UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

PREDICTING CRACK LOCATION IN PLATE USING NONLINEAR VIBRO-ACOUSTICS METHOD

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PREDICTING CRACK LOCATION IN PLATE USING NONLINEAR VIBRO-ACOUSTICS METHOD

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A thesis submitted in fulfillment of the requirement for the Bachelor of Mechanical Engineering (with Honours)

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I declare that this thesis entitled “Predicting Crack Location in Plate Using Nonlinear Vibro-Acoustics Method” is the result of my own work except cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ____________________

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Date : ____________________

APPROVAL

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

Signature : ____________________________

Name : PM DR. AZMA PUTRA

Date : ____________________________

DEDICATION

To my beloved mother and father

ABSTRACT

The presence of damage such as a crack in a structure can be due to many reasons. The breakdown due to the presence of crack can arise in three (3) stages, namely the crack initiation, crack propagation and catastrophic overall failure. Therefore, a minor crack occurs in a very sensitive structure such as the aircraft which fails to be indicated or detected at the earlier stage can lead to a major failure in which can cause accident to happen. Hence, it is important to investigate the effect of natural frequency excitation in predicting the crack location in an aluminum plate using the nonlinear vibro-acoustics method as a model to the real scenario. The aluminum plate (AL-2024) with the size of (400mm x 150mm x 2mm) was used as the test specimen. The vibro-acoustics method is a method based on the fact that a high frequency ultrasonic wave propagates in the testing structure is modulated by the low frequency excitation. Besides that, the interaction between a high frequency vibration and a low frequency vibration results in nonlinear acoustic wave modulation. The nonlinear acoustic wave effects are closely related to the energy dissipation in materials or the nonlinear elasticity properties of the materials. Modal test analysis needs to be conducted to find the natural frequencies of the aluminum plate; the screening test and the Finite Element Analysis were applied to ensure the natural frequency obtained was correct. The low and high frequency waves were subjected simultaneously on the aluminum plate by using the mechanical shaker and PZT transducer respectively. The amplitude modulation intensity, R-values were used to determine the effectiveness of the frequency to predict the crack location in the aluminum plate. The knowledge of vibration mode shape needs to be used in order to predict the exact location of the crack in aluminum plate.

ABSTRAK

Terdapat pelbagai punca kepada berlakunya kerosakan seperti retak pada sesuatu struktur. Oleh itu, retakan kecil yang berlaku dalam struktur yang sangat sensitif seperti pesawat tidak dapat ditunjukkan atau dikesan pada peringkat awal, mampu mengakibatkan kerosakan besar yang boleh menyebabkan kemalangan berlaku. Oleh itu, adalah amat penting untuk mengkaji kesan pengujaan frekuensi semula jadi untuk mengesan lokasi retakan pada plat aluminium menggunakan kaedah vibro-akustik. Plat Aluminum (AL-2024) berukuran (400mm x 150mm x 2mm) digunakan sebagai bahan ujikaji. Kaedah vibro-akustik adalah suatu kaedah berdasarkan fakta yang menyatakan gelombang ultrasonik berfrekuensi tinggi dalam struktur ujian dimodulasi oleh pengujaan frekuensi yang rendah. Selain itu, hubungan interaksi antara getaran berfrekuensi tinggi dan getaran berfrekuensi rendah menghasilkan modulasi gelombang akustik secara tidak linear. Kesan gelombang akustik secara tidak linear ini berkait rapat dengan pelesapan tenaga dalam bahan atau sifat kekenyalan tidak linear bagi sesuatu bahan. Seterusnya, Analisis ujian modal perlu dilaksanakan untuk mengesan frekuensi semula jadi bagi plat aluminium dan dengan menggunakan ujian saringan dan Analisis Unsur Finite untuk memastikan dapatan kaji frekuensi semula jadi adalah tepat. Pengujaan frekuensi rendah dan gelombang frekuensi tinggi dikenakan secara serentak pada plat aluminum dengan menggunakan penggetar mekanikal dan transduser PZT secara asingan. Nilai R, intensiti modulasi amplitud digunakan untuk menentukan keberkesanan frekuensi dalam mengesan lokasi retakan pada plat aluminum. Pengetahuan mengenai bentuk mod getaran perlu diaplikasikan untuk mengesan lokasi tepat retakan pada plat aluminum.

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LIST OF ABBEREVATIONS

SHM	Structural Health Monitoring
NDT	Nondestructive Testing
VAM	Vibro-Acoustics Method
UTM	Universal Testing Machine
EDM	Electronic Discharge Machine
FEA	Finite Element Analysis
FE	Finite Element
PZT	Piezoelectric Transducer
FFT	Fast Fourier Transform
SLDV	Scanning Lase Doppler Vibrometer
BBA	Boardband Amplifier
S-N	Stress and Number of cycle
UT	Ultrasonic Testing
MT	Magnetic Particle Testing
AE	Acoustic Emission

LIST OF SYMBOL

R	=	Amplitude modulation intensity
A_0	=	Carrier peak amplitude
A_1	=	First sideband amplitude on the left of carrier peak amplitude
A_2	=	First sideband amplitude on the right of carrier peak amplitude
f_c	=	High frequency/frequency of carrier peak
f_m	=	Low excitation frequency

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Structural Health Monitoring (SHM) plays an important role in maintenance, especially in structural damage detection. In SHM, there are a series of processes and characterization strategies in the maintenance for engineering structure such as building structure, aircraft structure and pipeline structure. A series of processes in SHM involves the observation or inspection of a system by using sensor for a long period of time and also the statistical analysis of these features to determine the crack damage on the particular structure. Yu and Giurgiutiu (2009) said that, the structural crack or damage can be detected or diagnosed by using embedded sensing elements which collect the data all the time about the sensitive structural components. The data collected from the tested structure can be used for further analysis to detect the abnormality happened on the structure, especially in high sensitivity structure. The engineers can then take actions such as the maintenance or replacement of the component of the structure at the early stages to prevent catastrophic failure. The common damage is the change on the material and geometric properties of a structure which includes crack, hole, corrosion etc.

There are many method used in various fields of engineering to detect the damage in the structure such as the Nondestructive Testing (NDT) method. Previous study by Sutin et al (1998) claimed that the NDT method is a method that can measure or inspect the structure without destroying it and thus ensure the structure remains as it original shape and functionality. The NDT methods which can be used in the damage detection are nonlinear vibro-acoustic, radiography, ultrasonic testing, dye penetrate, magnetic particle, infrared thermography and acoustic emission. The selection of the testing method is dependent on the type of testing structure together with the operating conditions and the environment. For example, the infrared thermography method can only be used when the system is operating or in online state; this is because the method detects the abnormality based on the surface temperature of the testing object. Besides that, the nonlinear vibro-acoustic method is more preferable to carry out during the offline state as this method needs to introduce two different frequencies, one low excitation frequency and one high frequency vibration without any disturbance and noise.

1.2 PROBLEM STATEMENT

Minor failure occurs in sensitive structure which does not get detected in the earlier stage can lead to a catastrophic failure. When the whole system is breaking down, it requires extra breakdown maintenance fees to repair the failure. The worst possible scenario is that the production cycles have to come to a halt due to the failure and this causes a huge loss in production and thus reduces the productivity of the company. All these chaos end up with extra expenses needed to repair or to carry out great maintenance work. In short, it is much more affordable to prevent it from becoming a problem in the first place.

The common damage on a structure is fatigue crack. From the previous study by the Robert Stone (1983) about the steel materials, the materials possess a threshold stress limit below which fatigue cracks will not initiate. This threshold stress value is often referred to as the endurance limit. In steels, the life associated with this behavior is generally accepted to be 2 x 106 cycles. In the other words, if a given stress state does not induce a fatigue failure within the first 2 x 106 cycles, future failure of the component is considered unlikely.

Fatigue crack present in a structure can due to various reasons. A small crack in a very sensitive structure can lead to catastrophic failure. For example, presence of a small crack in the body of aircraft can cause accident to happen. Besides that, presence of a small crack in a pipeline system can lead to explosion of the pipeline and affect the people surround it. Thus, the non-linear vibro-acoustic method (VAM) can be used to detect the crack by introducing two (2) frequencies, one is the low frequency excitation and the other one is the high frequency vibration. However, it requires both the vibro-acoustic method (VAM) and also the knowledge of vibration mode shape to predict the exact location of the crack in a structure. Plus, there are not much of studies in predicting the location of the crack in a structure. Hence, this study is carried out to predict the crack location in an aluminum plate by using the VAM.

1.3 OBJECTIVE

1. To investigate the effect of the vibration mode shape on crack detection.
2. To predict the crack location in aluminum plate by using the non-linear vibro-acoustic method (VAM).

1.4 SCOPE

The scope of this study is about the prediction of the crack location of an aluminum plate with the size of (400mm X 150mm). The preparation of the aluminum plate specimens of the same size is important to obtain the highest accuracy possible of the experimental results. After that, three (3) different fatigue crack locations which are the middle, above middle and edge are prepared at three (3) different aluminum plates by using the Instron Universal Testing Machine (UTM). Before using the UTM to prepare the fatigue crack, a notch (5.0 mm) to initiate the fatigue crack is prepared by using the Electronic Discharge Machine (EDM).

The range of the natural frequency of the specimen was obtained by using the Finite Element Analysis (FEA) simulation. However, the usual procedure was to test the first specimen with random frequency to obtain the natural frequency of the specimen in the experiment. This process was known as the modal test analysis, which was to obtain the exact value of natural frequency of the specimen and to confirm it by using the screening test simulation. The specimen was then excited at its natural frequency, which was a low frequency excitation, and simultaneously provided with a high frequency vibration by the PZT transducer to obtain the amplitude of vibration occurring at the every position in the plate.

After that, the data was obtained by using several types of transducer for further analysis. The time domain spectrum was transformed by using the Fast Fourier Transform (FFT) in Matlab into the frequency domain spectrum for further analysis on the crack location. The frequency domain spectrum provides the information of side band around the carrier peak frequency that allows the user to obtain the R-value and compare with the vibration mode shape to determine the crack location in the aluminum plate.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Literature review is an objective, critical summary of published research literature relevant to a topic under consideration research. In literature review, studies related to the crack detection are reviewed as they provide information closely related to the topic. Information such as cause and mode of the vibration, fatigue failure, frequency domain approach, vibro-acoustic method, and experiment procedure to be used can be obtained through literature review. Literature review also shows the potential weakness and strength of this study and an up-to-date understanding of the subject. The purpose of literature review is to create familiarity with current thinking and research on a particular topic, and may justify future research into a previously overlooked or understudied area. The most important reason of doing literature review is to identify the problem in the study and give an overall view of the title to ensure falling on the right track for this study. The information from articles, journals or references books could help to understand and gather the ideas to proceed with this study. Hence, a complete literature review must be included to accomplish the title in this study.

2.2 DAMAGE IN STRUCTURE

According to the Budynas et al (2014), generally, damage can be defined as any change occur or subject into a system that affects the performance of the system from its original functionality. The concept of the damage would be clearer if there is a comparison between the damaged and undamaged system or structure. Therefore, with comparison it shows the original function of the particular system and the structure. Since this study focuses on the crack occur or detection on the structure, so it is limited to the changes occur to the structural geometric or material. For example, a crack or damage occurs in the structure will alter the geometric and change the properties of the structure such as strength or stiffness of the structure. Hence, the primary function of the structure will be altered and changed; break down of the structure might occur if the intensity of the damage intensity increased. The result of the present damage in the structure might cause immediate effect on the overall system, it depends on the severity of the damage and also the position of the damage in the structure (Sohn et al., 2003).

Based on the previous study by Qiao et al (2012) claimed that there are many reasons to cause damage in a structural system, such as corrosion, thermal affects, earthquakes and overloads towards a structural system. The risk of damage in a structural system, for example a crack on an aircraft due to scheduled discrete of landing purpose will result in accidents such as aircraft break downs and crashes. Furthermore, unscheduled discrete such as natural disaster earthquake will cause the structure of the building to break down and the whole building will collapse (Sohn et al., 2003). However, a reliable method on the detection of the crack and prediction of the crack location on a structure at the early stage is very important to prevent the catastrophic failure from occurrence. Besides that, it can reduce the cost of maintenance if the damage or crack is found at the earlier stage (Alberto et al., 2004).

2.3 FATIGUE FAILURE

Based on the study by Guili et al (2012) stated that fatigue, or more precisely known as the metal fatigue, refers to the breakdown of a part due to cyclic stress. The breakdown arises in three (3) stages, namely the crack initiation, crack propagation and catastrophic overload failure, which each of the stages takes a length of time dependent on various factors, such as the properties of the elemental raw material, magnitude and orientation of stresses applied, as well as the processing timeline. Fatigue failures arise from stress levels applied significantly lower than the stress levels sufficient to account for static breakdown. Typically, fatigue failures are described as low cycle mean less than 1,000 cycles or high cycle mean more than 1,000 cycles. The threshold value differentiating between low cycle and high cycle is subjective; however, under general situations, it is based on the characteristics of the raw material at the microstructural level as a response to the stresses applied (Robert Stone, 1983).

Normally, fatigue breakdown begins at the surface of the material. From the previous study by Rahman (2007) claim that fatigue breakdown begins at both the surface and the interior of the part. In the S-N curve, the twofold material characteristics in fatigue is demonstrated via a stepwise shape. Fatigue can also begin from the interior of a material, usually at microscopic internal imperfections, after strengthening of the surface of the material has been conducted. Such a fatigue failure is commonly detected for high cycle fatigue for case-hardened steels, quench-hardened steels via induction heating or surface toughened steels via shot peening. The same materials break down from the surface as in usual scenarios at higher stress levels causing lower cycles of lifetime (Nishi Jima, 1999).

According to the Abdel-Alim (2003), the definition of fatigue failure is the tendency of material to fracture due to progressive brittle cracking under continuous or cyclic stresses of a force specified to be lower than the usual strength. Even though fatigue breakdown is brittle, the failure consumes time to proliferate as a factor of intensity and frequency of the cyclic stress. Yet, very little indication is visible before breakdown in the event the crack is not detected. Lu et al (2016) claim that, large number of cycles is needed to result in fatigue breakdown at a certain peak stress; however as the peak stress intensifies, the number of cycles becomes smaller. For mild steels, the cyclical stresses can be advanced endlessly if the peak stress, also termed as the fatigue strength, is lower than the endurance limit value (Gao et al., 2011).

