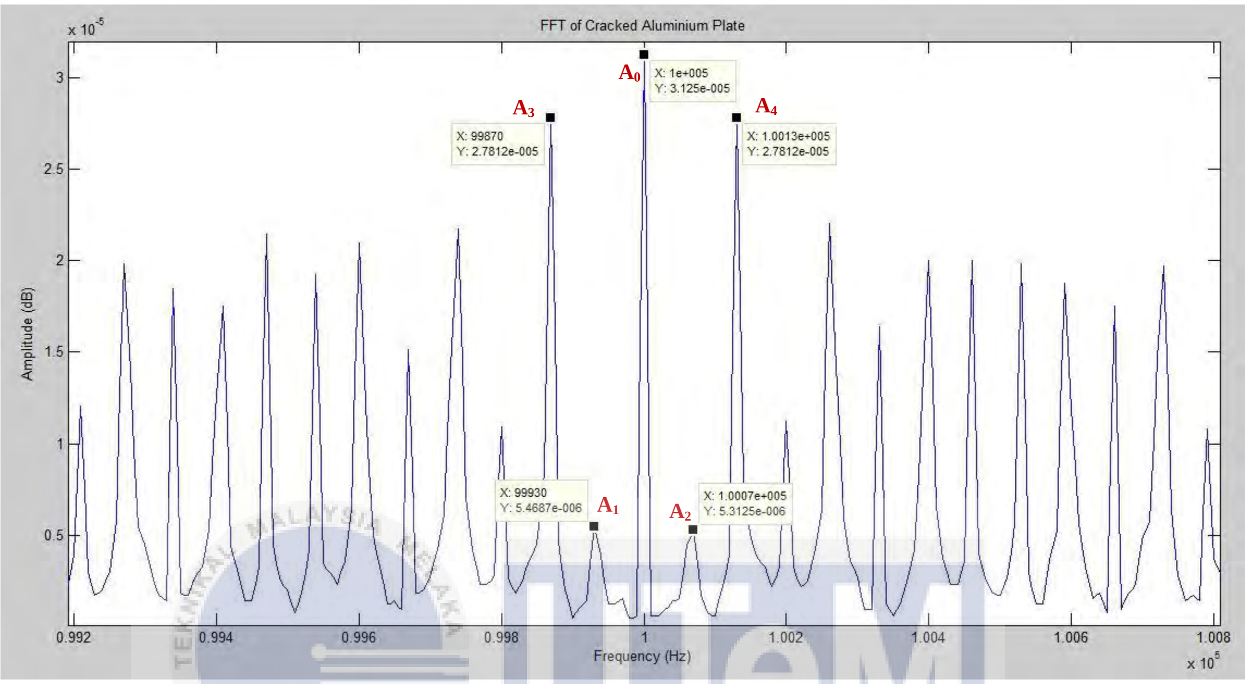

Figure B.1 FFT for 100 kHz (HF) 66 Hz (LF)

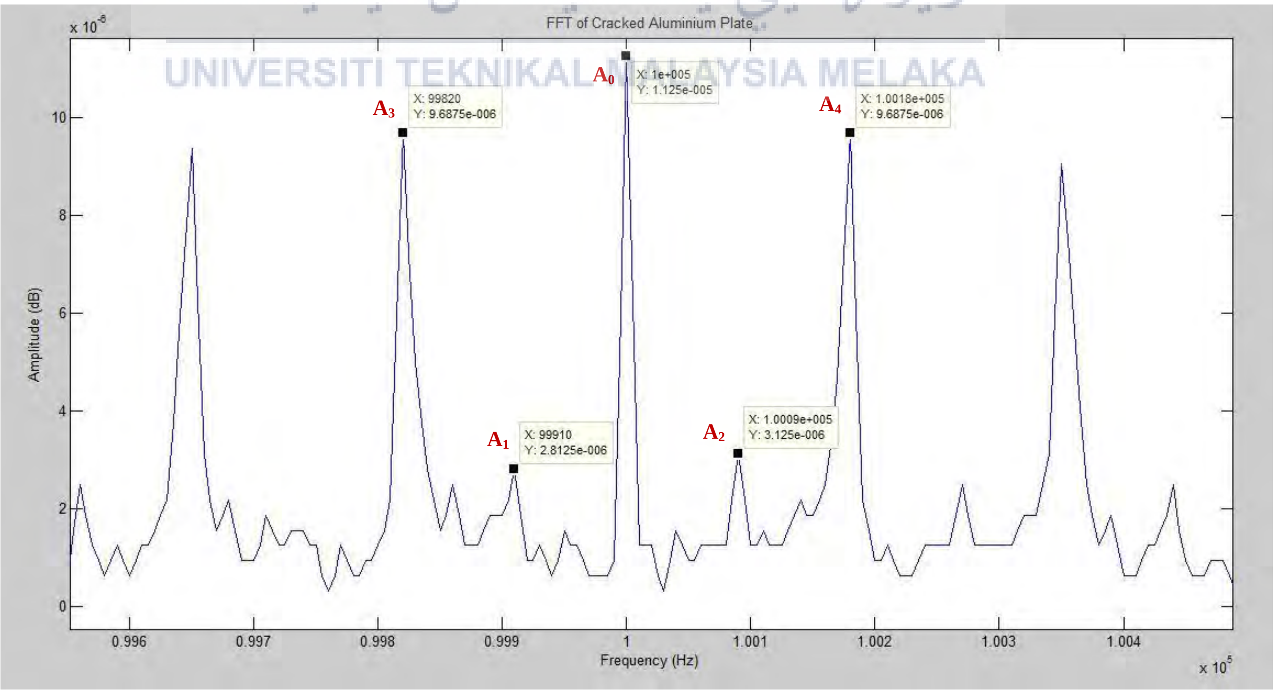

Figure B.2 FFT for 100 kHz (HF) 88.5 Hz (LF)

