EFFECT OF VARIOUS LOW FREQUENCIES FOR CRACK DETECTION IN NON-LINEAR VIBRO-ACOUSTIC METHOD

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EFFECT OF VARIOUS LOW FREQUENCIES FOR CRACK DETECTION IN NON-LINEAR VIBRO-ACOUSTIC METHOD

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This report is submitted
in fulfillment of the requirement for the degree of
Bachelor of Mechanical Engineering (Plant & Maintenance)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

DECLARATION

I declare that this project report entitled "Effect Of Various Low Frequencies For Crack Detection In Non-Linear Vibro-Acoustic Method" is the result of my own work except as cited in the references

Signature : ....

Name : ....

Date : ....

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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 : ....

Date : ....

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DEDICATION

To my beloved mother and father

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ABSTRACT

Structural Health Monitoring is a very common and popular in maintenance engineering to maintain the performance and reliability of the structure. This technique is used to detect detection in the structure for further maintenance. Non-linear vibro-acoustic is a unique technique that suitable for fatigue crack detection. Vibro-acoustic technique is a method which introducing two type of frequency into a structure for defect detection. The two frequencies are high frequency acoustic wave and low frequency excitation. Wave distortion effects will be produced when the acoustic wave interact with the damaged in the structures. There are few parameters which will affect the non-linear vibro-acoustic test which included high frequency acoustic wave, low frequency vibration excitation, excitation locations and location of sensor. However, the study of non-linear effect of low frequency excitation to detect the crack is still not much done by previous researcher. Thus, experimental works performed with resonance and non-resonance frequency as low frequency excitation to determine the non-linear effect of low frequency in the vibro-acoustic test. Nonlinear acoustic tests performed on an aluminium plate with total of 10± 1mm fatigue crack and result proved that the low frequency excitation will affect the modulation intensity in vibro-acoustic test.

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ABSTRAK

Struktur Pemantauan Kesihatan adalah popular dan sangat biasa diguna dalam bidang kejuruteraan penyelenggaraan untuk mengekalkan prestasi dan kebolehharapan struktur. Teknik ini digunakan untuk mengesan bocoran dalam struktur untuk aktiviti penyelenggaraan. Nonlinear vibro-akustik adalah teknik yang unik yang sesuai untuk mengesan retak lesu. Teknik Vibro-akustik adalah satu kaedah yang memperkenalkan dua jenis frekuensi ke dalam struktur untuk mengesan kerosakan. Kedua-dua frekuensi frekuensi tinggi gelombang akustik dan pengujaan frekuensi rendah. Kesan distorsi akan dihasilkan apabila gelombang akustik berinteraksi dengan yang kerosakan dalam struktur. Terdapat beberapa parameter yang akan menjejaskan ujian nonlinear vibro-akustik termasuk frekuensi tinggi gelombang akustik, getaran frekuensi rendah, lokasi pengujaan dan lokasi sensor. Walaubagaimanapun, kajian kesan pengujaan frekuensi rendah untuk mengesan retak dalam nonlinear vibro-akustik masih tidak banyak dilakukan oleh penyelidik terdahulu. Oleh itu, kerja-kerja eksperimen dilakukan untuk menentukan kesan frekuensi rendah dalam ujian vibro-akustik dengan menggunakan frekuensi resonans dan bukan resonans sebagai pengujaan frekuensi rendah. Ujian vibro-akustik dilakukan pada plat aluminium dengan celah sepanjang 10 ± 1mm dan hasilnya membuktikan bahawa pengujaan rendah akan menjejaskan kekuatan modulasi dalam ujian vibro-akustik.

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ACKNOWLEDGEMENTS

First and foremost, I would like to express my appreciation to my supervisor Dr. Ruztamreen bin Jenal for give me opportunity to complete my final year project with him. His advice and guidance helps me to solve problem arise during this project. I am grateful for his patience throughout the research.

I would also very thankful to all technicians that spending their time to teaching and helping me to prepare specimen and carry out the experiment correctly. Their guidance, critics, and advice are very important keys that lead to success of this project.

Besides, I would like to dedicate my gratitude to a master student named Mr. Tino for spending his time to guide and share his knowledge and experience on vibro-acoustic test. This helps me to increase my understanding for the experiment.

In addition, I would like to thanks my beloved family, my friends and everyone who provided support directly or indirectly throughout this study.

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LIST OF ABBEREVATIONS

SHM	Structural Health Monitoring
NDT	Nondestructive Test
PZT	Piezoelectric Transducer
FRF	Frequency Response Function

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CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, Structural Health Monitoring (SHM) technique is a very common technique which used in the maintenance engineering to maintain performance and reliability of the structures. SHM is the process of defect detection to plan for further maintenance activities. There is various damage detection methods used to detect different type of damages on the structure more effectively.

Damage in structure is the main cause which could affect the structure's performance. Jean Lemaitre (2005) [1] define damage as that creation and growth of microvoids or microcracks that propagated in the structure. Damages which commonly found in the metal structures are fatigue failures, ductile failures, and brittle failures [1].

Fatigue crack is the major causes of aircraft accident since in the 1948 [2]. Fatigue is localized damage which caused by repeatedly applied loads. The fatigue crack still occur in the structure although the strength of material is much higher compare to the normal maximum stress which applied to the structure. When the material is subjected to frequent loading and unloading, the stress will occur in the microscopic crack and cause the size of crack increase. Finally when the crack reaches certain size, the crack will propagate rapidly and fracture of structure will occur.