A good example of fatigue failure is breaking a thin steel rod or wide with your hands after bending it back and forth several times in the same place. Another example is an unbalanced pump impeller resulting in vibrations that can cause fatigue failure. Figure 2.1 below are the examples of fatigue failure occur in pipe:

(a)

(b)

Figure 2.1: (a) Fatigue failure occur at welded joint and (b) Fatigue failure occur piping system

2.4 METHOD FOR CRACK DETECTION

There are many methods used in various fields of engineering to detect the damage in structures such as the Nondestructive Testing (NDT) method. The NDT method is a method that can measure or inspect the structures without destroying it and ensure the structure remains as its original shape and functionality. The NDT methods which can be used in damage detection are vibro-acoustic, radiography, ultrasonic testing, dye penetrate, magnetic particle, infrared thermography and acoustic emission.

The vibro-acoustic modulation (VAM) technique is the most widely used method for crack detection. The effect of modulation of a high frequency vibration by a low frequency vibration is known as the VAM method (Duffour et al., 2005). According to Trochidis et al (2014) the presence of crack will cause the modulation which is generated by the nonlinear interaction of vibration. The result can be transformed from the time domain into the frequency spectrum for further analysis. In the frequency domain spectrum there are two peaks of frequency, one is the low frequency and the other is the high frequency vibration. The presence of crack in the structure will have the side band around the peak frequency. The damage index or known as the severity of the damage is related to the intensity of the modulation.

Radiography is one of the two (2) main volumetric testing methods, along with the ultrasonic. It is a NDT method that uses short-wave X or gamma radiation to detect the damage in the structure. Radiography involves the penetration of radiation to the test structure so that the radiation passes through the structure that is being inspected to detect any abnormality of the structure; the radiation comes from a source with high energy supply. Radiation penetrates matter to a certain extend of measurement, the radiation will be captured on the photographic film if the penetration is strong enough to pass through the object (Robert 2015).

According to Robert (2015), ultrasonic Testing (UT) is a NDT method that has high sensitivity and penetrating power. UT uses an ultra-high frequency sound energy to inspect and check the structure and make measurements. The sound energy is supplied into the structure to be inspected and the sound will propagate in the structure and reflect back to the sending unit that can be presented on the visual display. The UT inspection method can be used from various directions to inspect the flaws in large structures such as civil building, pipeline and also aircraft. By knowing the speed and the time taken for the sound to return back to the sending unit, it can detect the abnormality of the structure.

Dye penetrate is also a NDT method that uses different type of low viscosity liquid that can penetrate to a crack or hole in the test structure. The technique is based on the ability of the liquid to be drawn into a very clean surface to examine the damage in the structure. The process of the dye penetrate method begins with the application of the dye on the surface of the test structure after cleaning the surface. After a few minutes, clean up the surface carefully and apply the developer to allow the penetrant from the voids to seep up into the developer and can be seen by our naked eyes. Lastly, analysis work has to be done to identify the location of the voids. The dye penetrate method can be performed on magnetic or non-magnetic materials but it does not give significant result on porous materials (Robert 2015).

Magnetic Particle Testing (MT) is the application of the magnetic field to the test structure which can be permanent magnetized or electromagnetic. The structure to be examined must be a ferromagnetic material such as iron, nickel, cobalt or some alloy materials. This method uses the magnetic fields and small magnetic particles such as dry powder or suspended liquid solution to detect the damage or crack in the test structure. If there is flaw in the structure it will alter the magnetic flux line and will be shown by the magnetic particle filling.

According to Robert (2015), Infrared Thermography is a proactive troubleshooting and predictive maintenance that is used to detect the abnormal hot spot on the test structure. The primary source of the infrared radiation is heat and the infrared radiation lies between the visible light and microwave portion of the electromagnetic spectrum. An object that has a temperature above absolute zero emits the radiation in infrared zone. Infrared thermography is a visualized method that shows the result by difference in colors. The abnormal spot on the test structure will show in red color which receives much heat energy.

According to Robert (2015), Acoustic Emission (AE) method is one of the NDT methods by using the transient elastic waves to detect the flaw or damage in a structure. Acoustic emission applies a localized external force such as change in pressure, load or temperature. The waves will propagate in the test structure if the source triggers the release of energy in the form of wave. The waves are picked up by a transducer and fed via an amplifier to pulse analyser, then to an oscilloscope. The displayed signal is then evaluated.

Based on Robert (2015), all NDT methods have advantages and disadvantages, the result of each NDT method depends on the application and the testing object. There is no perfect method for crack detection, but there is only the most suitable method for a particular situation. In predicting crack location, it needs both reliable and suitable technique, coupled with the knowledge of vibration mode shape of the testing structure. With knowledge of the vibration mode shape at every low frequency excitation, it gives the information on nodal and anti-nodal areas which are the maximum and minimum amplitudes of deflection when the testing object vibrates.

2.5 NONLINEAR VIBRO-ACOUSTICS METHOD

The nonlinear vibro-acoustics method can be divided into few sub-category for better understanding. The first is the explanation on using nonlinear instead of linear effects. Then, the definition vibro-acoustics method is given by previous studies. Lastly, how the signal is processing after obtained the result from the experiment by using the nonlinear vibro-acoustics method.

2.5.1 Nonlinearity Effects

According to the Nazarov et al (1988), the interaction between a high frequency vibration and a low frequency vibration results in nonlinear acoustic wave modulation. The nonlinear acoustic wave effect is closely related to the energy dissipation in materials or the nonlinear elasticity properties of the materials. The nonlinear elasticity effects of the material will increase when there are defects such as damage or crack on the object. Furthermore, previous study by Van et al (1997) claimed that, the nonlinear elasticity can be classified into two (2) main categories which are classical and non-classical elasticity. The nonlinear order is second order or above in the relation between the stress-strain or the relation between the strain and energy density, which is known as the classical nonlinear elasticity. If the discrete memory shows more complicated result in the relation of stress-strain or strain energy density, the memory is known as non-classical nonlinear elasticity. The reason to use nonlinear vibro-acoustics method instead of linear system is due to the fact that the linear system without any nonlinearities will give a response with only 2 fundamental frequencies component present in the frequency domain spectrum. But in the damaged structure, the response must contain more frequencies which is not only 2 fundamental frequencies (Guyer et al., 1999).

2.5.2 Vibro-Acoustics Method (VAM)

Based on the previous study by Trochidis et al (2014) claimed that, the virbo-acoustics method is a method based on the fact that a high frequency ultrasonic wave propagates in the testing structure is modulated by the low frequency excitation. The effect of modulation of a high frequency vibration by a low frequency vibration is known as the VAM method (P. Duffour et al., 2005). Hence, the vibro-acoustic modulation method is based on two (2) types of frequencies excitation, one is the low frequency vibration which is natural frequency and another is a high frequency ultrasound wave. The low frequency has higher energy while the high frequency has much lower energy compared to the low frequency excitation. Because of this, the low frequency which is the natural frequency of the object is subjected to the testing object to open up the crack which can be easily detected by the propagation of the high frequency wave. Figure 2.2 below is the example of closing and opening action of the crack when the vibration is introduced:

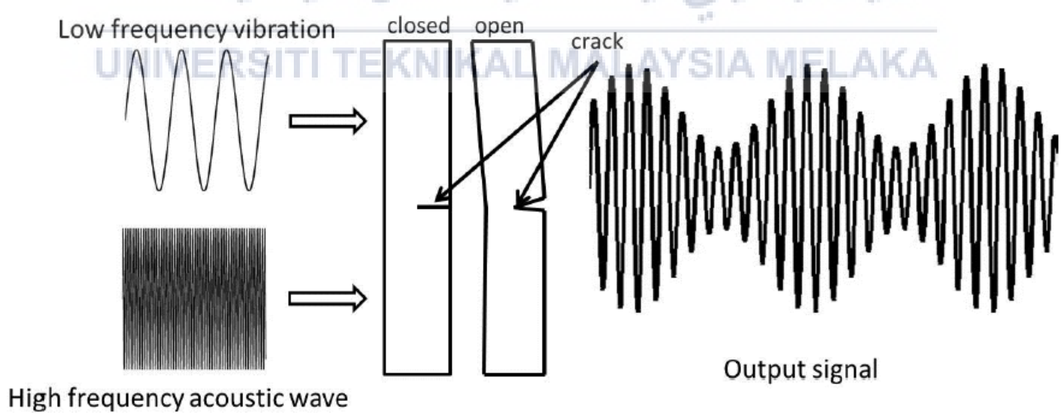


Figure 2.2: Schematic diagram of closing and opening action due to the signal modulation in the damage structure. (Klepka et al., 2013)

2.5.3 SIGNAL PROCESSING

In nonlinear vibro-acoustics method, the excitation of both low frequency and high frequency are introduced simultaneously to the structure, result in forming amplitude modulation. The output signal which is obtained from the experiment normally in time domain spectrum needs to convert into frequency domain spectrum for further analysis. The conversation of time domain spectrum into frequency domain spectrum is by using the Fast Fourier Transform (FFT). Figure 2.3 and Figure 2.4 show the input and output signal.

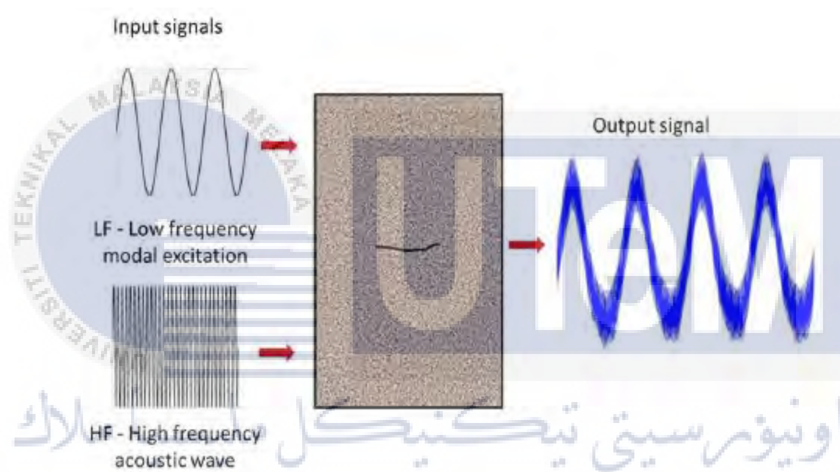
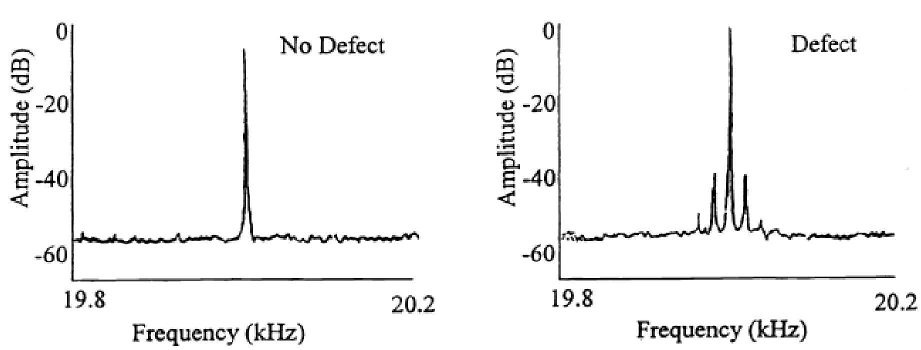


Figure 2.3: Example of introduce low and high frequency excitation to the testing structure by using VAM (Klepka et al., 2016)



(b) (c)

Figure 2.4: (a) Example of signal without crack and (b) Example of signal with crack.

According to Ooijevaar, et al (2016), the signal in the time domain can be seen as a combination of many shifted or scaled impulses. This is because the result is record according to the time range in the parameter setting. The plot for the time domain is the amplitude of the strength of the signal at any instant of time. In vibro-acoustic method, the time domain shows that the high frequency vibration is modulated by the low frequency excitation. The example for the time domain is shown in Figure 2.5 (a).

According to Chrysochoidis et al (2011), the frequency domain spectrum can separate all the sine or cosine wave that add in a very complex form in time domain signal. Thus, the frequency domain spectrum composes many sine and cosine wave of different frequencies and amplitude into a more simple graphical view. The spread out data shown in the time domain will be resolved into a single frequency component as distinct impulses in the frequency domain. Each individual frequency component in the frequency domain spectrum represents a signal from the time domain. Figure 2.5 (b) shows the example of frequency domain.

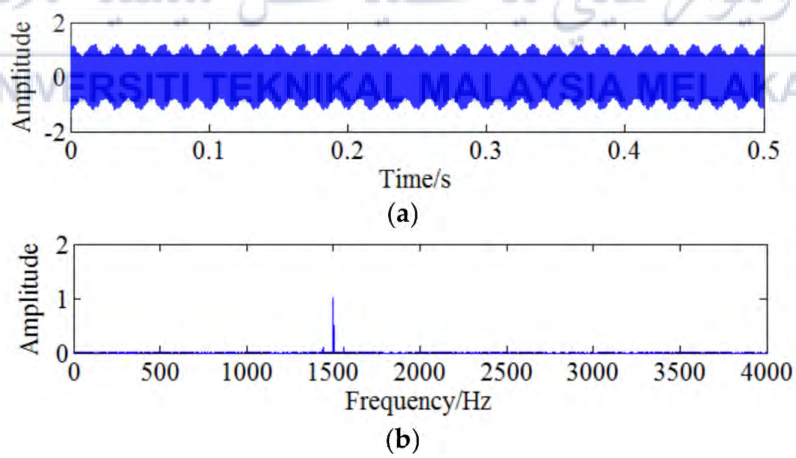


Figure 2.5: (a) Example of time domain spectrum and (b) Example of frequency domain spectrum.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter describes the methodology used in this project to obtain data input from experiment on specimen used. The flow chart of the general methodology of the project is shown in Figure 3.1. This project start with fabrication of specimen, aluminum plate with the size if (400mm X 150mm). Several defect is created on the aluminum plate for the study of crack location prediction through frequency domain. First, carry out the modal test analysis to obtain the natural frequencies of the aluminum plate and FE simulation is used to ensure the natural frequencies obtained were first, second, third and fourth mode of vibration. After that, the low frequency excitation is set to the natural frequencies obtained and excite by the mechanical shaker. Then, carry out the experiment testing by setting the high frequency vibration as 60 kHz and excite by the PZT transducer to obtain the data required to predict the crack location in the aluminum plate. The data obtained is analysis through R-value from the frequency domain spectrum and graphical to validate the result. In the end of the study prediction of the location of the crack in the aluminum plate is obtained. Figure 3.1 shows the flow chart of the general methodology.