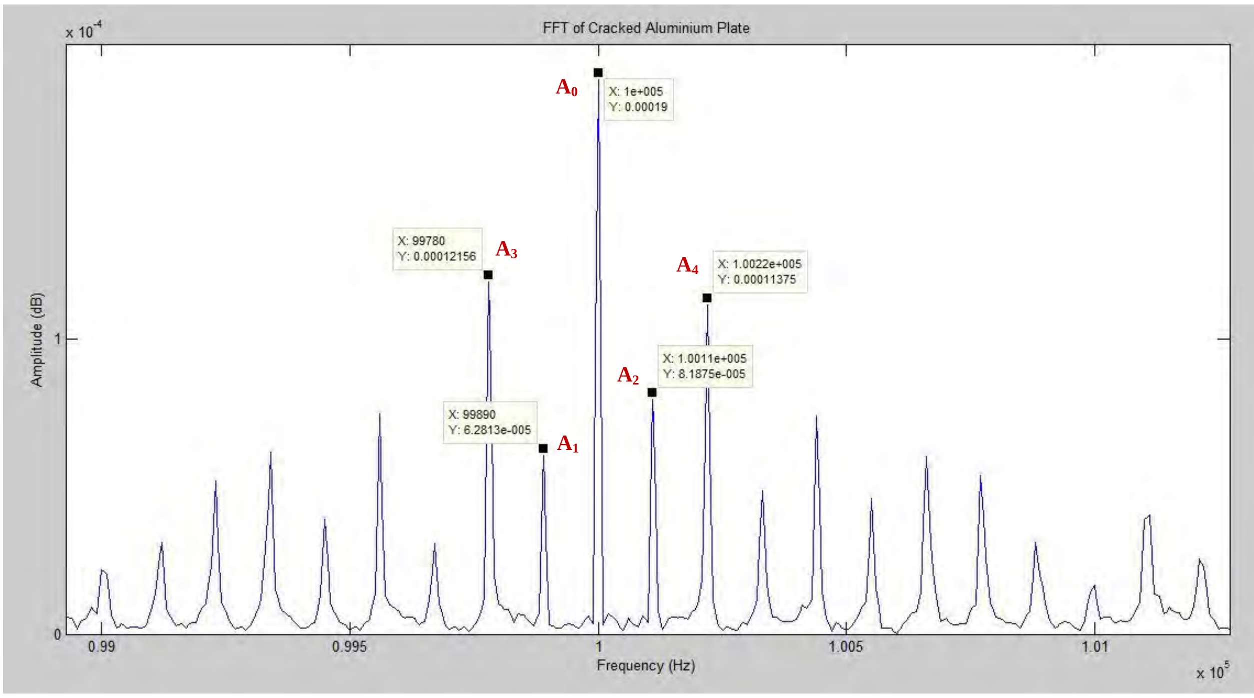

Figure B.3 FFT for 100 kHz (HF) 110.5 Hz (LF)

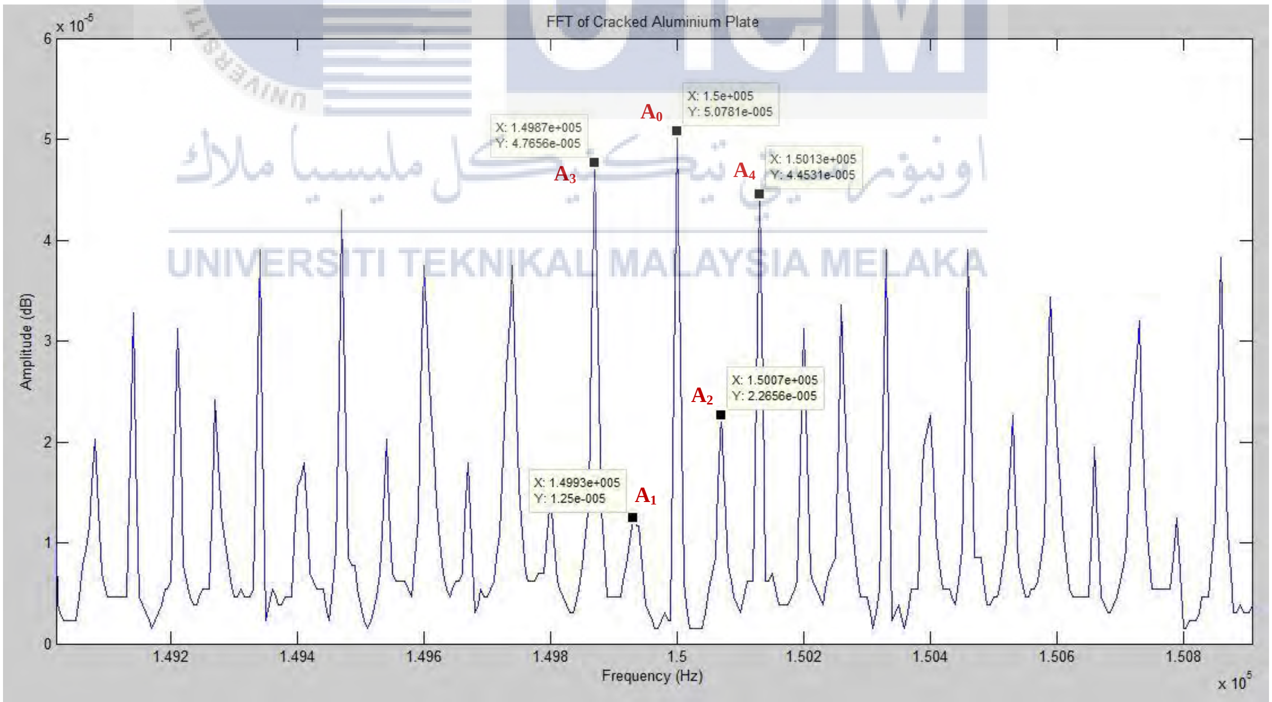

Figure B.4 FFT for 150 kHz (HF) 66 Hz (LF)