In maintenance engineering, various Nondestructive Test (NDT) methods are used to detect the damage which occurs in the structure. NDT consist of two type of measurement system which are contact and non-contact. The main purpose of NDT is to evaluate the structure's condition without damaging it. As recalled by Staszewski et. al. (2004) [3] and Gdoutus [4], there are various NDT techniques commonly used to evaluate the crack on the structure such as dye penetration, ultrasonic, acoustic emission, eddy-current and magnetic particle. The main purpose for using NDT techniques is to detect the crack without damaging the structures.

Dye penetration is a method which uses dye or color to detect surface flaw. Color or dye will apply on the surface of surface claw and then post–penetrant material such as chalk will be applied on it. After that, the color line will be seen the flaw. This technique is very fast and efficient on detecting surface flaw.

Ultrasonic is a method which uses very high frequency sound waves to defect crack. The sound waves will propagate through the specimen and if there is any flaw surface or crack the wave will be reflected. Next by using transducer, the wave will be changed into electrical signal and displayed on the monitor screen. The location of the crack can be determined by some calculation on the travel time.

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Acoustic emission is a method which used for testing for stationary equipment such as tanks, pipelines and pressure vessels [5]. Due to the high sensitivity of the acoustic emission, this method can detect the growth and formation of the micro-crack [6, 7].

Infrared thermography is also one of the methods which widely used to detect the crack. There are three classical techniques of thermographic which mostly use in the industry, known as lock-in thermography, vibrothermography and pulsed thermography are described by Chen (2007) [8]. Besides these three classical active thermographic techniques, there are various different thermographic techniques can be done based one the subsequent aspects such as type of heating, the size and shape of excitation source, and the arrangement between sample and heating source [9].

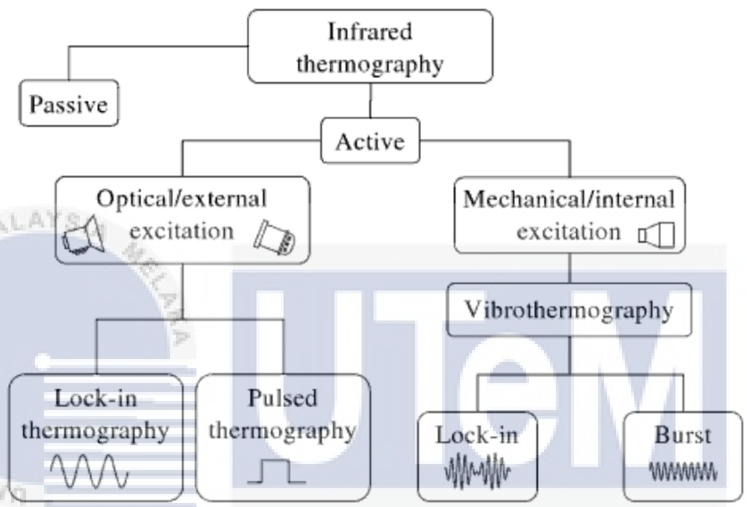

Figure 1-1: Infrared thermography approaches [8]

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Vibro-acoustic method is another method for crack detection which can effectively detect the defection. There are two types of frequency which introduced in this method included high frequency acoustic wave and low frequency excitation. In his method, the interaction between the two waves is used to determine the cracking. Wave distortion effect will be occurs whenever the geometric properties is changing. In this method, low frequency excitation is a very critical element. This is because the level of excitation may maximize the effect of crack on natural frequencies and the effect of the crack on energy dissipation and modulations.

1.2 Problem Statement

Vibro-acoustic technique is a method which introducing two type of frequency into a structure for defect detection. The two frequencies are high frequency acoustic wave and low frequency excitation. There are few parameters which will affect the non-linear vibro-acoustic test which included high frequency acoustic wave, low frequency vibration mode, excitation locations and location of sensor. However, the study of non-linear effect of low frequency excitation to detect the crack is still not much done by previous researcher. Therefore, study of non-linear effect of low frequency will be done through the non-linear vibro-acoustic test.

1.3 Objective

The objectives of this project are as follows:

1. To determine the relationship between low excitation frequencies and modulation intensity.
2. To investigate the effect of low frequency excitation on the amplitude modulation effect.

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1.4 Scope of Project

The scopes of this project are:

1. Specimen preparation and crack preparation for the vibro-acoustic test.
2. Modal analysis to obtain modes of vibration and mode shapes of the specimen.
3. Vibro-acoustic test to identify the effect of low frequency for crack detection in this method.

CHAPTER 2

LITERATURE REVIEW

2.1 Damage in Structures

Damage in structure can be defined as the change of geometries properties of the material in a structure which will degrade the stiffness of material and cause decreasing of load carrying capacity. Reifsnider in 1980 proposed a sequence of the formation of damage which can be summarized as below:

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i) Crack nucleation in off-axis plies.
ii) Crack coupling as a result of the interface debonding once the crack tips reach the interfaces.
iii) Formation of a wider broken region by the previous method.
iv) Crack growing through the thickness by crack coupling.
v) Final fracture of fibres within the direction of the load.

Fracture of solid is mainly caused by the stress in two modes which are ductile and brittle. Most of the metals can withstand some large deformation without failing to allow the metals to be use in different structures. As the increase in deformation past the yield point, the micro cracks will be formed as shown in Figure 2-1.