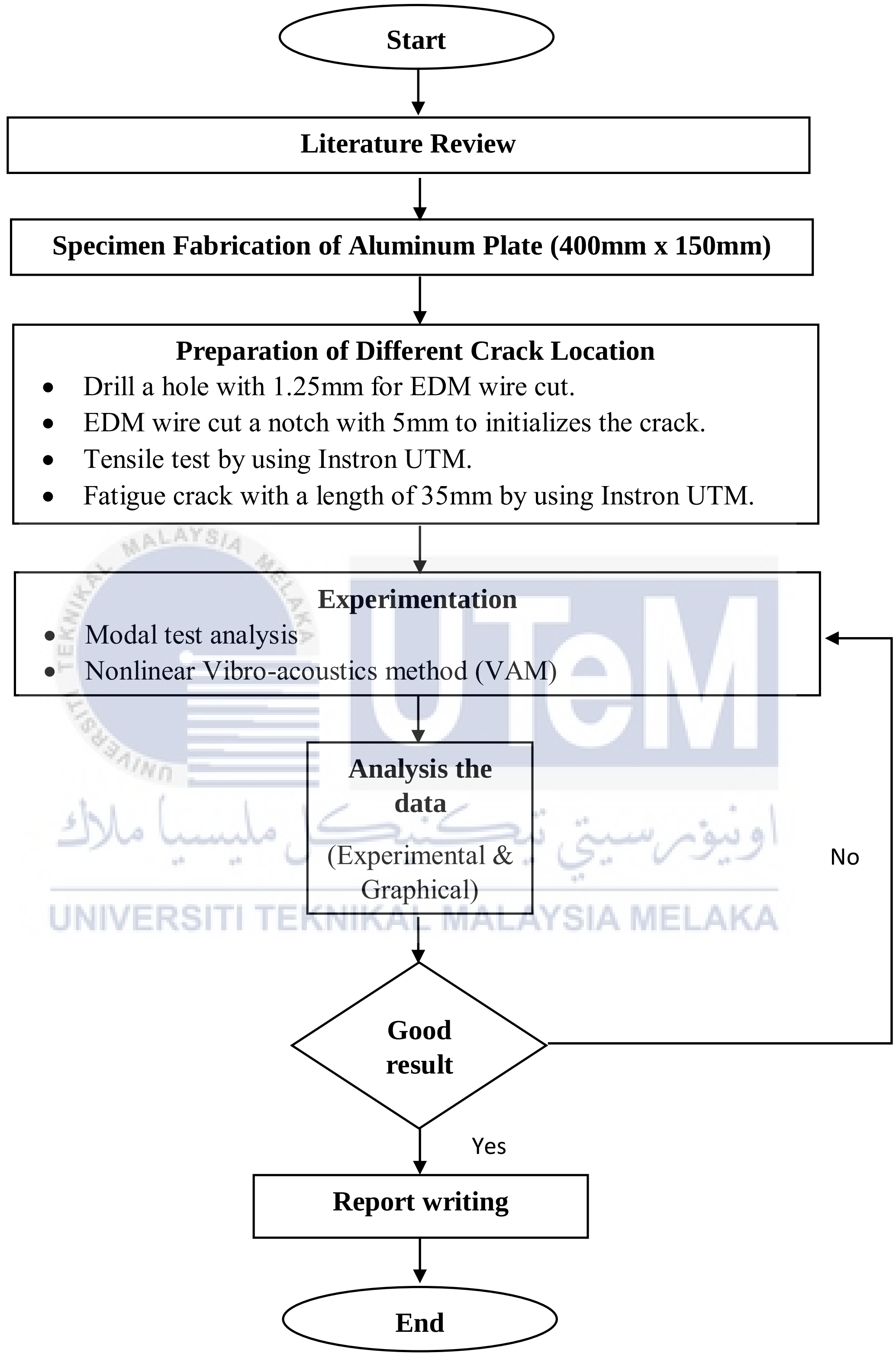


Figure 3.1: Flow chart of the general methodology

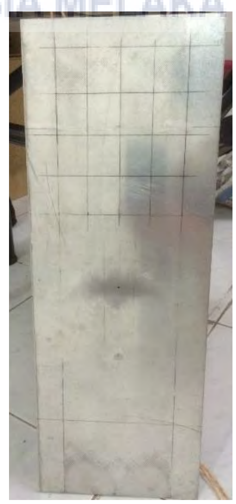
3.2 PREPARATION OF TEST SPECIMEN

The aluminum test specimen was prepared for the experimental used. The material properties of the aluminum is shown in Table 3.1. The material used is aluminum plate (AL-2024) with the size of 400mm x 150mm x 2mm. The aluminum AL-2024 is a high strength aluminum alloy. The test specimen was prepared with three different crack locations on three different aluminum plates which are the crack location at middle, above middle and at the edge as shown in Figure 3.5. Figure 3.2 shows the example of the aluminum plate.

Table 3.1: The material properties of the aluminum plate

Material Property	**Detail**
Name	Aluminum Al-2024
Density	2780 kg/m^3
Young's Modulus	72400 MPa
Poisson's Ratio	0.33
Size	400mm x 150mm x 2mm

(a)



(b)

Figure 3.2: (a) Aluminum plate without crack and (b) Aluminum plate with crack

3.2.1 Pre-Crack Preparation

There are few process or step to create the fatigue crack on the aluminum plate. The first step to create the crack is drilling a small hole for Electrical Discharge Machine (EDM) wire cut as shown in Figure 3.3 (a) to create the notch to initial the crack. The small drilled hole is 1.25mm diameter while the notch length is 5mm. After that, by using the Instron Universal Tensile Machine (UTM) as shown in the Figure 3.3 (b) to direct the crack and the crack will propagate in the direction of the notch and extend to the desired length. The crack desired length is 30mm which is 15mm to each side from the drill center. The dimension of the aluminum plate together with the drill hole and notch is shown in Figure 3.4. Before undergoes the fatigue test, the aluminum plate need to undergo tensile test to obtain the maximum and minimum load of the testing specimen.

(a) (b)

Figure 3.3: (a) Electrical Discharge Machine (EDM) and (b) Instron Universal Tensile Machine (UTM)

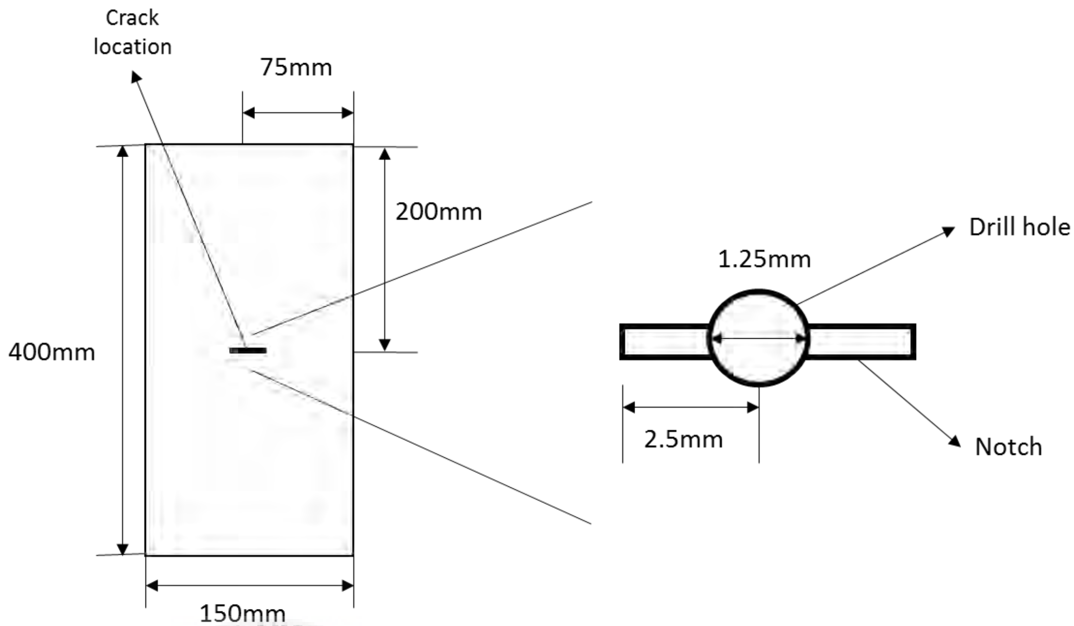


Figure 3.4: Schematic diagram of the aluminum plate and the dimension for drill hole and notch length.

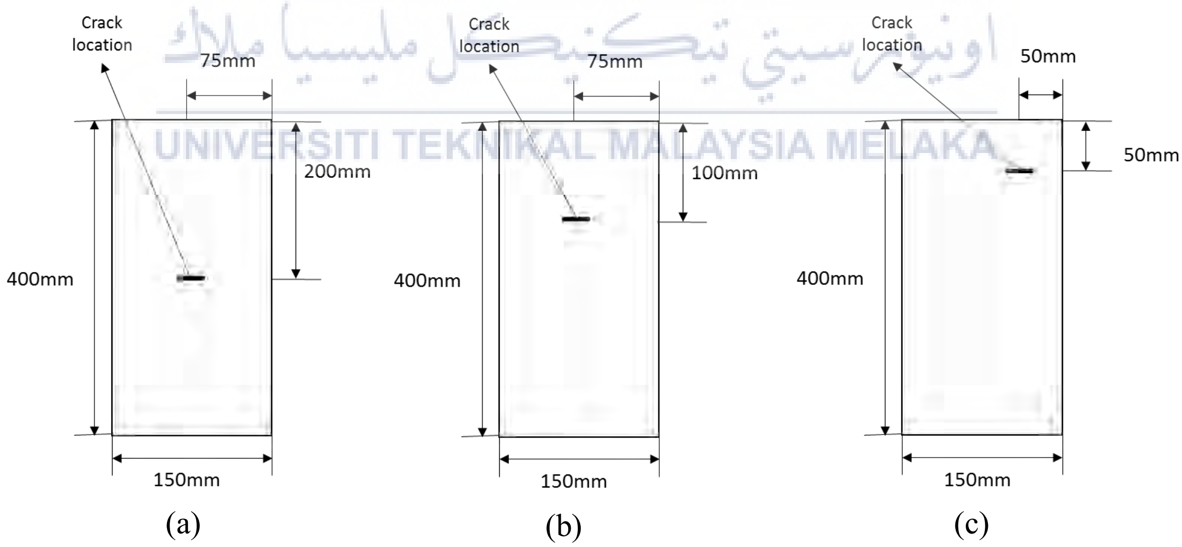


Figure 3.5: (a) The crack location at middle, (b) The crack location at above middle and (c) The crack location at the edge

3.2.2 Tensile Test

Generally, a measurement on the resistance of the plate toward a static force have to be done before create the crack. The measurement is known as tensile test that can be done by using the Instron Universal Tensile Machine (UTM). The tensile test is carry out to determine the maximum value, minimum value, mean value and amplitude value of load that the aluminum plate can applied. Before carry out the tensile test, the aluminum plate need to align correctly on the Instron UTM machine to ensure the result obtain is accurate. The schematic diagram of the alignment of the UTM jigs on the aluminum plate is shown in Figure 3.6. The gridline of the UTM jigs is the blue shaded area that shown in Figure 3.6.

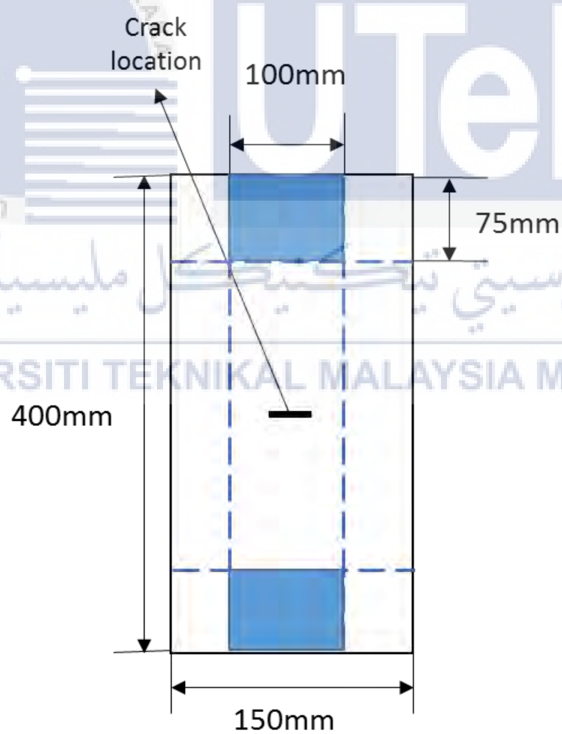


Figure 3.6: Schematic diagram of the alignment of the UTM jigs on the aluminum plate and the blue shaded areas are the gridline of the UTM jigs.

3.2.3 Fatigue Test

Fatigue test is used to produce the fatigue crack after the drilled hole and notch have been created. The fatigue test parameter is obtained from the measurement of maximum and minimum load by the tensile test. The formation of the fatigue crack is due to the cyclic load applied to the aluminum plate. The desired fatigue crack length is 35mm is created by using the Instron Universal Tensile Machine (UTM). The procedure to produce the fatigue crack was first enter the parameter setting such as maximum load, minimum load, mean load, amplitude load and the frequency of the cyclic load applied. Then, clamped the aluminum plate to the Instron UTM jigs with the proper alignment of the gridline. After all the setting and setup was done, start the Instron UTM machine to produce the fatigue crack. Every 5000 cycles need to check the crack length to prevent the crack overshoot. This is because the speed of formation of the crack increase when the crack line started to propagate. There is a hold button to stop the process when the machine is running abnormally. Figure 3.7 shows the schematic diagram of the fatigue crack size.

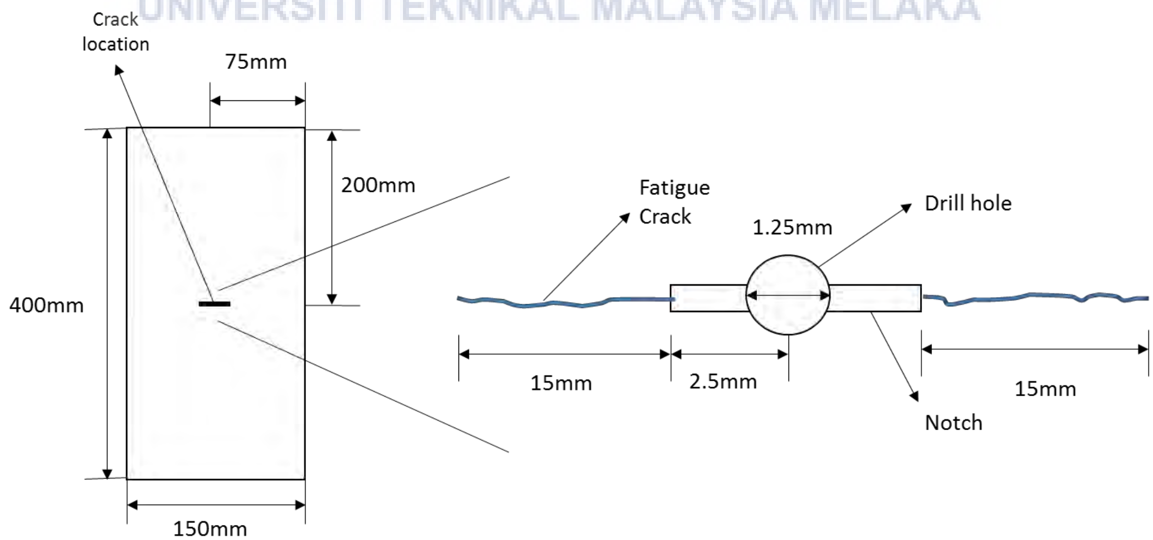


Figure 3.7: Schematic diagram of fatigue crack size

3.3 MODAL TEST ANALYSIS

Modal test analysis was carry out to determine the natural frequencies and the vibration mode shape of the aluminum plate. In this study, two modal test analysis which are experimental modal analysis and Finite Element (FE) simulation method was carry out to ensure the natural frequencies and the vibration mode shape obtained is accurate.