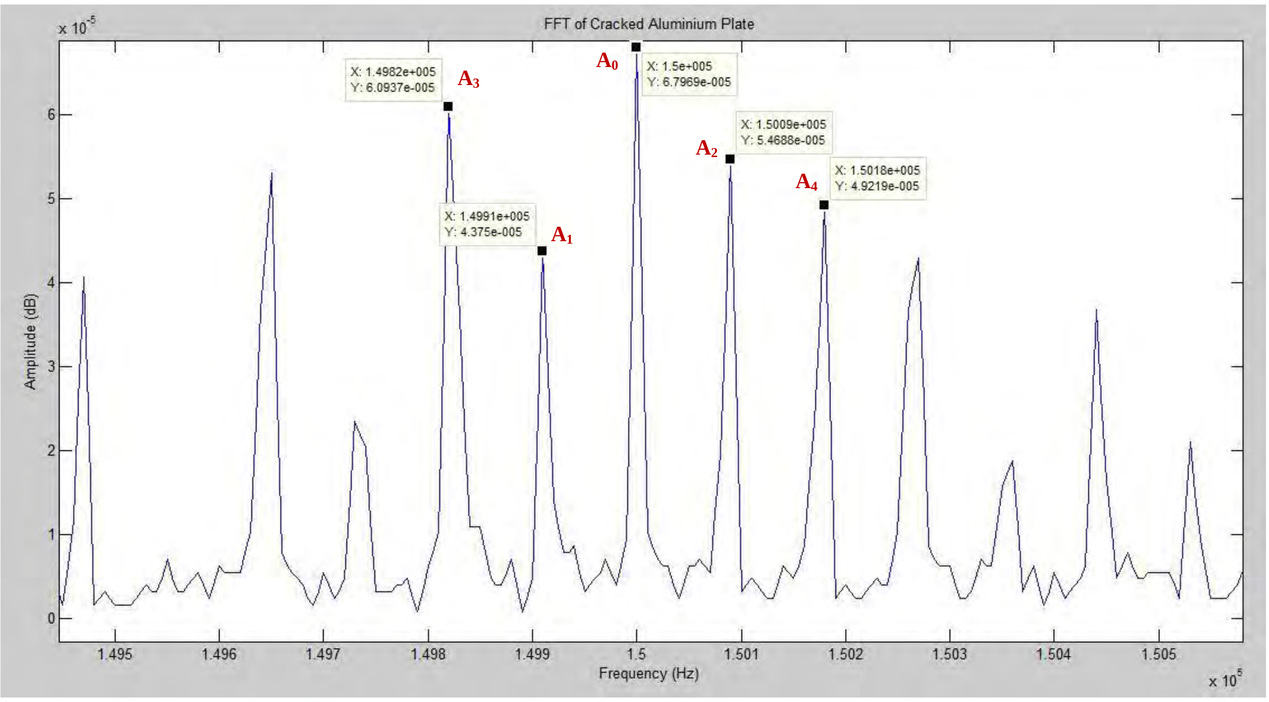

Figure B.5 FFT for 150 kHz (HF) 88.5 Hz (LF)