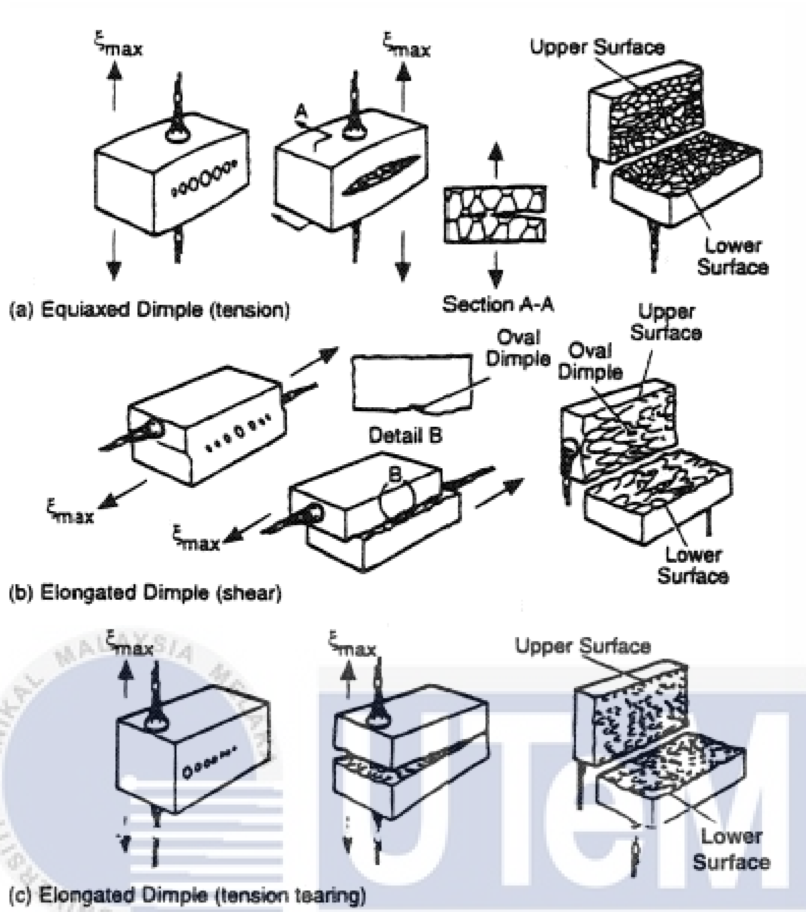

Figure 2-1: Example of fracture surfaces from microvoid coalescence. [10]

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2.2 Fatigue Crack

Up to 90% of screw ups of in-carrier metal structures have been attributed to fatigue cracks [11]. This is because the fatigue crack will grow rapidly and caused the fracture of the structure once the crack is obvious and detectable by the techniques of conventional linear. Thus, the detection of fatigue crack in early stages is very important [12]. Several studies have shown that non-linear feature of the fatigue crack is hard to be achieved by conventional linear ultrasonic techniques [12-15].

No matter how high is the strength of the structure, fatigue crack might still occur due to repeatedly applied loads. Thus, fatigue analysis is carried out by methods based on fatigue test and estimation of cumulative damage to characterize the fatigue properties. The formation and propagation of fatigue damage can be described in a few stages. In the first stage, the microstructural changes will cause the formation of nucleation. After that, microcracks will occurs and growth to form a dominant crack. This is the stage where the crack initiates to begin the crack propagation. Next stage is the propagation of dominant crack which will lead to a macro dominant crack. This will cause the instability of the structure and in the end the structure will fracture.

The fatigue crack will appeared with different mode when different stress is applied on the structure. The basic modes of fatigue modes are shown in Figure 2-2. The fatigue can extend as the three basic modes, which are defined as:

Mode I: This is the opening mode where the crack surfaces move directly apart in y-direction.

Mode II: This is the sliding mode where the crack surfaces slide over each other in direction which perpendicular to the leading edge of crack (x-direction).

Mode III: This is the tearing mode where the crack surfaces move relatively to one another and parallel to the leading edge of the crack (z-direction).

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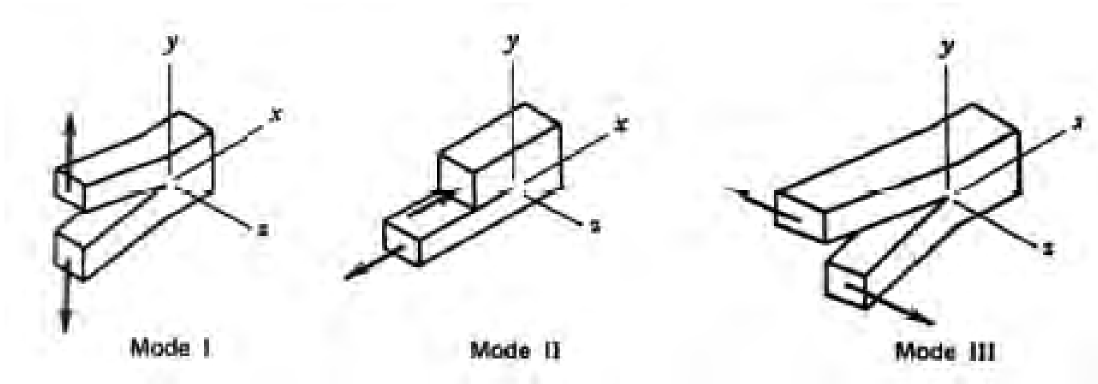

Figure 2-2: Three basic modes of fatigue crack [16].

2.3 Method of Detect Fatigue Crack

In recent years, applying of nonlinear effects of acoustic waves in discovering defect has been extensively studied. This is because of the advantage of this effect on detecting tiny crack or the early phase of defect [3] and it is easier to detect the crack compared to traditionally use linear measurement [20].

Since 1970s, nonlinear acoustics has been studied by Rudenko, Sutin, Zaitsev and others. There are several reports relating to the nonlinear effect in defect detection in soils, glass and metals. Study of nonlinear from acoustic waves has been done. In 1979, Morris *et al.* observed the formation of fatigue cracks in aluminium alloy using second harmonic generation [17]. In 1993, Shkolnik. used nonlinear ultrasonic parameters to evaluate the material properties of concrete [18]. In 1994, in order to detect the defects in metal, sound modulation excited with vibration method is used by Korotkov et al. [19]. Nonlinear ultrasonic has been used by Nagy (1998) [20] in order to detect the fatigue cracks in plastics, metals, composites and adhesives. In 2005, studied on cross-modulation in glass samples with thermal cracks has been done by Vladimir et al [53].