3.3.1 Experimental Modal Analysis

The experiment modal analysis is used to obtain the value of the natural frequencies and the vibration mode shape by using the Scanning Laser Doppler Vibrometer (SLDV). The excitation signal was generated sweep frequency by using the Textronix AFG 3022 signal generator and the signal is amplified by the TIRA BAA 60 power amplifier. The signal generator parameter were set as shown in Table 3.2. The excitation of random frequency was introduced by the TIRA S50018 mechanical shaker that attached to the aluminum plate at the bottom right position. The output signal were captured by the single head Scanning Laser Doppler Vibrometer (SLDV) and recorded into the Textronix DPO 4032 oscilloscope. Figure 3.8 shows the schematic diagram of the experiment setup for experiment modal analysis.

Table 3.2: Signal generator parameter

Item	**Setting Value**
Sweep frequency	1-2000 Hz
Sweep time	2 seconds
Amplitude	2 Vpp
Sampling size	25K samples

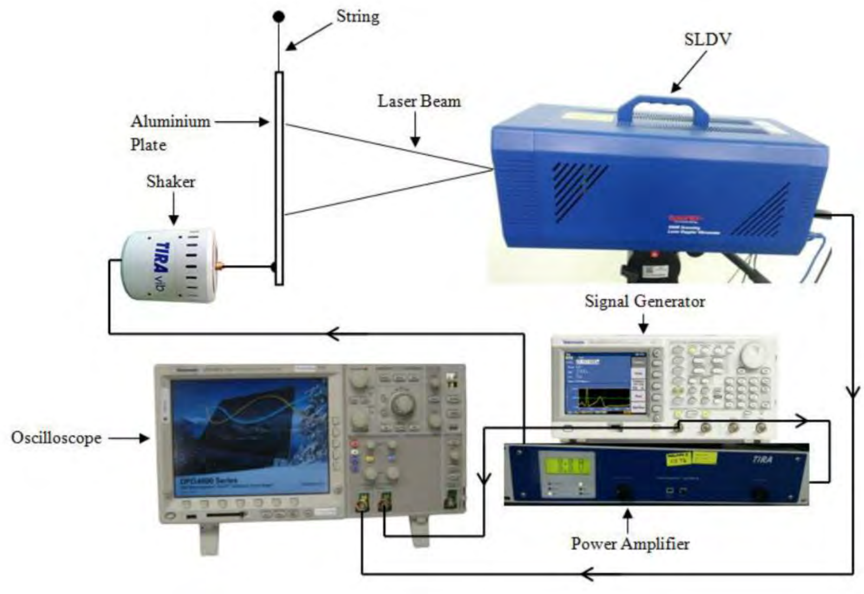


Figure 3.8: Schematic diagram of the experiment setup for experiment modal analysis

3.3.2 Finite Element (FE) Simulation Analysis

Finite Element (FE) analysis is a computer simulation method that widely used in engineering field. The FEA is a numerical method for solving the engineering problems and can show it in animation way. The FE simulation analysis was perform by using the ABAQUS software. The result obtained from the ABAQUS simulation is to ensure the natural frequencies and vibration mode shape obtained from the experiment modal test analysis was correct and accurate. There were few steps involve to complete the simulation by using the ABAQUS software. First was creation of the part design of the aluminum plate with proper dimension. Second was define the material properties such as Young's modulus and Poison's ratio. Third was assignation of the section properties and then assembly the model. Next was configuration of the analysis. After that, apply the boundary condition and apply meshing of the model before run the simulation. Lastly, submit the job module and analysis the result.

3.4 NONLINEAR VIBRO-ACOUSTICS METHOD

The effect of modulation of high frequency vibration by low frequency vibration is known as vibro-acoustics modulation (VAM). The low frequency (natural frequency) obtained from the modal test analysis was used to excite the aluminum plate and also used to modulate the high frequency provided by the PZT transducer. The SLDV capture and measured the amplitude and velocity of the aluminum plate vibration responses in time domain. The aluminum plate is hang on a frame by using the thread/string. A TIRA S50018 mechanical shaker provide high energy low frequency excitation (natural frequency) and the PTZ transducer provide low energy high frequency vibration are both attached to the aluminum plate. The position of the mechanical shaker and PZT transducer that attach on the aluminum plate is shown in the schematic diagram in Figure 3.10.

The excitation signal was generated continuous frequency by using the Textronix AFG 3022 signal generator and the signal is amplified by the TIRA BAA 60 power amplifier. The output signal were captured by the single head Scanning Laser Doppler Vibrometer (SLDV) and recorded into the Textronix DPO 4032 oscilloscope. The overall experiment setup is shown as in Figure 3.9. The total point of measurement taken were 114 points which from 19 points (top to bottom) and each line have 6 points (left to right). The final result is average from the 114 points of measurement to enhance the accuracy of the experiment result for analysis. The result record in the oscillator is in time domain. So, by using the Matlab to average all the 114 point of measurement in time domain. After that, using the Fast Fourier Transform (FFT) to transform the time domain into frequency domain.

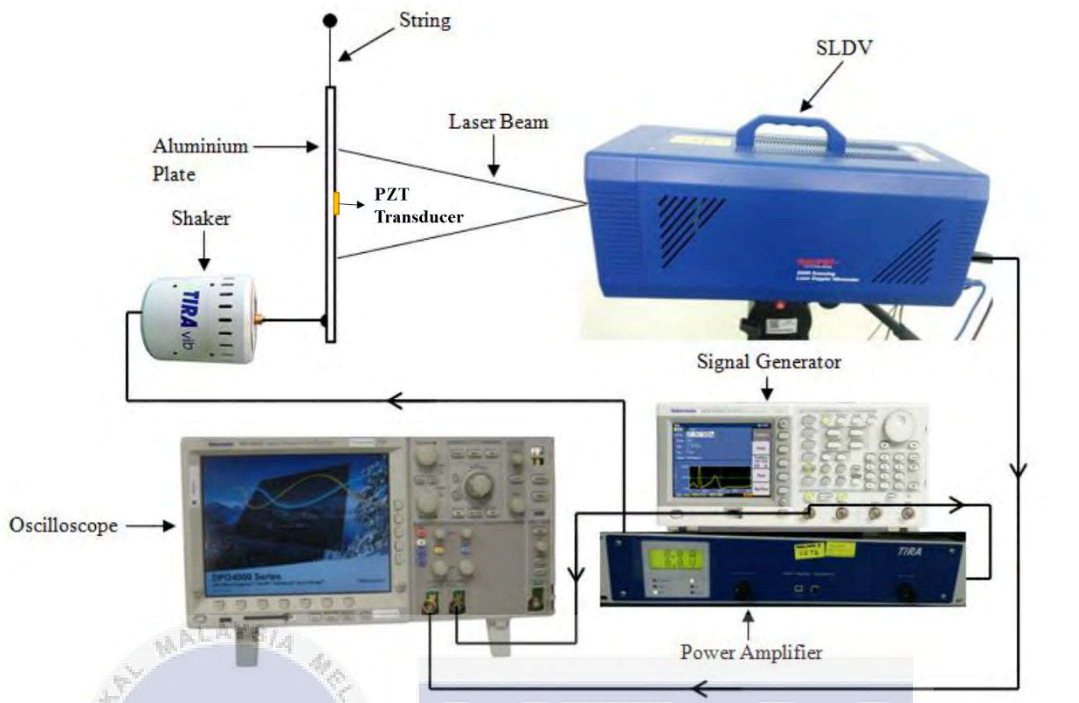
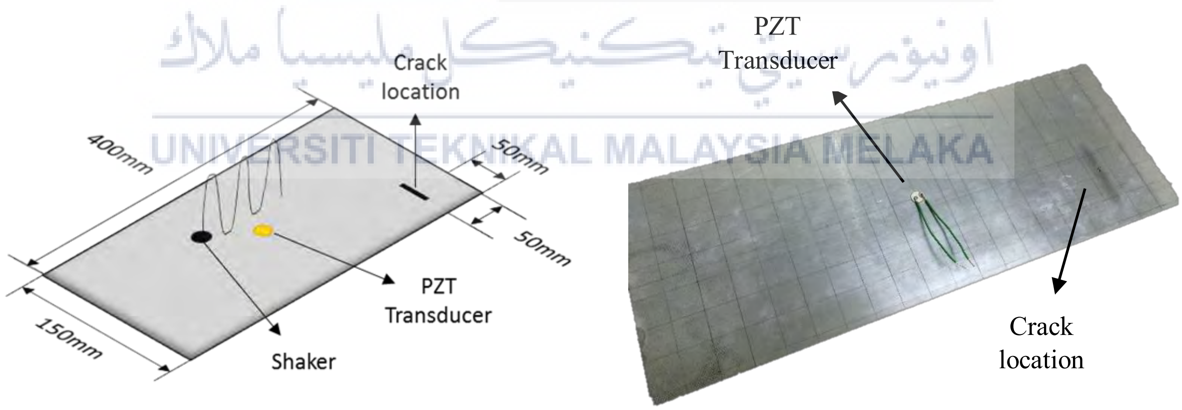


Figure 3.9: Schematic diagram of the experiment setup for vibro-acoustics method (VAM)



(a) (b)

Figure 3.10: (a) Schematic diagram and (b) Real diagram of the position for mechanical shaker and PZT transducer on the aluminum plate

3.5 DATA PROCESSING

The data captured by the SLDV recorded in the oscillator was in the form of time domain. The output signal obtained from the experiment normally in time domain spectrum need to convert into frequency domain spectrum for further analysis. The total point of measurement taken were 114 points which from 19 points (top to bottom) and each line have 6 points (left to right) is shown in Figure 3.11. The 114 points of measurement in time domain were averaged by using coding in Matlab before transform into frequency domain spectrum. This was to ensure the data obtained from the experiment was averaging to reduce the noise during the experiment. The conversation of final averaged time domain spectrum into frequency domain spectrum is using the Fast Fourier Transform (FFT). The frequency domain spectrum was used for further analysis on the prediction of crack location in the aluminum plate. Figure 3.12 shows the example of amplitude modulation in time domain and frequency domain.

In order to measure the intensity of the sideband, ratio of the first sideband frequency amplitude against the high frequency amplitude was used. The ratio is known as R-value and shown below:

$$R = \frac{A_1 + A_2}{A_0} \tag{3.1}$$

where A_0 is carrier peak amplitude and A_1 and A_2 are the first sideband amplitudes on the left and right of the carrier peak amplitude.

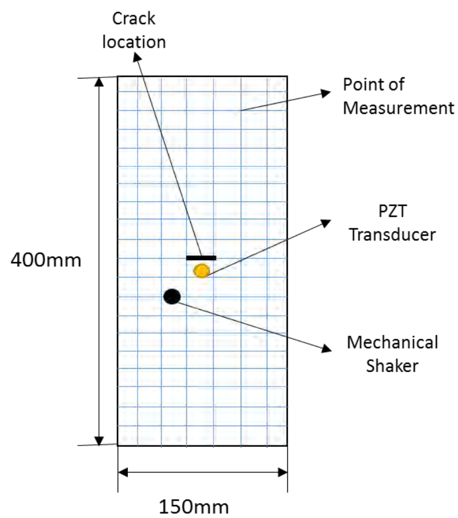
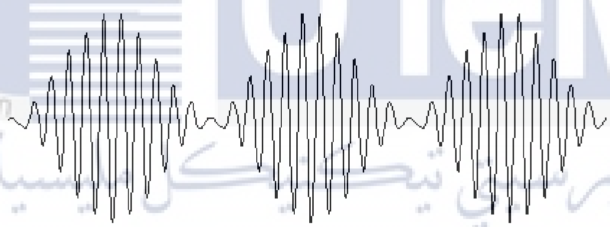
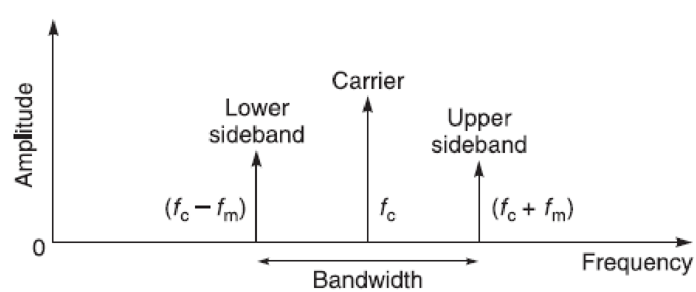


Figure 3.11: The total point of measurement is 114 which included 19 points (top to bottom) in vertical line and each horizontal line have 6 points (left to right)



(a)



(b)

Figure 3.12: (a) Example of amplitude modulation in time domain and (b) Example of amplitude modulation in frequency domain

3.6 VIBRATION MODE SHAPE

The mode shape is known as the pattern of vibration that show by a mechanical system at a specific frequency. At different frequencies, there will have different vibration mode shape as well. There few method to obtain the vibration mode shape such as experiment modal test analysis or the FE simulation analysis. In this study, the first four natural frequencies and its vibration mode shape is determine by using the experimental method and validate by using the FE simulation from ABAQUS software.

After obtain the R-value from the experimental data and compare among the first four to identify which natural frequency produce the highest R-value. The natural frequency with the highest R-value is then compared with it vibration mode shape to predict the exact location of the crack in aluminum plate. The knowledge of vibration mode shape is important in determine the crack location in this study. Figure 3.13 shows the example of vibration mode shape of the plate.