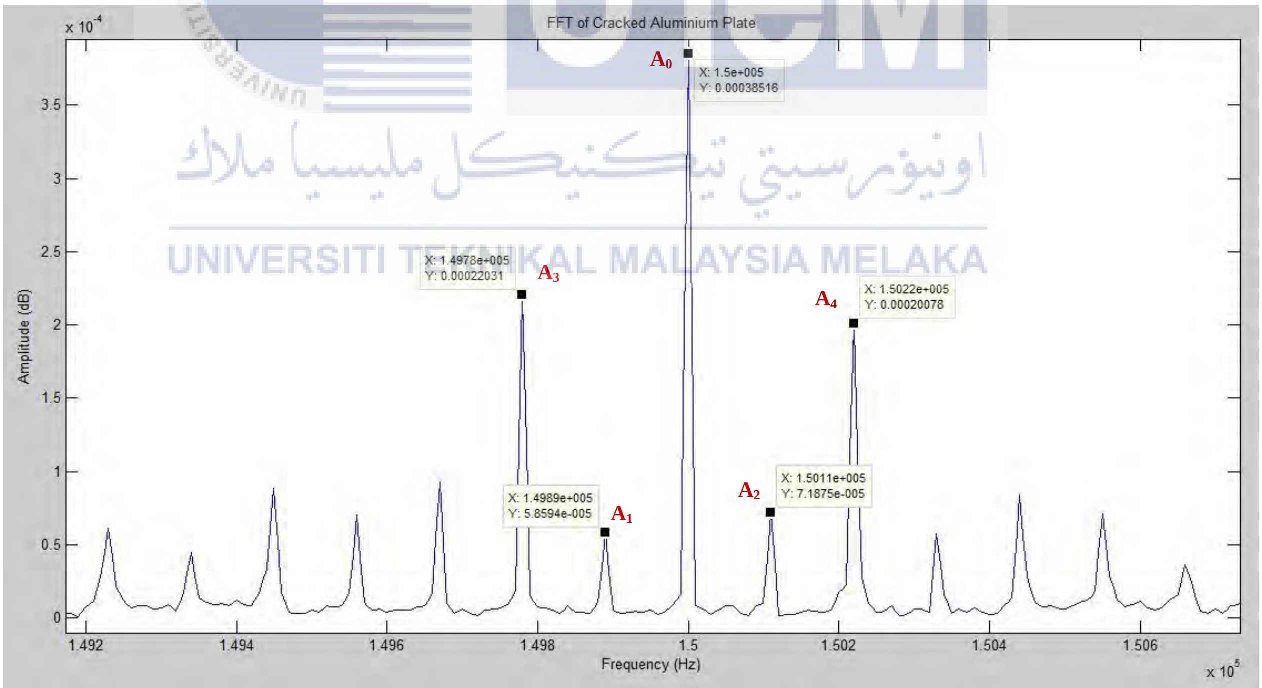

Figure B.6 FFT for 150 kHz (HF) 110.5 Hz (LF)

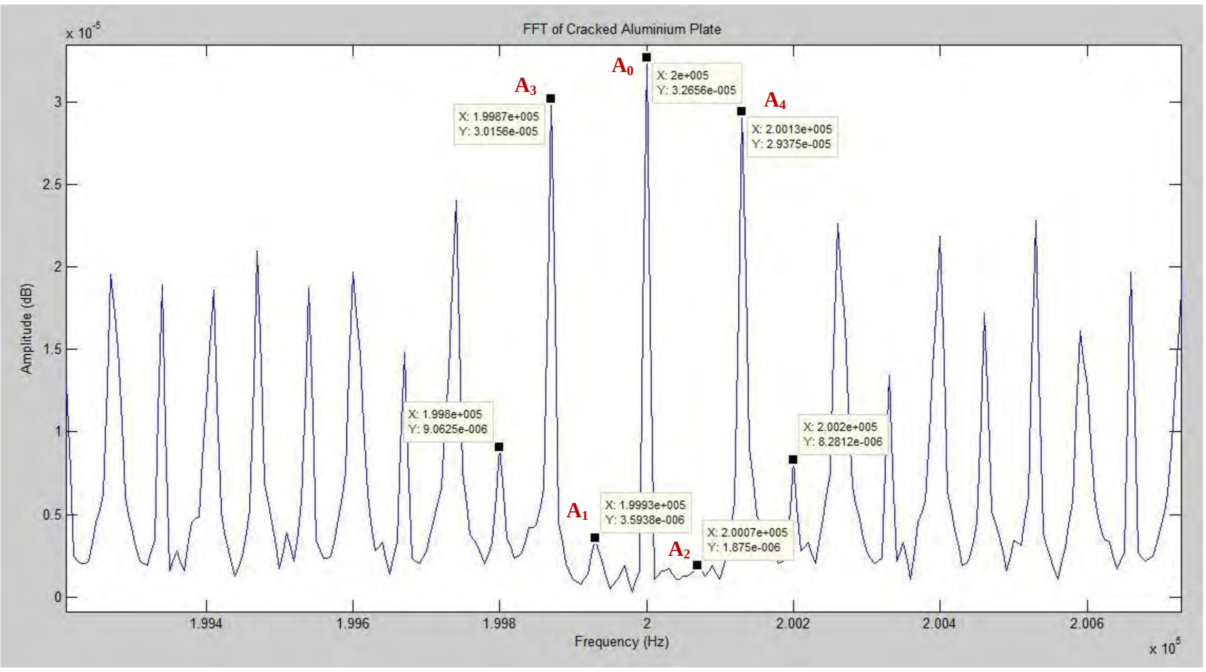

Figure B.7 FFT for 200 kHz (HF) 66 Hz (LF)