The further study has been done in the nonlinear acoustic wave modulation. In 2009, Simondi et al. [21] used a low-profile piezoceramic actuator and a PZT transducer to introduce simultaneous low-frequency excitation and high-frequency ultrasonic waves respectively to a test specimen. In 2006, a novel of nonlinear-modulation method for crack detection has been proposed by Zaitsev (2006) [22]. The cross modulation effect which used in this approach can be visualize as in Figure 2-3.

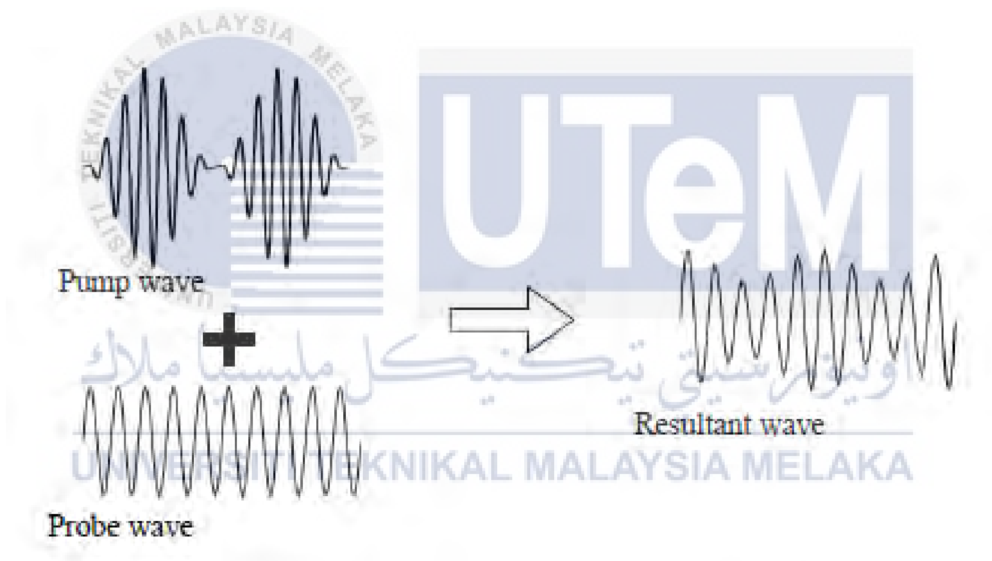

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Figure 2-3: Schematic figure of cross modulation between pump wave and probe wave. [23]

Nonlinear ultrasonic technique has been chosen to observe the nonlinear acoustic effects from the wave interaction in damaged structures. Nonlinear feature of the fatigue crack will cause an active nonlinear radiation and this makes the nonlinear ultrasonic techniques became unique defect-sensitive equipment for this type of flaws [24].

In previous research, experimental works has been done by using the method of amplitude modulation of high-frequency ultrasonic with low frequency vibration excitation for damage detection. These work including few methods such as Impact-Modulation (IM) method [25, 26], Vibro-Modulation (VM) method [27-32], Nonlinear Wave Modulation Spectroscopy (NWMS) method [33-35], and Vibro-Acoustic Method [36-40]. Each of the method use is based on the nonlinear acoustic effects to analyse defection of structure concept but they have different approach for experimental setup and introduction of the low-frequency vibration and high-frequency ultrasonic waves.

Besides the experimental method, analytical modelling method also has been done by some researchers. From the mathematical models which developed by the researchers, the nonlinear effects which caused by the wave distortion when interacted with nonlinearity or non-uniformity of its medium are shown. Nonlinear medium discontinuity or reduced element [41, 42] of the nonlinear medium will makes a significant different in form of harmonics or sidebands generation. Besides the mathematical models method, receptance analysis [43] also used to analyse the system's vibration response. Receptance analysis is an analytical method which decomposes a system into a few sub-systems. Duffour et al. also used this approach to model a beam schematically which described in Figure 2-4. The beam was divided into three parts, the beam no. 2 which is very short represent the cracked section and the cross section area might be changed according to the crack depth.

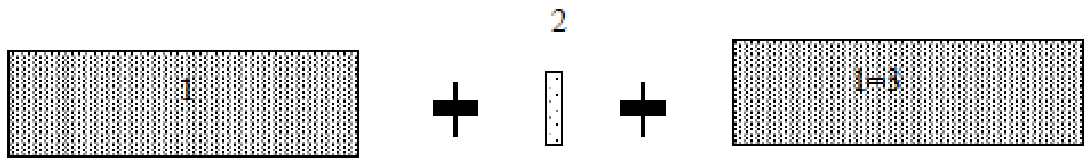

Figure 2-4: A cracked beam is decomposed into three plain beams where the cracked section is represented by a short reduced cross section beam [40].

The calculation of natural frequencies and mode shape coefficients for the beam section will be done and the data obtain will be done using the mathematical models to obtain the R values.

2.4 Vibro-acoustics Methods

There are various approaches for experimental setup and introduction of the low-frequency vibration and high-frequency ultrasonic waves. In the earliest experiment, impact hammer are used by Donskoy et al. (2001) [14] to introduce a low frequency vibration. The experimental apparatus setup is shown in Figure 2-5. After investigation on the relationship between the sideband effect and the system parameters, Donskoy et al. proved that this approach is capable of distinguishing the difference between the integrity decreasing defects and the other structural in homogeneities.