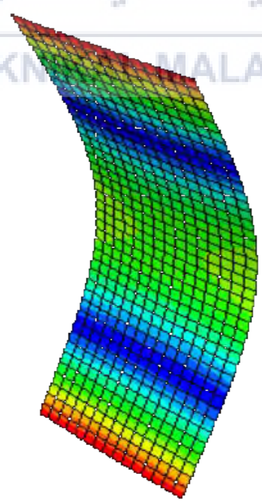


Figure 3.13: Example of vibration mode shape of the plate

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter describes the result obtained from the experiment. Before carry out the experiment, the preparation of the specimen which was the aluminum plate with desired size and crack location was prepared. After that, carry out the tensile test to obtain the maximum load, minimum load, mean load and amplitude load value for the parameter setting in fatigue test. The fatigue test was carry out for the formation of fatigue crack. For the nonlinear vibro-acoustics method, first, the aluminum plate was vibrated and tested under random frequency to obtain the natural frequencies of the aluminum plate at different mode of vibration under modal test analysis. Then, the first, second, third and fourth natural frequency of the aluminum plate was confirmed by the FE simulation. Furthermore, using the nonlinear vibro-acoustic method which is vibrate the aluminum plate at low frequency by shaker and high frequency by the PZT transducer. The result obtained was then calculated into R-value for further analysis on crack location detection.

4.2 TENSILE TEST

The tensile test is use to obtain the data for the calculation of maximum load, minimum load, mean load, and amplitude load value of the cyclic load that needed to apply to the aluminum plate when carry out fatigue test. The mechanical properties of the aluminum plate is obtained from the tensile test by using the Intron UTM and summaries in Table 4.1.

Table 4.1: The mechanical properties obtained from the tensile test

Mechanical properties	**Value**
Maximum load for yield (kN)	> 35.62
Tensile stress at max load for yield (MPa)	> 118.73
Maximum load (kN)	35.62
Tensile stress at maximum load (MPa)	118.73
Modulus, E-modulus (GPa)	29.22
Modulus, chord-cursor (GPa)	-
Extension at break (Standard) (mm)	6.28

The maximum load for the aluminum plate is 35.62 kN while the maximum load for yield is more than 35.62 kN. The tensile stress at maximum load for the aluminum plate is 188.73 MPa while the tensile stress at maximum load for yield is more than 118.73 MPa. Furthermore, the E-modulus is 29.22 GPa and the extension at break of the aluminum plate is 6.28mm.

4.2.1 Calculation the Number of Maximum, Minimum, Mean, Amplitude Load

Maximum Load = 75% of maximum yield load

= 35.62 x (75/100)

= 26.7150 kN

Minimum Load = 0.1 of maximum load

= 0.1 x 26.7150

= 2.6715 kN

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

$= \frac{26.7150 + 2.6715}{2}$

= 14.6933 kN

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

$= \frac{26.7150 - 2.6715}{2}$

= 12.0218 kN

The maximum load is 26.1750 kN which is 75% of maximum yield load. The minimum load is 2.6715 kN which is 0.1 of maximum yield load. The maximum and minimum load are the limit of the load that can be apply to the plate. The mean load is 14.6933 kN which is the average number of the load while the amplitude load is 12.0218 kN which is the difference between the maximum and minimum load.

4.3 FATIGUE TEST

The fatigue test is used to create the fatigue crack with three different crack locations on three different aluminum plates which are the crack location at middle, above middle and at the edge. The desired total crack length for each location is 35mm in each aluminum plate. The number of cycles need to create fatigue crack at the middle is 129,290 cycles with the maximum load of 26.7150 kN, minimum load of 2.6715 kN and loading frequency of 7. The number of cycles need to create fatigue crack at above middle is 90,393 cycles with the maximum load of 26.7150 kN, minimum load of 2.6715 kN and loading frequency of 7. The number of cycles need to create fatigue crack at the edge is 169,746 cycles with the maximum load of 26.7150 kN, minimum load of 2.6715 kN and loading frequency of 7. The time taken to create the crack is around 5-6 hours for each plate. Table 4.2 summaries the data of number of cycles needed to create crack for each plate.

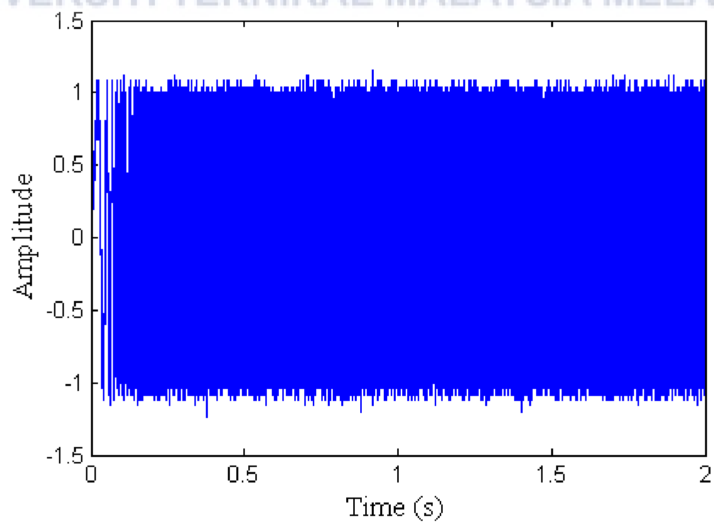
Table 4.2: The number of cycles, loads, and loading frequency to create crack

Item	**Crack Location**		
	Middle	**Above Middle**	**Edge**
Crack length (mm)	35	35	35
Number of cycles	129,209	90,393	169,746
Maximum load (kN)	26.7150	26.7150	26.7150
Minimum load (kN)	2.6715	2.6715	2.6715
Loading frequency (Hz)	7	7	7

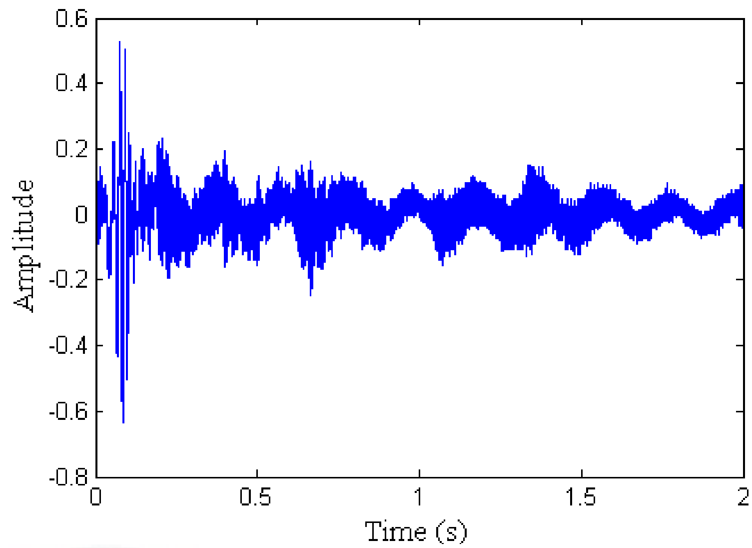
4.4 MODAL TEST ANALYSIS

The modal test analysis was used to obtain the natural frequencies of the aluminum plate and FE simulation was used to ensure the natural frequencies obtain were first, second, third and fourth mode of vibration. The excitation signal was generated using signal generator and amplified by power amplifier. The excitation was subjected to the aluminum plate by a mechanical shaker at the position show on the Figure 3.9 and the aluminum plate was suspended by soft string. A mechanical shaker is a device that used to excite the object or structure such as aluminum plate at low frequency according to its amplified input signal. Many types of input signals are available for modal testing, but the most common used were sine sweep and random frequency vibration profiles.

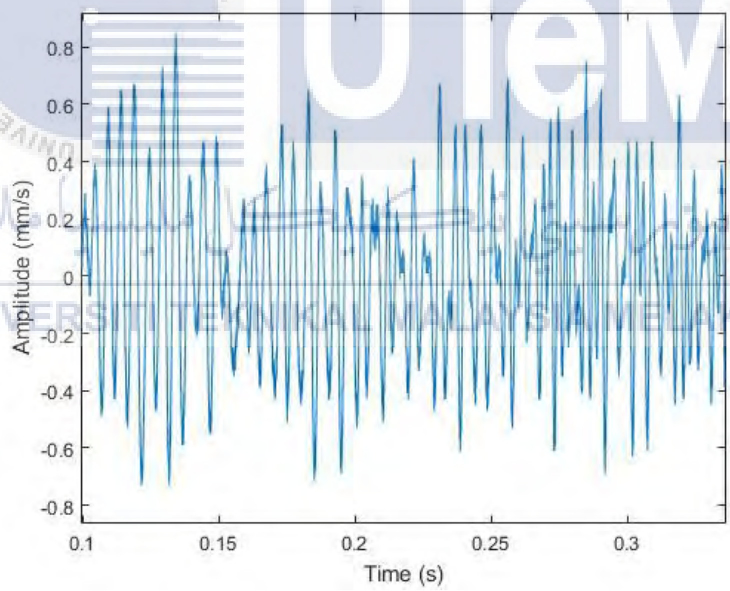
The output signal responses of the aluminum plate from the low frequency vibration excitation were captured by a single head Scanning Laser Doppler Vibrometer (SLDV) and recorded into oscilloscope type. Figure 4.1 shows the example of the aluminum plate response in time domain for the input and output signal.



(a)



(b)



(c)

Figure 4.1: (a) input signal, (b) output signal in time domain and (c) zoom in view of output modulation signal in time domain

4.4.1 Experimental Results

The result captured by the SLDV on the oscilloscope can be presented in frequency domain graph. The natural frequencies of the aluminum plate was obtained from the frequency domain graph. The peak of the graph show the first, second, third and fourth natural frequency respectively. An example of the frequency domain graph was shown in Figure 4.2.

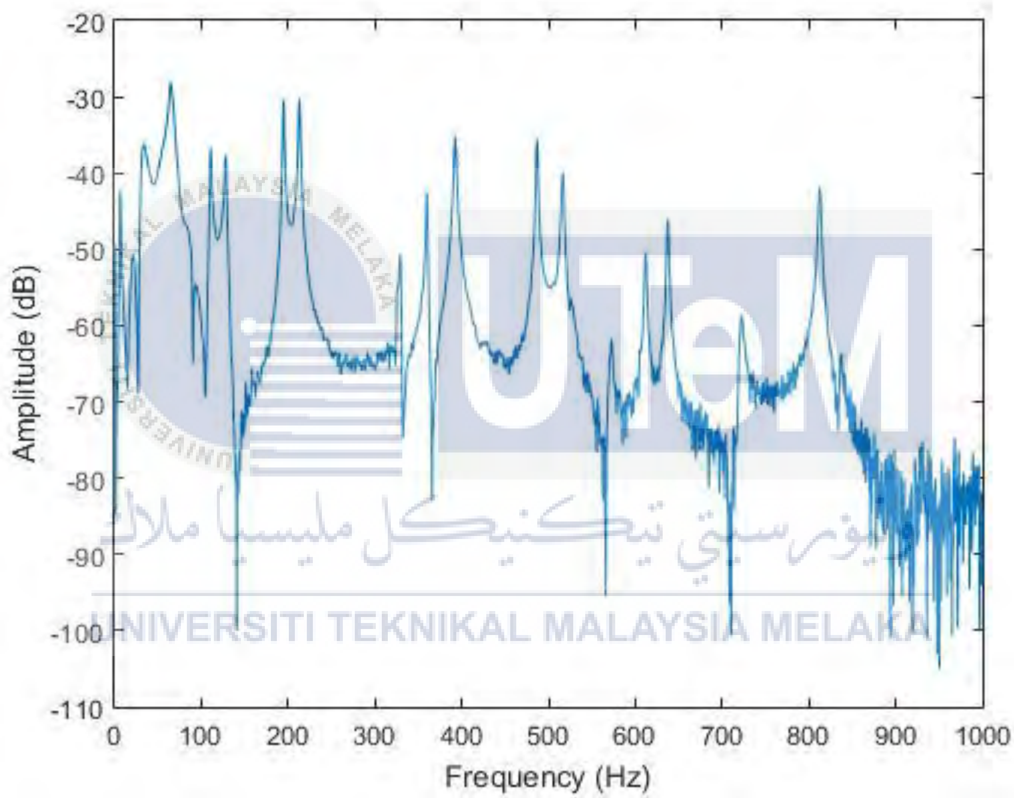


Figure 4.2: Example of frequency domain graph result from modal test analysis

The first four natural frequencies for crack location at the middle were 65, 109, 168, and 212 Hz. Moreover, for crack at the location above middle were 64.5, 111, 195, 213 Hz. Furthermore, for crack location at the edge were 60, 122, 181.5, 203 Hz. The value of first four natural frequencies of all three crack location had shown in Table 4.3.

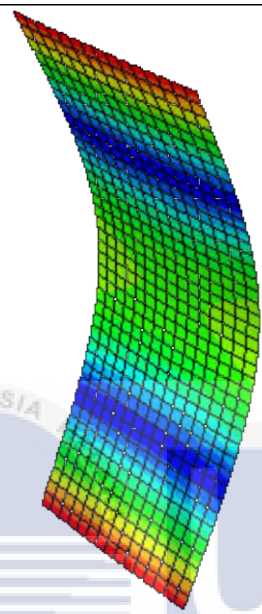
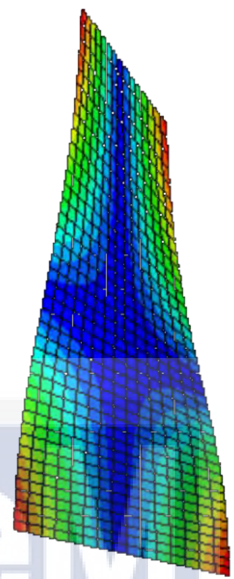
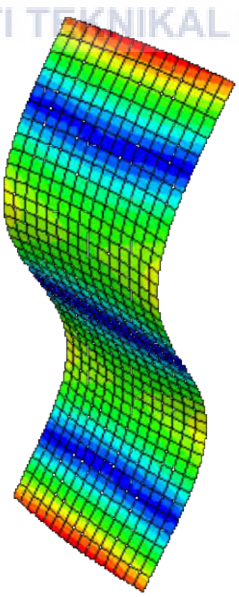
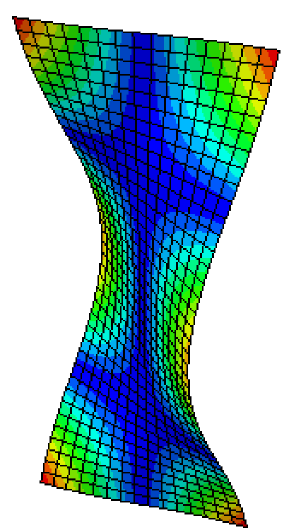
Table 4.3: First four natural frequency for several crack location

Natural Frequency	Crack Location		
	Middle	**Above Middle**	**Edge**
First	65 Hz	64.5 Hz	60 Hz
Second	109 Hz	111 Hz	122 Hz
Third	168 Hz	195 Hz	181.5 Hz
Fourth	212 Hz	213 Hz	203 Hz

4.4.2 FE Simulation

The first four natural frequencies and its vibration mode obtained from the experiment was confirmed by using the FE simulation. The first vibration mode shape was single band, the second vibration mode shape was single twisting, the third vibration mode shape was double band and the fourth vibration mode shape was double twisting. Table 4.4 shows the vibration mode shape of the first four natural frequencies.