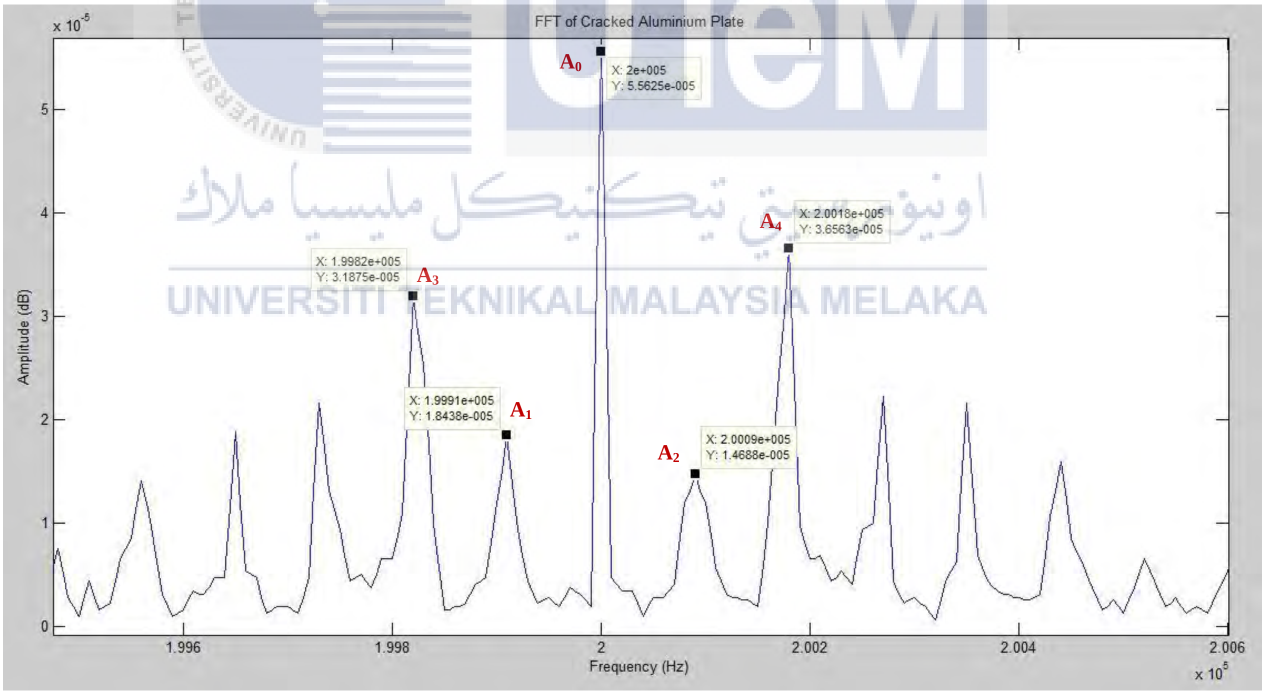

Figure B.8 FFT for 200 kHz (HF) 88.5 Hz (LF)

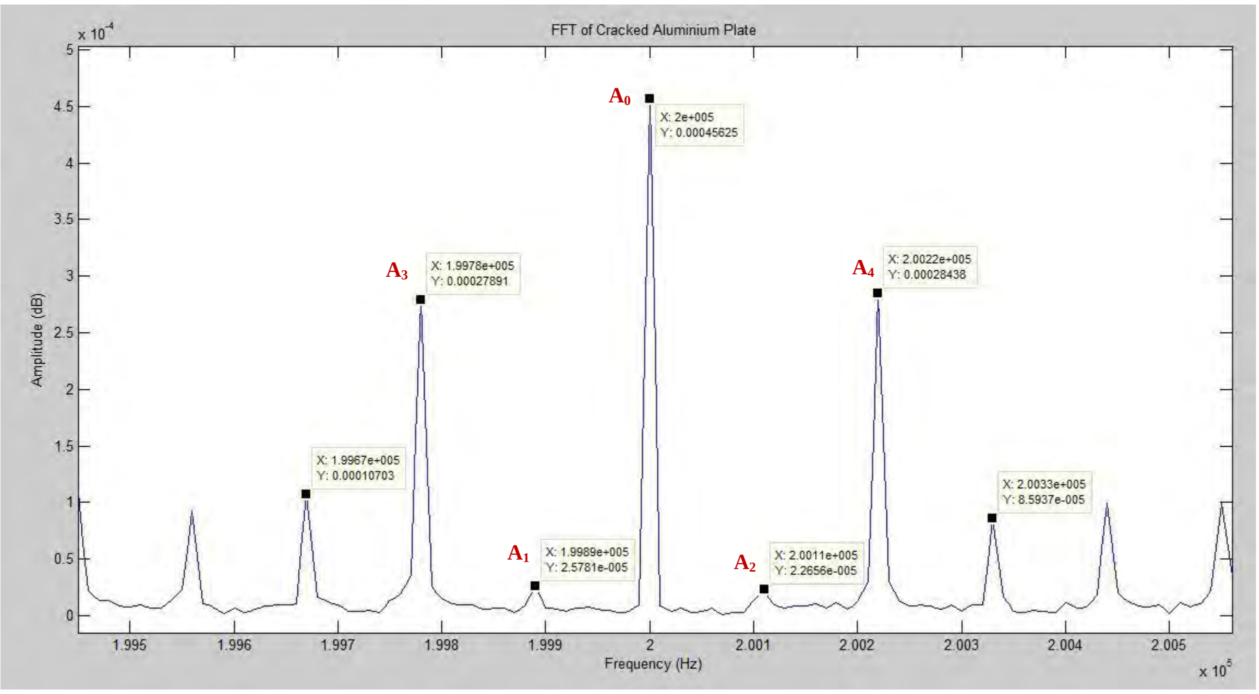

Figure B.9 FFT for 200 kHz (HF) 110.5 Hz (LF)