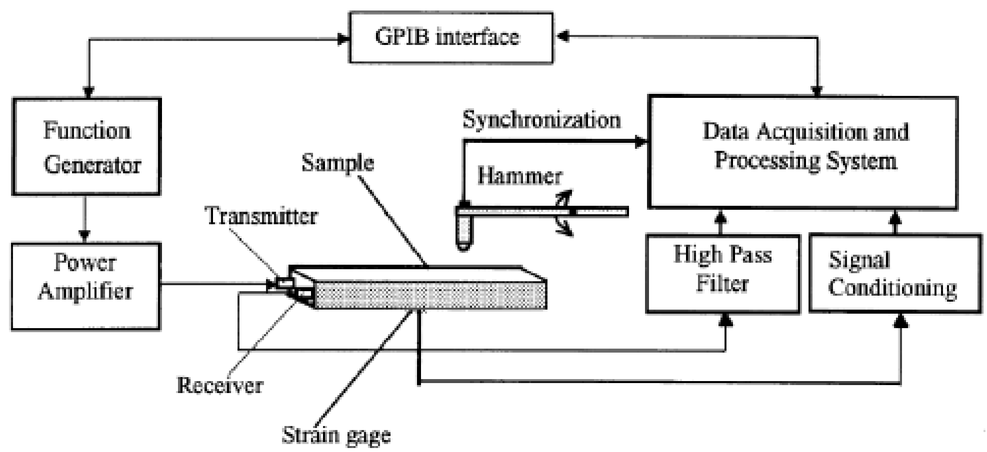

Figure 2-5: Setup of Impact Modulation (IM) technique on a beam [14]

This apparatus is replaced with shaker because shaker is more reliable and stable method to introducing low-frequency vibration. However, M. Morbidini et al. [44] reported that additional nonlinear acoustic effects and the sideband effects generated from specimen and defects cannot be detect when using the shaker as the low-frequency exciter. Thus, that more advance technologies which is piezo-ceramic stack actuator has been introduced by Parsons et al. [3] to produce the low-frequency vibration. The experimental apparatus setup is shown in Figure 2-6. According to Parsons et al., although the maximum excitation level of the mechanical shaker is higher than the piezo-ceramic stack actuator, they found out that the result from the piezo-ceramic stack actuator showed better result on the sidebands effect against the defects.

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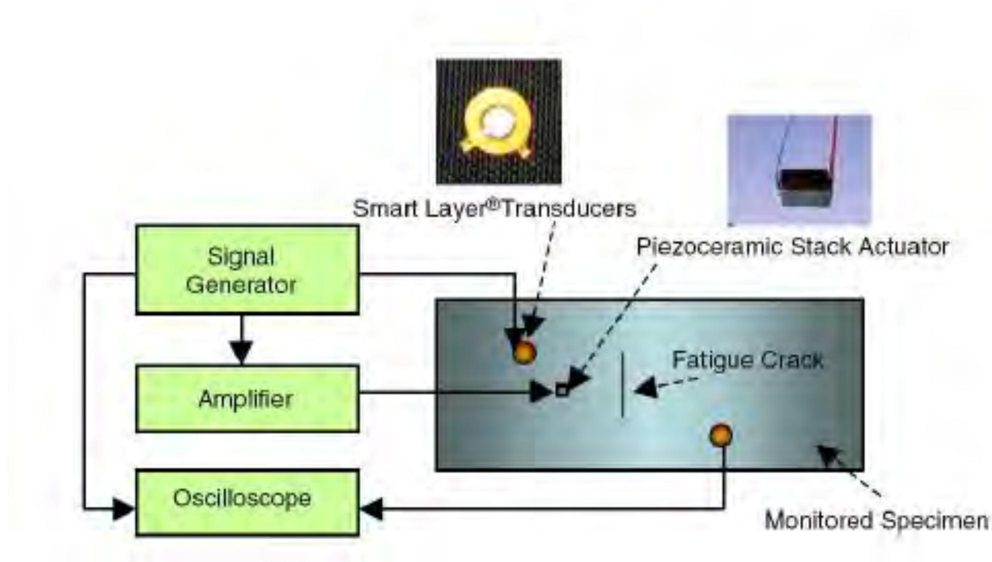

Figure 2-6: Experimental arrangement by using PZT transducer and stack actuator [3].

2.5 Nonlinear Vibro-acoustic Wave Modulation

In nonlinear vibro-acoustic method, the main thing in the study is the vibro-acoustic modulation which produced when two different excitation are introduced to the structure simultaneously. These two excitations included intensive low-frequency vibration and a high frequency ultrasonic wave.

When investigate undamaged structure, the response signal exhibits only the main frequency component which involved such as high frequency ultrasonic wave and low frequency excitation. When investigate damaged structure, spectrum of response signal reveals extra components which are modulation sideband around the high frequency component. The spectrums are illustrated in Figure 2-7.

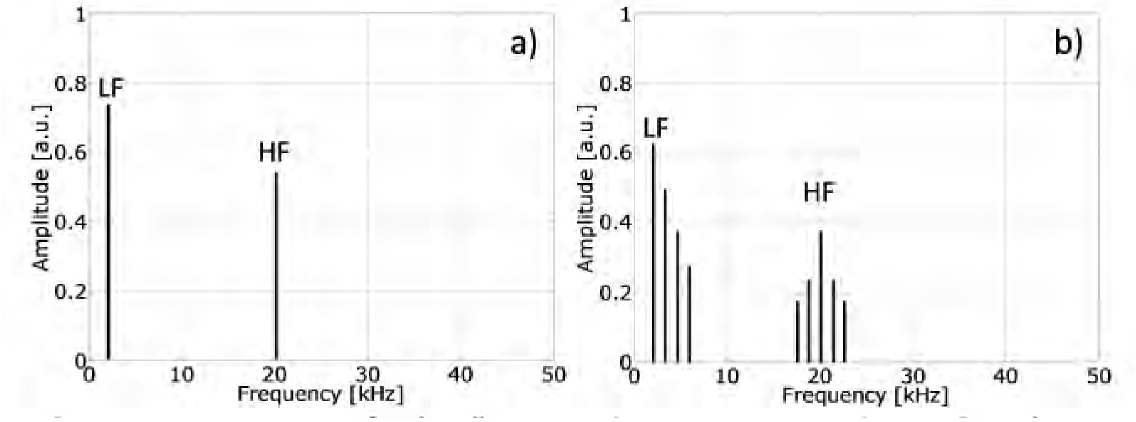

Figure 2-7: Frequency spectrum for response signal: (a) undamaged structure,

(b) damaged structure [45]