Table 4.4: Vibration mode shape

	First vibration mode (60-70Hz)	Second vibration mode (100-125Hz)
FE Simulation		
	Third vibration mode (160-195Hz)	Fourth vibration mode (200-220Hz)
		

4.5 NONLINEAR VIBRO-ACOUSTICS ANALYSIS

The effect of modulation of high frequency vibration by low frequency excitation is known as vibro-acoustics modulation (VAM). The low frequency (natural frequency) obtained from the modal test analysis was used to excite the aluminum plate and also used to modulate the high frequency provided by the PZT transducer. The SLDV measured the amplitude and velocity of the aluminum plate vibration responses in time domain. By using the Fast Fourier Transform (FFT) to transform the time domain into frequency domain.

After the aluminum plate was subjected to low frequency and high frequency, the sideband around the carrier peak of the high frequency which measure in frequency domain was the phenomenon of the VAM. The time domain for each point of measurement was recorded and using Matlab to average it into the final time domain signal. Figure 4.3 shows the example of the final time domain signal after averaged from 114 point of measurements.

The average of 114 points of measurement was obtained and transform the final result into frequency domain which excite at first four natural frequencies was recorded. In order to measure the intensity of the sideband, ratio of the first sideband frequency amplitude against the high frequency amplitude was used. The ratio is known as R-value and shown below:

$$R = \frac{A_1 + A_2}{A_0} \tag{4.1}$$

where A_0 is center peak amplitude and A_1 and A_2 are the first sideband amplitudes on the left and right of the center peak amplitude.

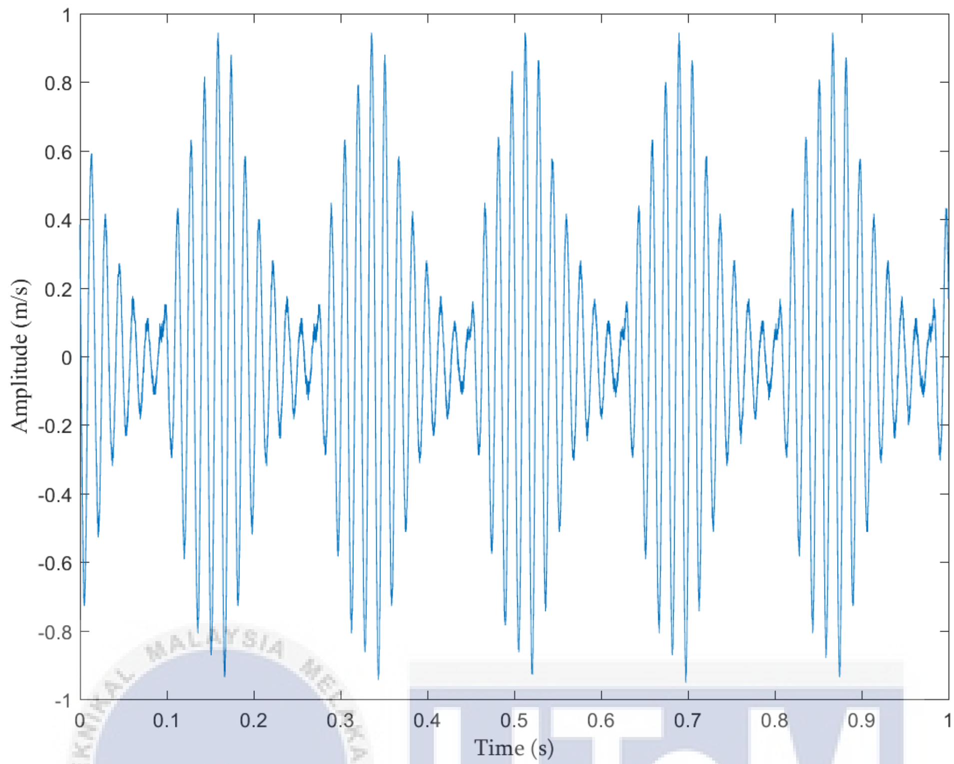


Figure 4.3: Example of the modulation signal in time domain after averaged from 114 points

4.5.1 Crack Location at Middle

The aluminum plate with crack location at middle was subjected an input low frequency which were first, second, third and four natural frequencies and simultaneously provided the high frequency which is 60k Hz by the PZT transducer. The output result of nonlinear vibro-acoustics analysis was recorded in both time and frequency domain. The average of 114 points of measurement was taken to plot the time domain graph and transform it into the frequency spectrum graph as shown in Figure 4.4-4.7. The ratio of the summation of the first sideband amplitude against the center peak amplitude was calculate and known as R-value is shown in Table 4.5.

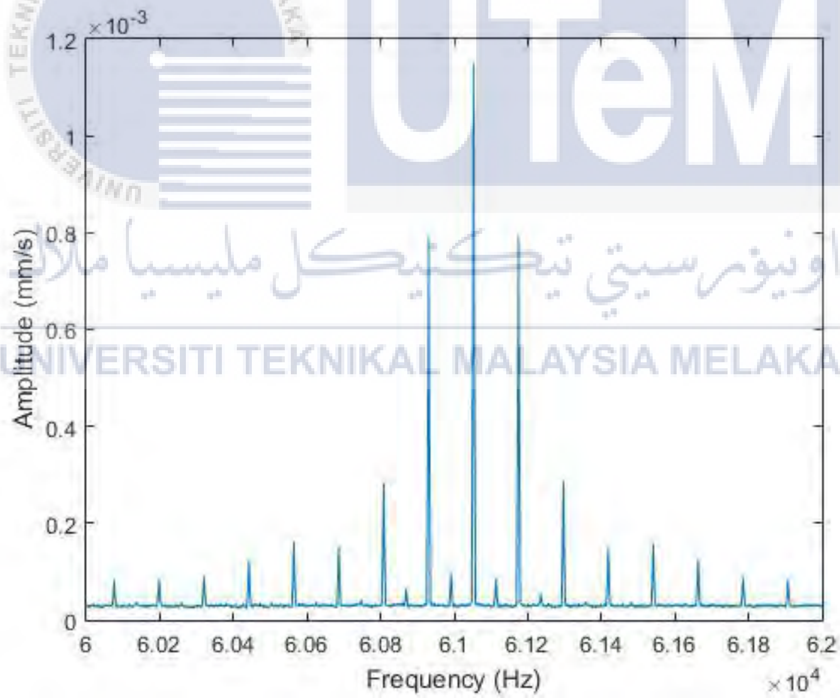


Figure 4.4: Frequency spectrum around 60k Hz for first natural frequency (65Hz)

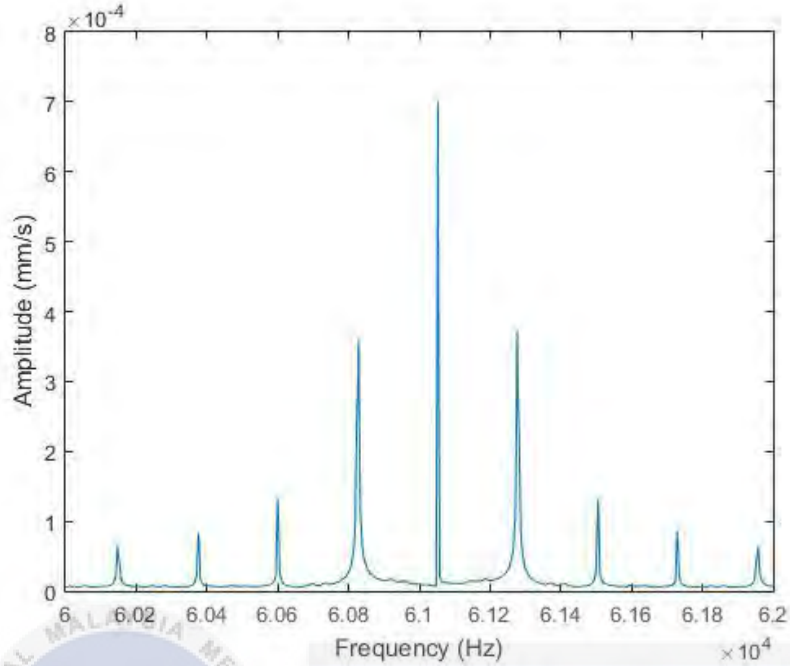


Figure 4.5: Frequency spectrum around 60k Hz for second natural frequency (109Hz)

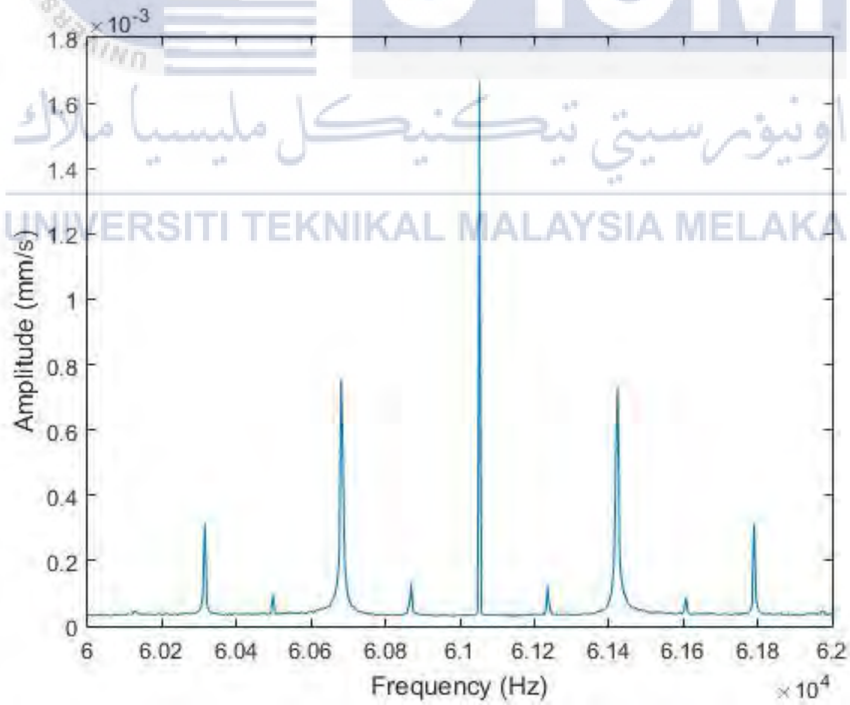


Figure 4.6: Frequency spectrum around 60k Hz for third natural frequency (168Hz)

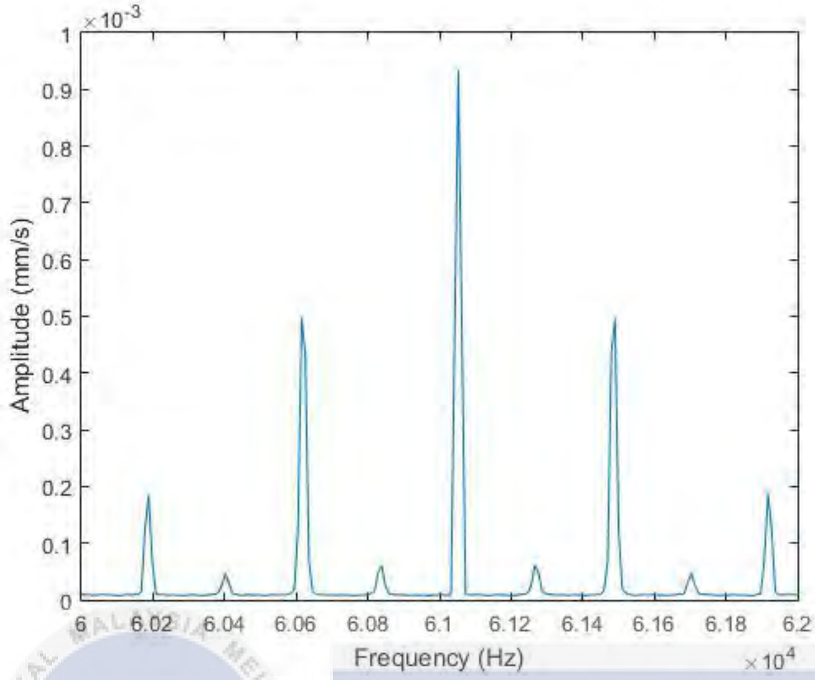


Figure 4.7: Frequency spectrum around 60k Hz for fourth natural frequency (212Hz)

Table 4.5: R-value for the first four natural frequencies for crack location at middle

Natural Frequency	**A0**	**A1**	**A2**	**R-value**
First	0.0000542	0.0000529	0.0000539	1.970479705
Second	0.0000690	0.0000490	0.0000464	1.382608696
Third	0.0000837	0.0000492	0.0000489	1.172043011
Fourth	0.0000975	0.0000602	0.0000604	1.236923077

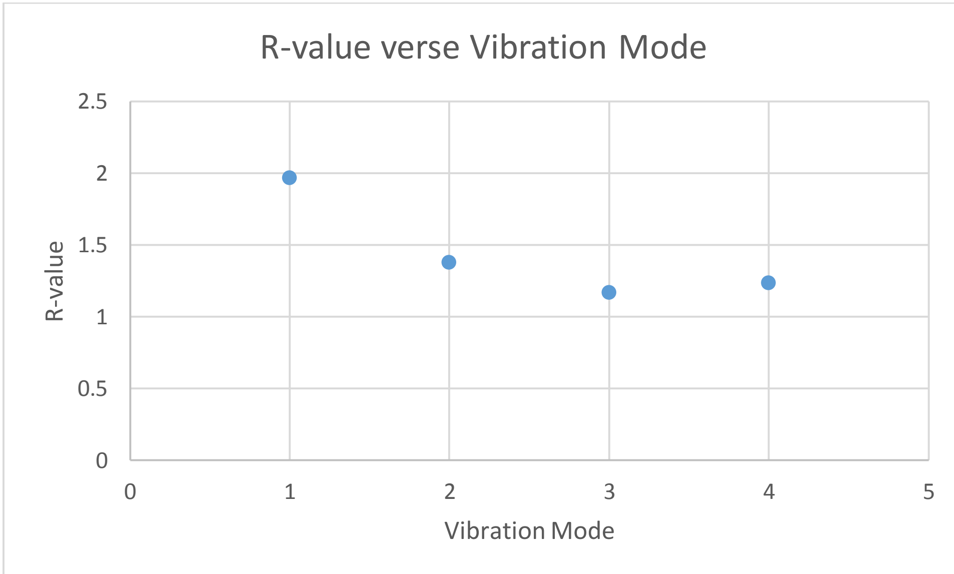


Figure 4.8: R-value verse vibration mode for crack location at middle

The R-value of the first natural frequency is the highest. This is because the amplitude of the first vibration mode is the highest among the second, third and fourth vibration mode. This can be observe from the R-value in Figure 4.8. Although, the R-value of the first vibration mode does not have significant result to indicate the location of the crack because the amplitude of the first mode vibration is always the highest. However, for the crack location at the middle the R-value of the first vibration mode is extremely high which is 1.97 when compare to the following mode of vibration. This mean that the first mode of vibration can open the crack biggest and result in highest R-value. By referring to the first vibration mode shape as shown in Table 4.4, the maximum deflection is at the middle. So, the ‘possible’ location of the crack is therefore at middle.