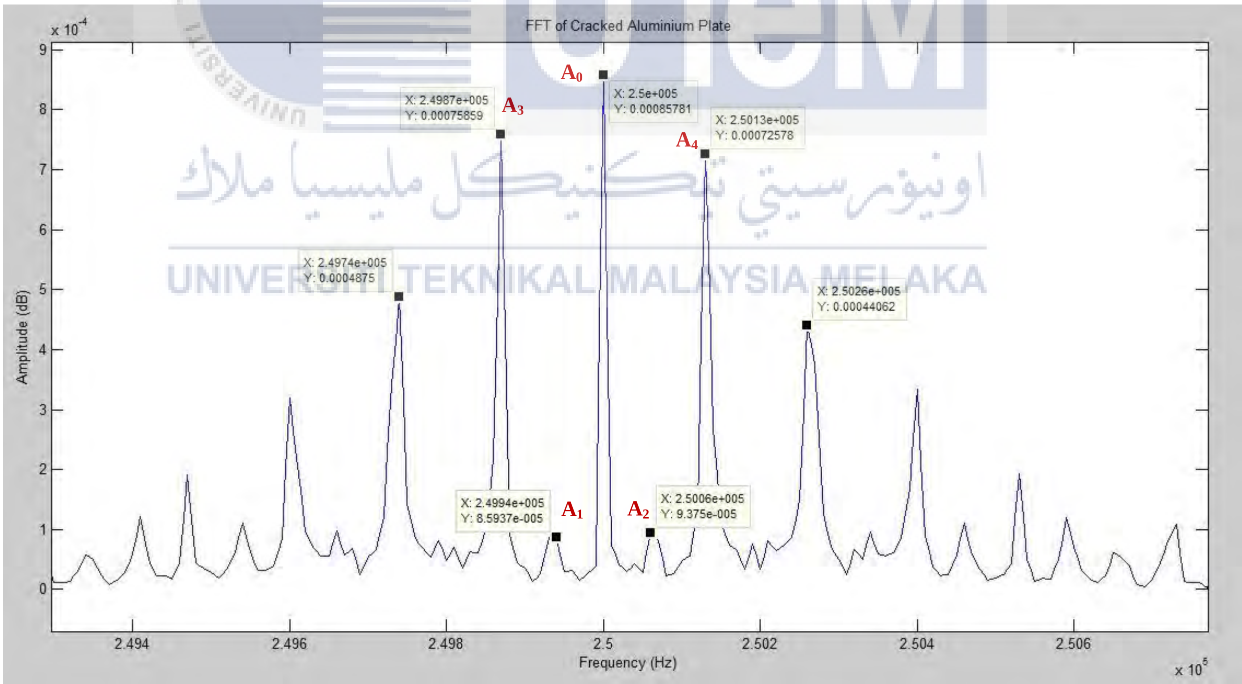

Figure B.10 FFT for 250 kHz (HF) 66 Hz (LF)

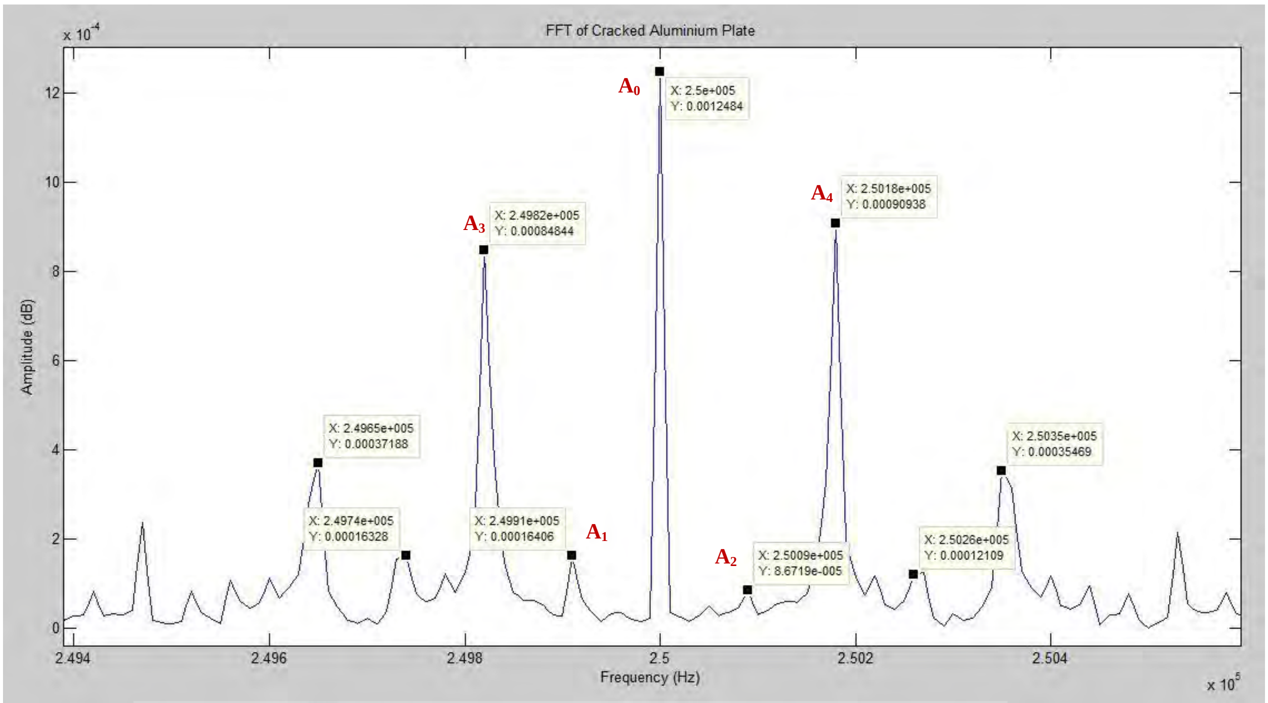

Figure B.11 FFT for 250 kHz (HF) 88.5 Hz (LF)