Donskoy et al. (2001) [14] stated two methods to identify crack size from the sideband effect. They took the ratio of the sideband amplitude against the vibration amplitude for measurement. This is due to sideband amplitude is linear proportion to vibration amplitude. There is another method which used by other researcher. Duffour et al. (2005) [42] and Simondi et al. [21] used intensity of modulation R-value which estimated from the relationship between the first sidebands amplitude and the amplitude of the high-frequency component. This measurement index is written as

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

Where A_o is amplitude of the high-frequency component and $A_{1,2}$ are amplitude of first sideband on the left and right of the ultrasonic spectrum.

In previous research, Pieczonka, L et al. [46] proved that R index is a very good indicator to detect the damages in the structure. In order to obtained better result, first few pairs of modulation sidebands will be considered in calculation of R index [47]. Thus, the index is calculated as ratio between sum of amplitude of i th pairs of sideband and the amplitude of high frequency, i.e.,

$$R = \frac{\sum_{i=1}^{n}(A_{LSB}^{i} + A_{RSB}^{i})}{A_o}$$

2.6 Natural Frequency

When an object is not disturbed by an outside force, it will vibrate at certain rate which is natural frequency. Each of an object has its own natural frequency and when the structures vibrate at the frequency it may causing resonance. This small force can always causing deformation or damage to the structure. As a rule, any object has several natural frequencies or vibration mode. At each specified natural frequency excitation, structure will have a unique structure deformation which known as mode shape. The basic mode shape is illustrated in Figure 2-8. There are some factors which may affect the natural frequency of the structure such as the stiffness and mass of the structure.

` The collapse of Tacoma Narrows bridge is a typical example which caused by resonate of structure. In 1940s, the Tacoma Narrows suspension bridge collapsed due to the induced vibration which caused by wind. Thus after this incident, researcher started to find out the method to determine the natural frequencies of any structures. Johnson et al. has studied about

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the resonance and nonlinear phenomena in rock [48] while Benjamin studied about wine glass resonance [49].

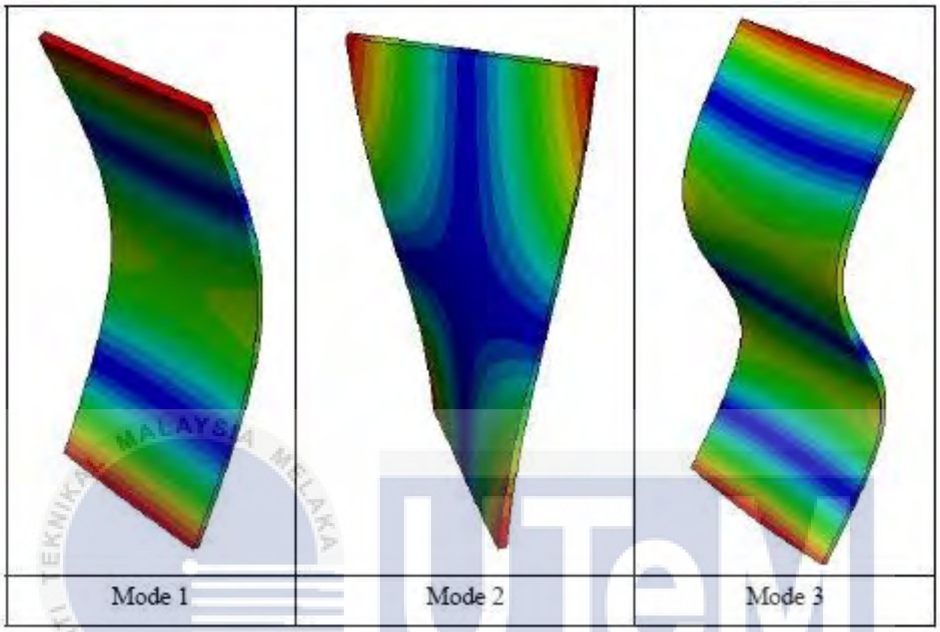

Figure 2-8: Three basic mode shapes. [20]

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The most common method which is use to determining the natural frequencies is using method of stimulation. Stimulation such as impact hammer and shaker will cause the structure to vibrate at its natural frequencies then the signal captured by sensor system. After that, these signals undergo modal analysis to determine the natural frequency of the object. Modal analysis is a method which analyse the response of structure when cyclic force applied on the structure. Frequency domain graph will be plot by using the measured data. The peak response in the graph is the natural frequency of the structure.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used to detect the fatigue crack through the vibro-acoustic method. The flow chart of the project is shown in Figure 3-1. This project starts by literature review for damage in structure, crack detection method and vibro-acoustic technique. Then, the project proceeds with specimen preparation which include the aluminium plate preparation and the crack generating process. Next, aluminium plate with 10mm of fatigue crack undergoes modal analysis to obtain its modes of vibration and mode shape. Finally, vibro-acoustic test is done on the aluminium plate to determine the influence of the low-frequency changes on nonlinear vibro-acoustic wave modulations for crack detection.