4.5.2 Crack Location at Above Middle

The aluminum plate with crack location above middle was subjected an input low frequency which were first, second, third and four natural frequencies and simultaneously provided the high frequency which is 60k Hz by the PZT transducer. The output result of nonlinear vibro-acoustics analysis was recorded in both time and frequency domain. The average of 114 points of measurement was taken to plot the time domain graph and transform into the frequency spectrum graph as shown in Figure 4.9-4.12. The ratio of the summation of the first sideband amplitude against the center peak amplitude was calculate and known as R-value is shown in Table 4.6.

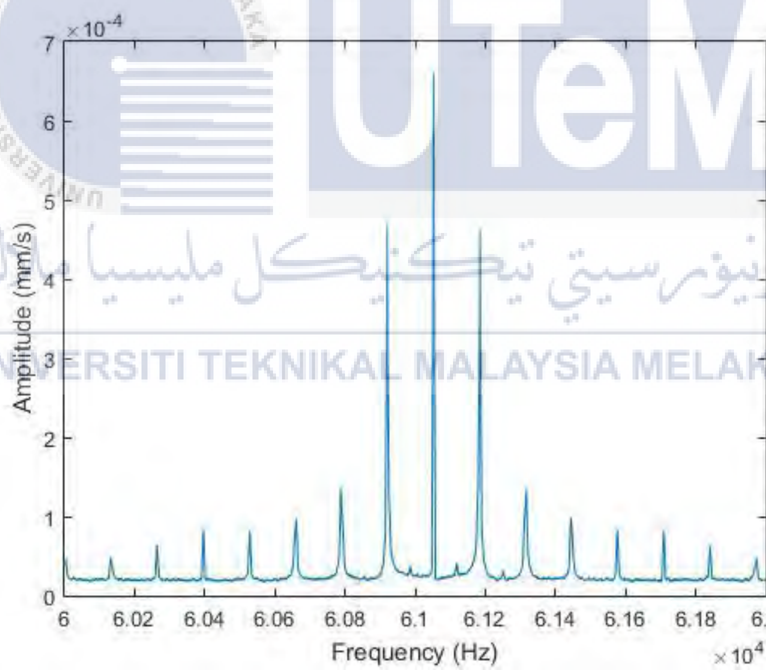


Figure 4.9: Frequency spectrum around 60k Hz for first natural frequency (64.5Hz)

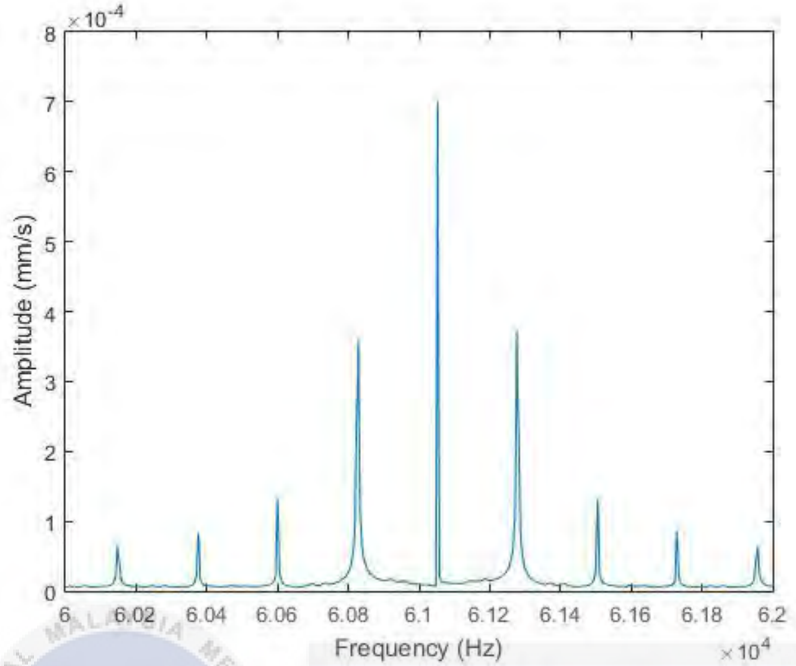


Figure 4.10: Frequency spectrum around 60k Hz for second natural frequency (111Hz)

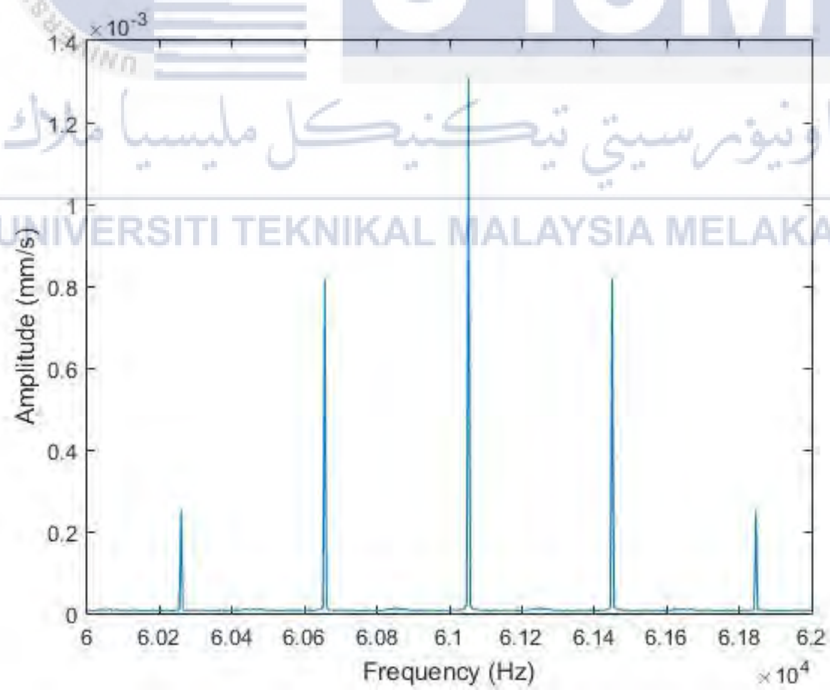


Figure 4.11: Frequency spectrum around 60k Hz for third natural frequency (195Hz)

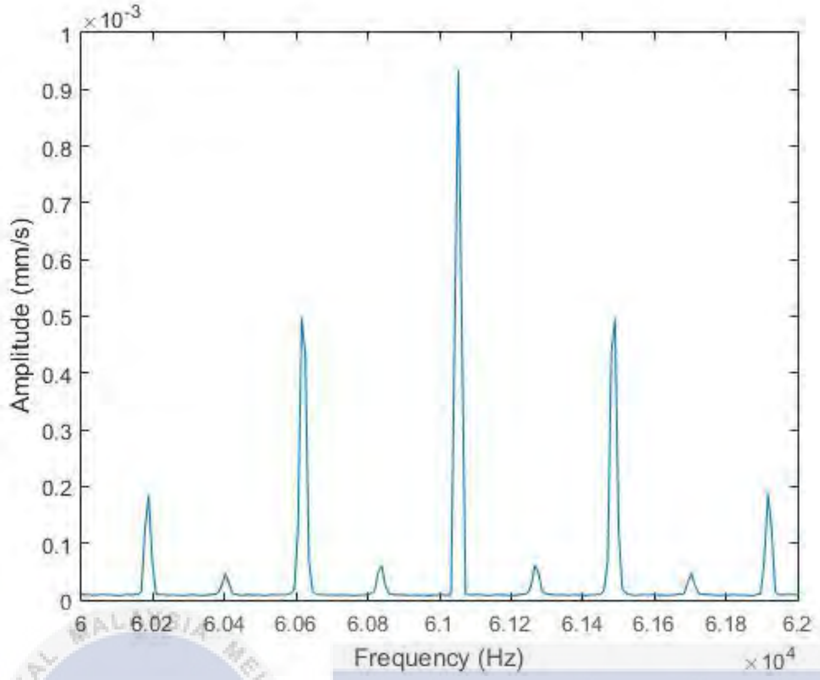


Figure 4.12: Frequency spectrum around 60k Hz for fourth natural frequency (213Hz)

Table 4.6: R-value for the first four natural frequencies for crack location at above middle

Natural Frequency	A0	A1	A2	R-value
First	0.0006609	0.0004687	0.0004624	1.40883644
Second	0.0007015	0.0003593	0.0003733	1.04433357
Third	0.0013110	0.0008170	0.0008189	1.24782609
Fourth	0.0009556	0.0004976	0.0004952	1.03892842

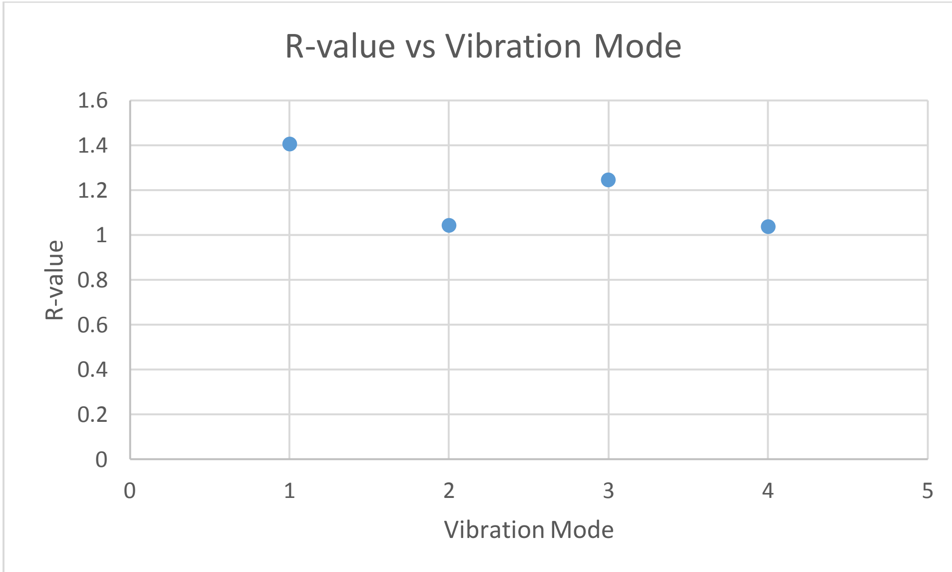


Figure 4.13: R-value verse vibration mode for crack location above middle

The R-value of the first natural frequency is the highest. This can be observe from the R-value graph in Figure 4.13. However, the R-value of the first vibration mode does not indicate the location of the crack. This is because the amplitude of the first vibration mode is the highest among the second, third and fourth vibration mode. This mean that even at the lowest vibration amplitude during the first vibration mode but the amplitude of vibration is still higher than the second, third and fourth vibration mode. Thus, the R-value of the second and third vibration mode can then be used to predict the possible crack location. It can be seen that the R-value of the third vibration mode is greater than the second and fourth mode, which now also indicates that the crack location is fall on the location above the middle. By referring to the third vibration mode shape as shown in Table 4.4, the 'possible' location of the crack is therefore at location above middle.

4.5.3 Crack Location at the Edge

The aluminum plate with crack location at the edge was subjected an input low frequency which were first, second, third and four natural frequencies and simultaneously provided the high frequency which is 60k Hz by the PZT transducer. The output result of nonlinear vibro-acoustics analysis was recorded in both time and frequency domain. The average of 114 points of measurement was taken to plot the time domain graph and transform into the frequency spectrum graph as shown in Figure 4.14-4.17. The ratio of the summation of the first sideband amplitude against the center peak amplitude was calculate and known as R-value is shown in Table 4.7.

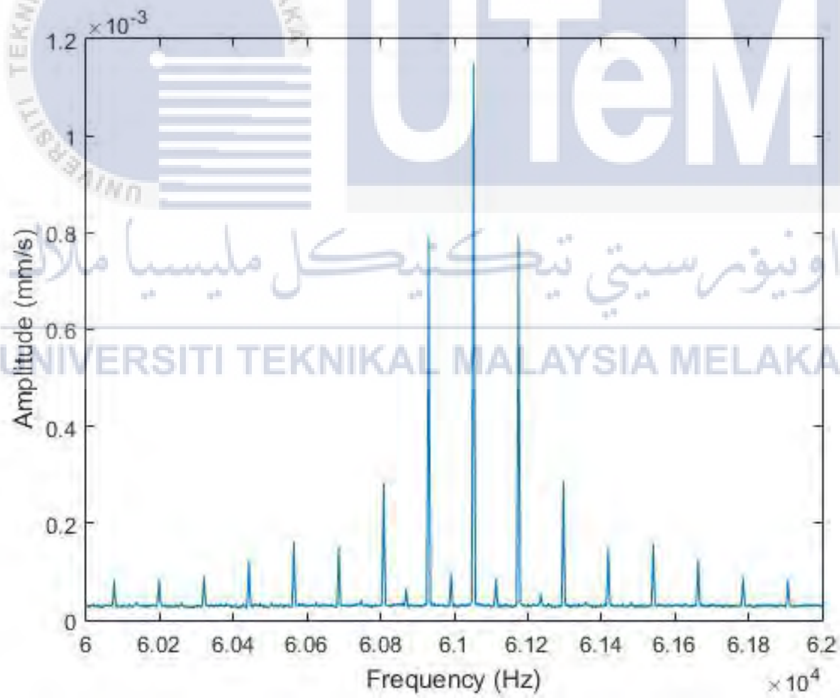


Figure 4.14: Frequency spectrum around 60k Hz for first natural frequency (60Hz)