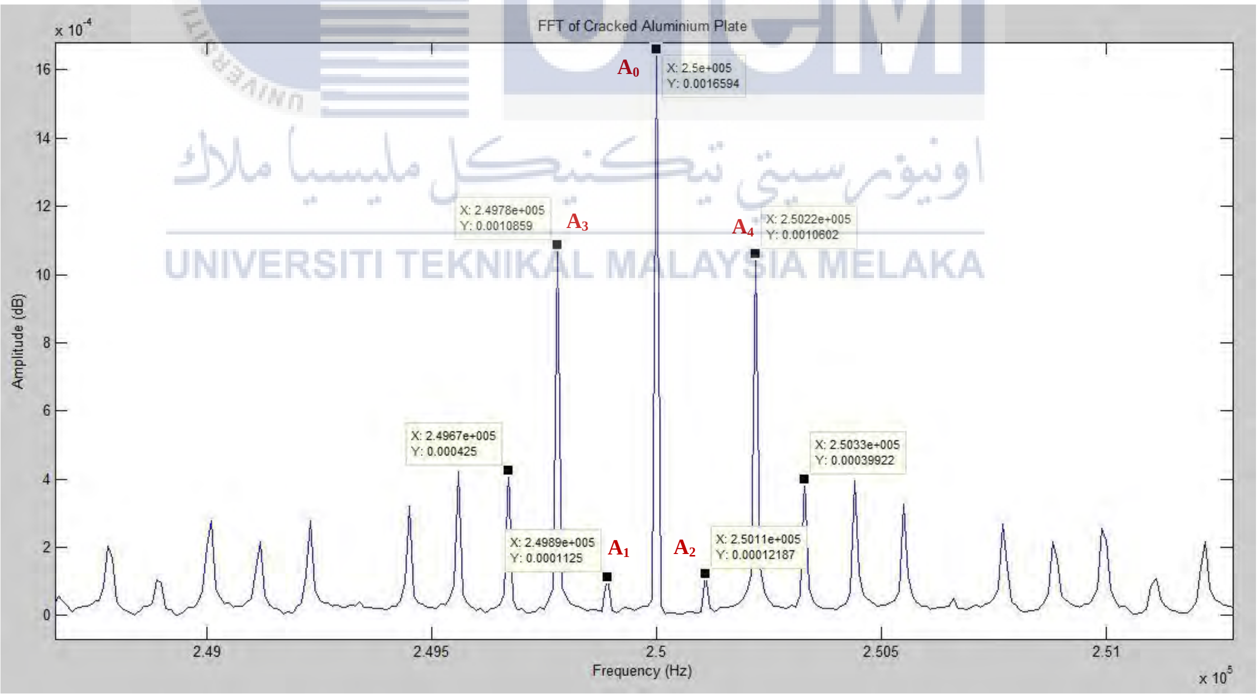

Figure B.12 FFT for 250 kHz (HF) 110.5 Hz (LF)

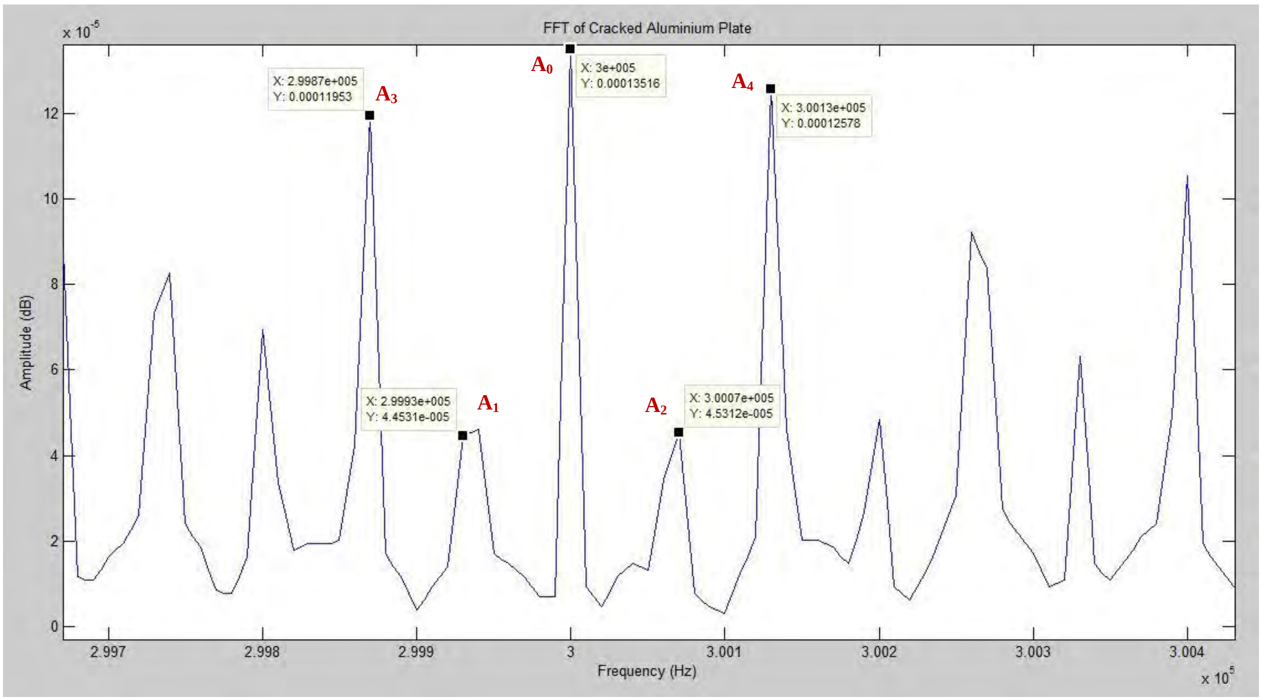

Figure B.13 FFT for 300 kHz (HF) 66 Hz (LF)