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3.2 Specimen Preparation

The plate used for is he project is aluminium plate with the dimension of 150mm x 400mm x 2mm. The modal of aluminium used is AL2024. Table 3-1 shows the properties of the material. This material is commonly used in aircraft structures because it has high strength and can withstand the fatigue [50, 51].

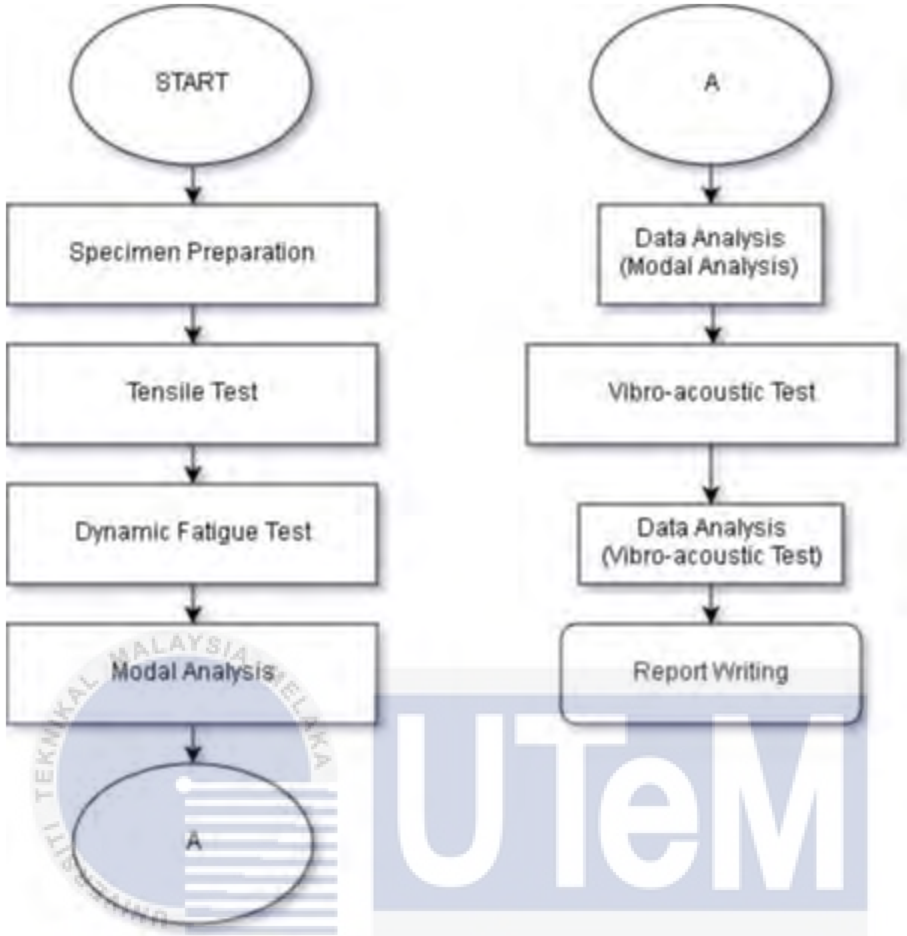

Figure 3-1: Flow chart of the methodology.

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Table 3-1: Properties of the aluminium plate. [52]

Name	Aluminium Al-2024
Density	2 780 kg/m^3
Young's Modulus	72400 MPa

In specimen preparation, an aluminium plate cut into a small aluminium plate with the size of 150 mm x 400 mm x 2 mm by using the hydraulic cutting machine. Next, a hole with the diameter of 1 mm ± 0.5mm is created by using the Electrical Discharge Machining (EDM) hole drilling machine. Brass electrode tube with 1mm is used to make the hole on the middle of the plate. Electrical Discharge Machine is chosen for creating hole because it can create a smaller hole compared to drilling machine. The size of hole need to be as small as possible to avoid it from changing the characteristic of the plate.

After that, EDM wire cut is used to produce slot at both side of the hole with the dimension of 1 mm. EDM wire cut machine apply the concept of electric spark erosion to discharge the specimen which cause it can produce tiny and accurate part. To produce desired shape, CNC coding is used to control the movement of the machine. Total length of hole and slots created on the specimen is 4mm in horizontal direction. The hole drilling and wire cutting are the pre-process for the fatigue crack generation process. The schematic diagram of the specimen is shown in Figure 3-2.

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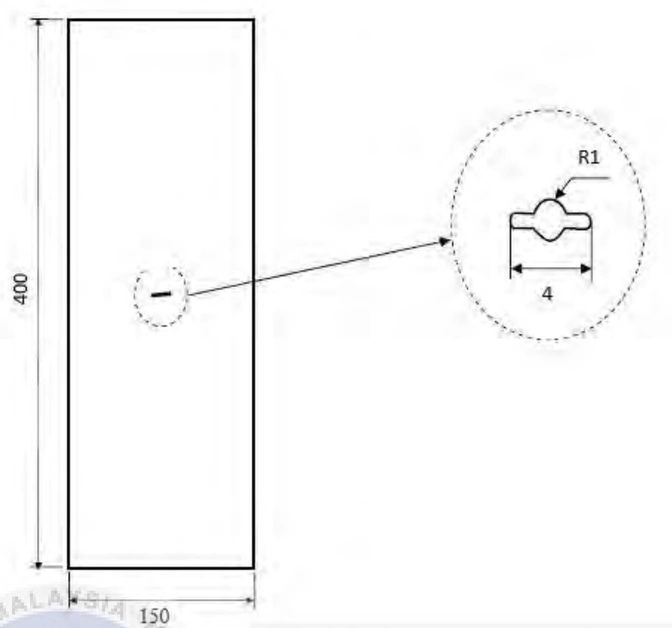

Figure 3-2: Schematic diagram of the specimen before fatigue crack creation.