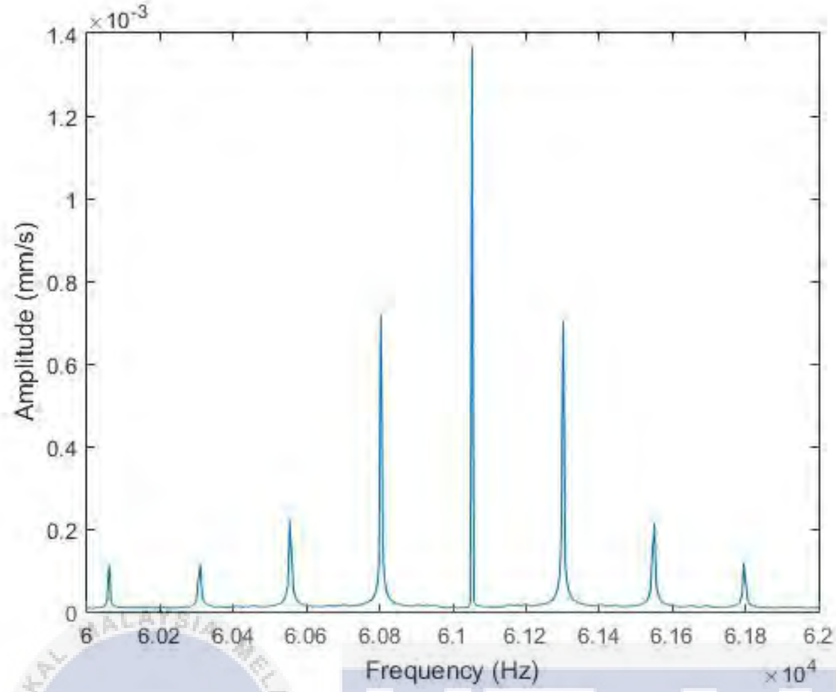


Figure 4.15: Frequency spectrum around 60k Hz for second natural frequency (122Hz)

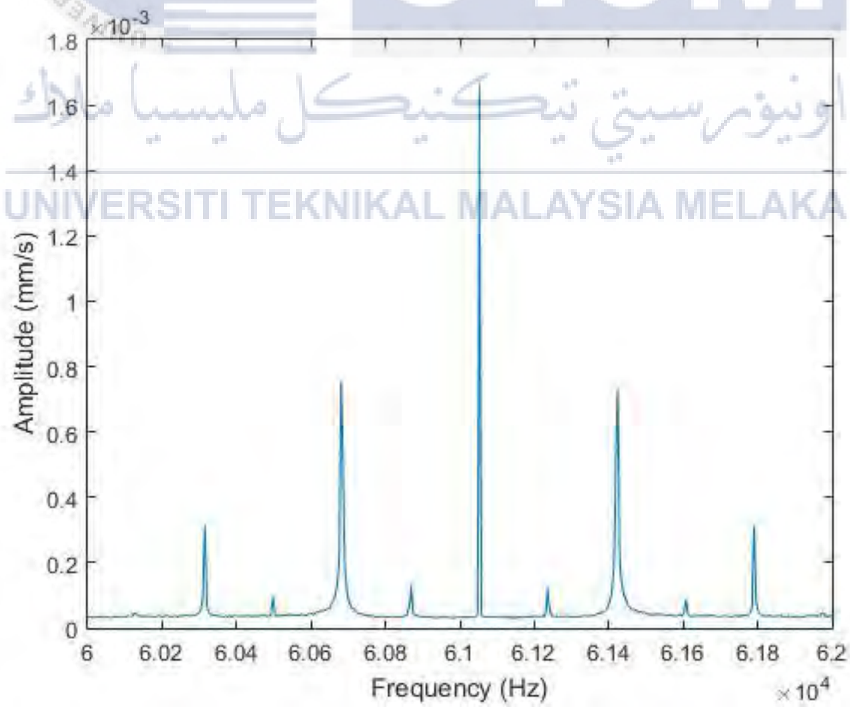


Figure 4.16: Frequency spectrum around 60k Hz for third natural frequency (181.5Hz)

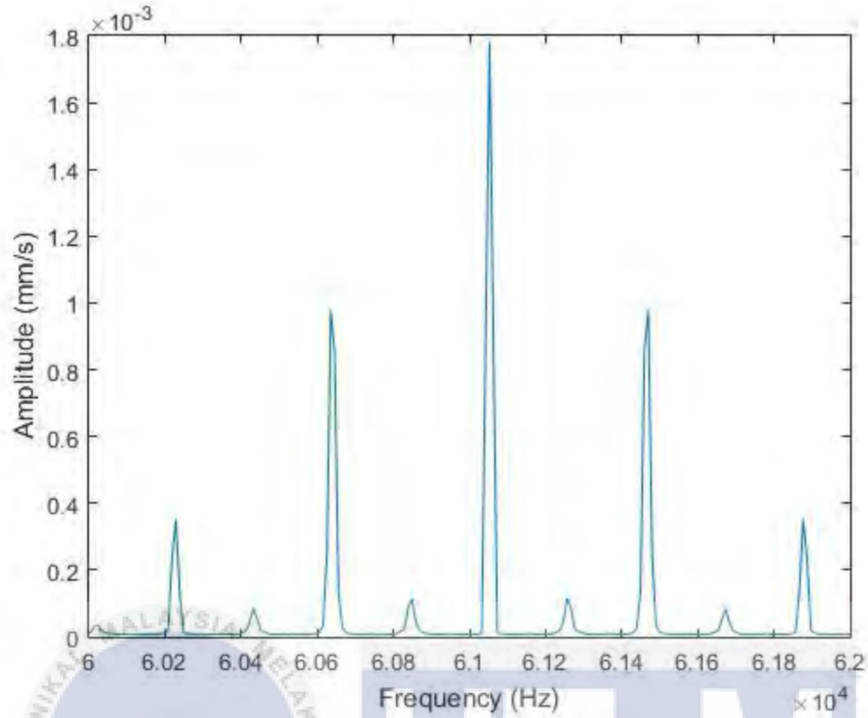


Figure 4.17: Frequency spectrum around 60k Hz for fourth natural frequency (203Hz)

Table 4.7: R-value for the first four natural frequencies for crack location at edge

Natural Frequency	A0	A1	A2	R-value
First	0.001152	0.000791	0.0007951	1.376822917
Second	0.001367	0.0007181	0.0007048	1.040892465
Third	0.001666	0.0007572	0.0007307	0.893097239
Fourth	0.001882	0.0009787	0.0009741	1.037619554

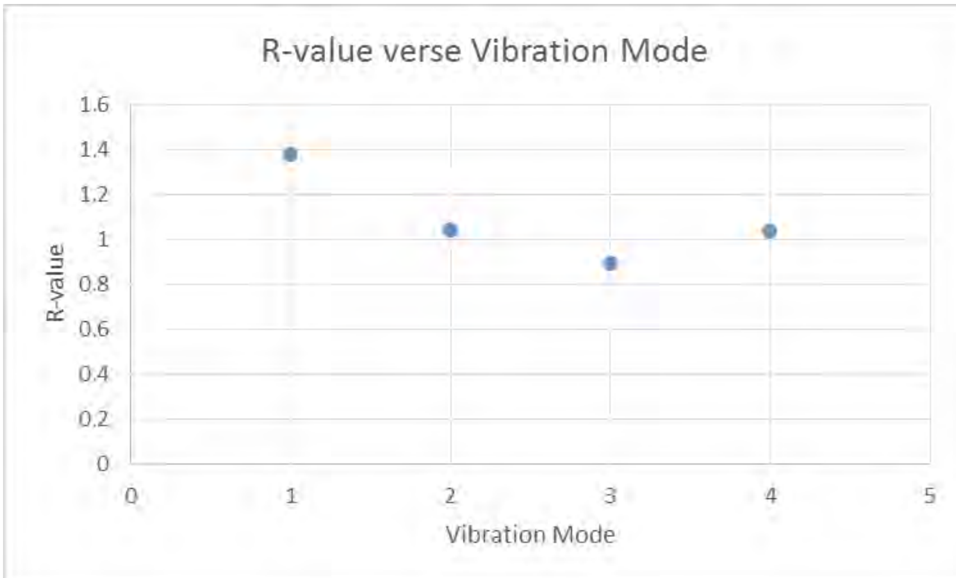


Figure 4.18: R-value verse vibration mode for crack location at edge

The R-value of the first natural frequency is the highest. This can be observe from the R-value in Figure 4.18. However, the R-value of the first vibration mode does not indicate the location of the crack. This is because the amplitude of the first vibration mode is the highest among the second, third and fourth vibration mode. This mean that even at the lowest vibration amplitude during the first vibration mode but the amplitude of vibration is still higher than the second, third and fourth vibration mode. Thus, the R-value of the second and third vibration mode can then be used to predict the possible crack location. It can be seen that the R-value of the second vibration mode is greater than the third mode, which now also indicates that the crack location is either at the center of the plate (1st mode, greatest at the middle) or at the edge of the plate (all modes, all edges have high amplitude). However, the value of R-value can be observed to be almost the same. The crack should located in the center of the plate, the 3rd mode must have shown much lower R-value, because the crack is exactly at the nodal point. So, the 'possible' location of the crack is therefore at the plate edge.

4.6 VALIDATION

The R-value of the first mode of vibration was the highest but it does not indicate the location of the crack. This is because the amplitude of the vibration of the plate is the biggest when excite at it first natural frequency. The first vibration mode shape is single band which result in bigger amplitude compare to double band or twisting mode of vibration. The vibration amplitude for the aluminum plate with crack location above middle was taken to ensure the amplitude of vibration for first mode is always highest. The crack location on the plate was located at point 5. At point 5 which is the location of crack, the amplitude for first mode of vibration is 0.2427 (mm/s) while the third mode of vibration is 0.1296 (mm/s). This indicate that the vibration amplitude for first mode of vibration is always higher than others mode of vibration. Measurement of 19 points was taken from top to bottom of the aluminum plate and the result is shown in Figure 4.19.

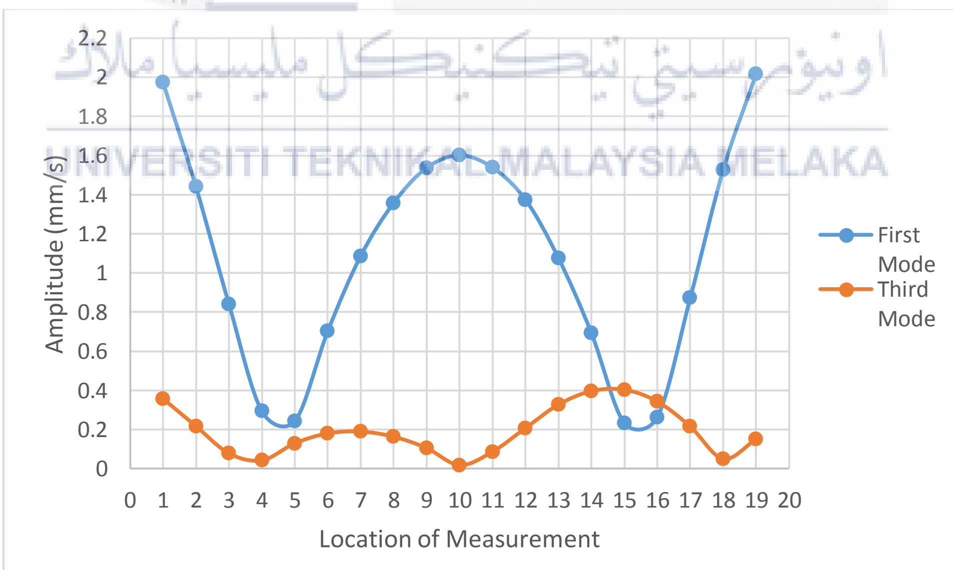


Figure 4.19: Compare vibration amplitude between first and third mode of vibration

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In conclusion, the aim of this study is to investigate the effect of vibration mode shape on crack detection and also to predict the crack location in the aluminum plate by using the nonlinear vibro-acoustics method (VAM). The result show that the damage structure can be detected due to the generation of the sideband responses while the undamaged structure can assume as linear system. The generation of sideband frequency responses allow us to calculate the amplitude modulation intensity which is R-value to predict the crack location in the aluminum plate.

- The R-value for the 1st vibration mode is the highest, which mean the first vibration mode open the crack biggest. By referring to the vibration mode shape, the first vibration mode shape is single band which have maximum deflection at the middle. So the possible crack location is at the middle.
- The R-value for the 3rd vibration mode is higher compare to the 2nd and 4th vibration mode, which mean the third vibration mode open the crack biggest. By referring to the vibration mode shape, the third vibration mode shape is double band which have maximum deflection at the area above the middle. So the possible crack location is above the middle.

- The R-value for the 2^{nd} and 4^{th} vibration mode is higher compare to the 3^{rd} vibration mode, which mean the second and fourth vibration mode open the crack biggest. By referring to the vibration mode shape, the second and fourth vibration mode shape is single twisting and double twisting respectively, which have maximum deflection at the edge. So the possible crack location is at the edge.

With the knowledge on vibration mode shape which show that, only the first vibration mode is not enough to predict the crack location. The following vibration modes is also important in predicting the crack location. Lastly, the crack location can be predict from the amplitude modulation intensity, R-value result from nonlinear vibro-acoustics method (VAM) and by referring to the vibration mode shape of each vibration mode.

5.2 RECOMMENDATION

In recommendation some good suggestion is needed to achieve better work in future for this study. There are some recommendation for the next researcher to improve in certain areas such as:

1. Use various types of material such as composite material instead of aluminum. In composite material might show different result because of the nonlinear elastic effects.
2. Use more complex structure as testing specimen instead of rectangular aluminum plate to enhance the usability in industry. For example, can use steel pipe as the testing specimen because pipeline is mainly use in oil and gas or any others industry for transportation of fluid.
3. To study the direction of crack propagation in a structure. This is because with the help of the direction of crack propagation, it is able to predict the outcome of the failure and to take earlier action in order to prevent the catastrophic failure.

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APPENDICES

Table: Gantt Chart for PSM 1

No	Task	Week															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Introduction to FYP																
2	Initial work & Brainstorming																
3	Article and Gantt Chart Submission																
4	Introduction & Methodology																
5	Journal Submission																
6	Equipment Setup																
7	Progress Report Submission																
8	Setup Experiment																
9	Conduct Experiment																
10	Report FYP 1 Submission																
11	Result Presentation																

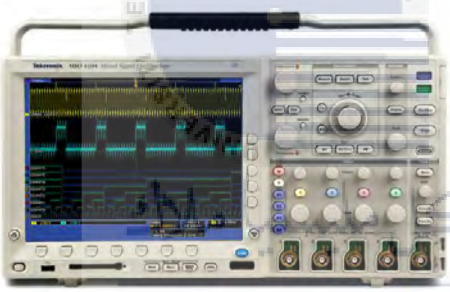
Table: Gantt Chart for PSM 2

No	Task	Week														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Preparation Specimen															
2	Setup Experiment															
3	Conduct Experiment															
4	Analysis the Data and Result															
5	Progress Report 2 Submission															
6	Preparation Report FYP 2															
7	Report FYP 2 Submission															
8	Result Presentation															

EQUIPMENT:

1. Scanning Laser Doppler Vibrometer (SLDV)

2. Oscilloscope (Tektronix DPO 4032)



3. Signal Generator (Tektronix AFG 3022)

4. Mechanical Shaker (TIRA S50018)

5. Power Amplifier (TIRA BAA 60)

6. Steel Frame