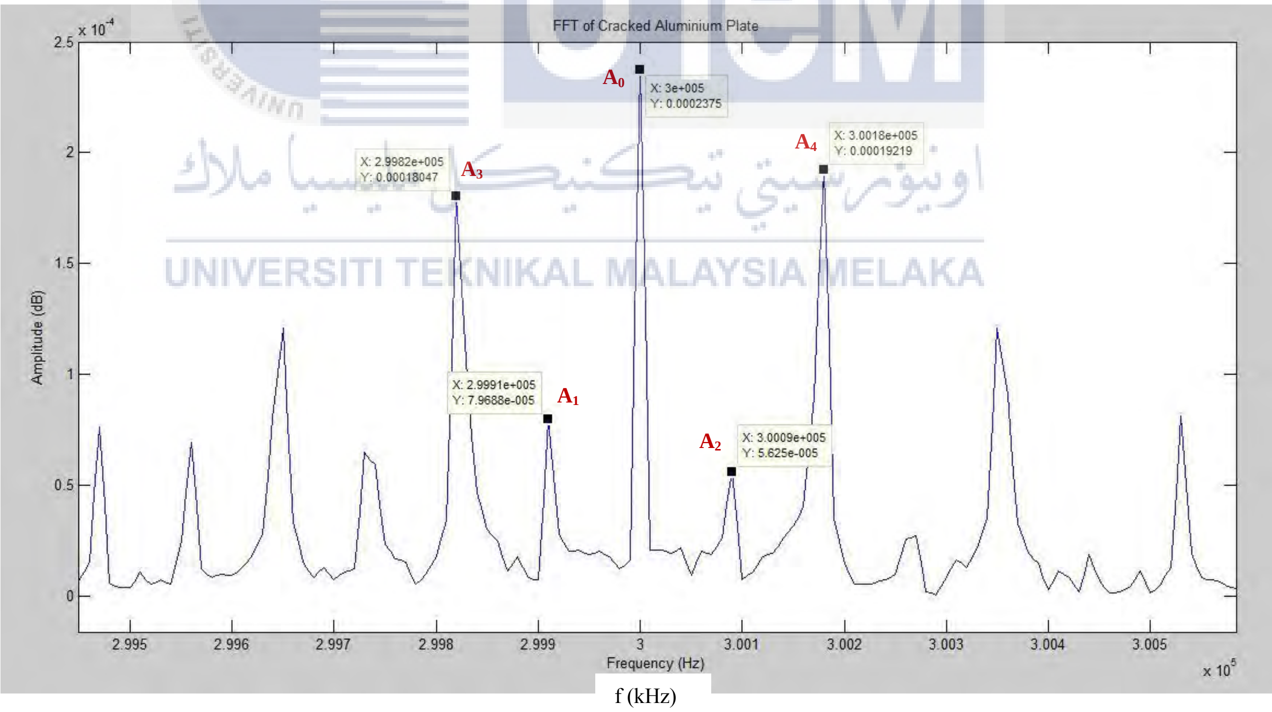

Figure B.14 FFT for 300 kHz (HF) 88.5 Hz (LF)

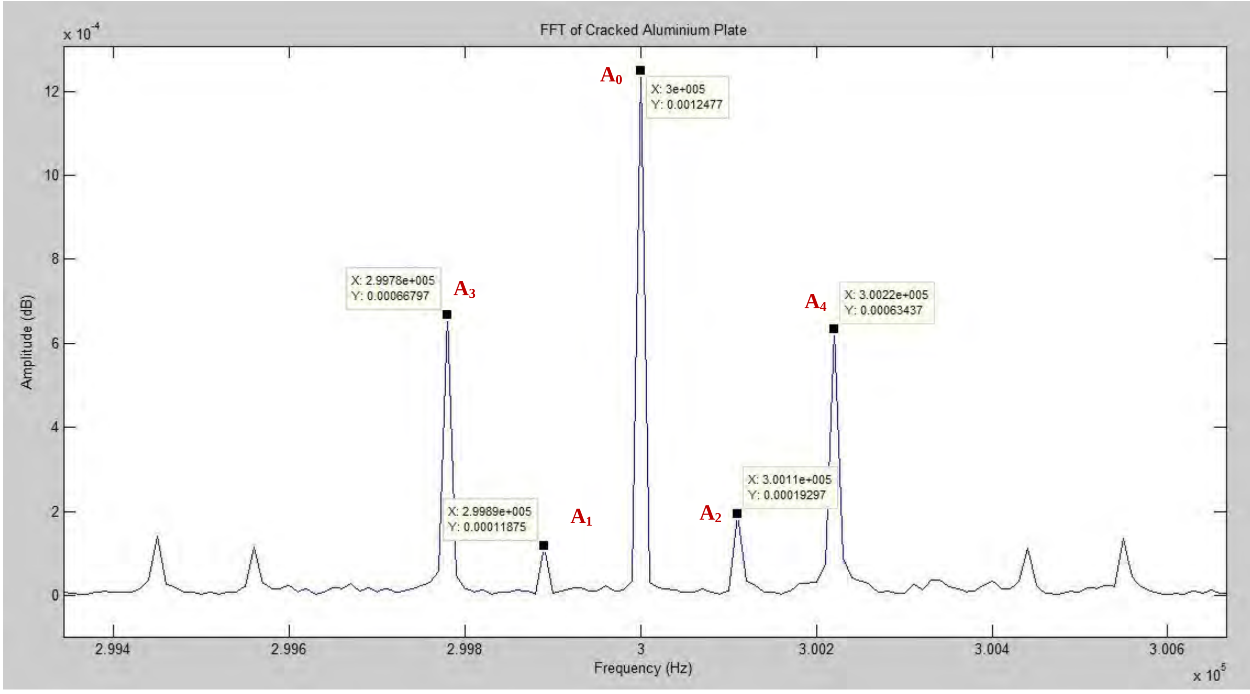

Figure B.15 FFT for 300 kHz (HF) 110.5 Hz (LF)