The aluminium plate then undergoes dynamic fatigue test to produce fatigue crack [54]. In order to produce the fatigue crack with 10 mm at each side of the slot, universal testing machine is used to apply cyclic loading to the plate. Before the dynamic fatigue test, tensile test had been done to obtain some mechanical properties of aluminium plate such as max load for yield, tensile stress at max load for yield, maximum load and tensile stress at maximum load. The data obtained are shown at Table 3-2.

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Table 3-2: Parameter of the mechanical properties of aluminium plate obtained from tensile test.

Max load for yield (kN)	Tensile stress at max load for yield (MPa)	Maximum Load (kN)	Tensile stress at Maximum Load
>35.62	>118.73	35.62	118.73

The maximum load, minimum load, means load and amplitude load can be obtained by doing some calculation on the data obtain from the tensile test. For this fatigue test, a few parameters had been set such as the percentage for the maximum load calculation and the ratio for the minimum load calculation. The maximum load for the test is 26.72kN while the minimum load is 2.67kN. Mean load which is 14.695kN can be obtained by taking the average value between maximum load and minimum load. For amplitude load, it can be obtained by taking the average different between maximum load and minimum load and its value is 12.03kN. The calculations for the parameters set are shown below:

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$$Maximum\ Load = 75\%\ of\ Yield\ Load$$

$$= 35.62kN \times 75\%$$

$$= 26.72\ kN$$

$$Minimum\ Load = 0.1\ of\ Maximum\ Load$$

$$= 26.72kN \times 0.1$$

$$= 2.67\ kN$$

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

$$= \frac{26.72kN\ +\ 2.67kN}{2}$$

$$= 14.695\ kN$$

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

$$= \frac{26.72kN -\ 2.67kN}{2}$$

$$= 12.03\ kN$$

After obtained the value, dynamic fatigue test is done to generate 10mm of fatigue crack on the specimen. Value of amplitude and mean load on the Universal Testing Machine are set as in calculation. For safety purpose, maximum and minimum limit are used instead of maximum and minimum load to ensure the load won't exceed the limit and spoil the specimen. The values for maximum and minimum load are 28kN and 1kN with frequency of 10Hz.

During the process, the plate must be monitored from time to time because once the crack is generated it will propagate rapidly and might exceed the length that we need. Due to the crack is very hard to detect by naked eye, a magnifier and torchlight are needed during the observation process. The number of cycles and the current load which applied to the plate can be observed in the system controller monitor as shown in Figure 3-3.

Figure 3-3: System controller monitor for Universal Testing Machine.

The crack of 10mm is obtained after 96012 cycles with frequency of 10Hz and approximated time used is 2 hours and 40 minutes. Figure 3-4 shows fatigue crack which generated by dynamic fatigue crack while Figure 3-5 the process flow for the specimen preparation.

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Figure 3-4: Fatigue crack generated by dynamic fatigue crack.

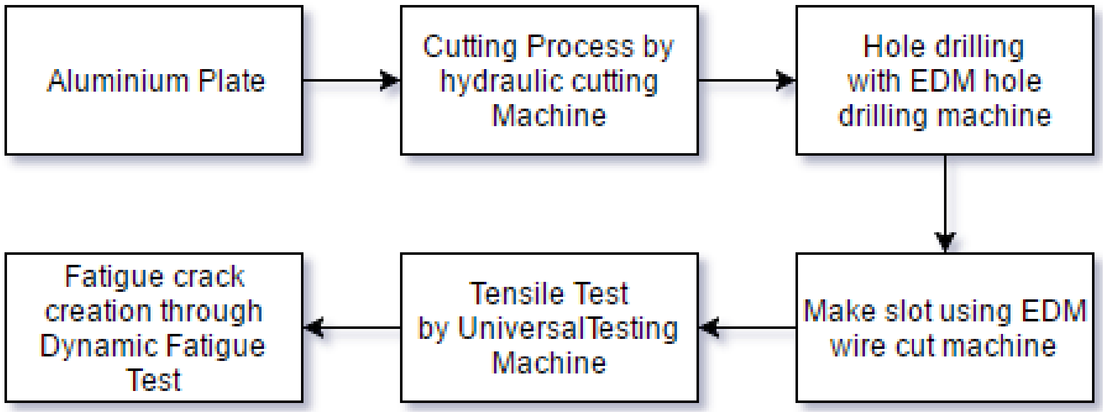

Figure 3-5: Process flow for the specimen preparation.

3.3 Modal Analysis

It is important to determine the modal parameters of the plate in order to know the movement of crack edges and the response of plate surface to the low frequency excitation in vibro-acoustic testing. As a rule, every structure consist unique natural resonant frequencies. External force which excited at natural frequency of the structure will cause the structure respond extensively.

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Experiment modal analysis was performed on the cracked aluminium plate in order to obtain its modes of vibration and mode shape. Experiment equipment and arrangement is show in Figure 3-6. A 150 mm x 400 mm x 2 mm aluminium plate tied with a thread and electromagnetic shaker attached to the corner edge of the plate. The main purpose for hanging the cracked aluminium plate is to eliminate nonlinearities from boundaries. Sweep frequency excitation generated by the arbitrary waveform generator and then amplified by amplifier. Input parameter for modal analysis is shown in Table 3-3. Output response measured by laser doppler vibrometer then analysed using Tektronix DPO4032 Oscilloscope. Figure 3-7 shows the input signal and the response signal produced by the plate in time domain during the modal test analysis. Fives set of data is obtained to get more accurate result.

Table 3-3: Input parameter for modal analysis.

Parameters	**Setting value**
Sweep frequency	1~2000 Hz
Sweep time	2s
Amplitude	1Vpp

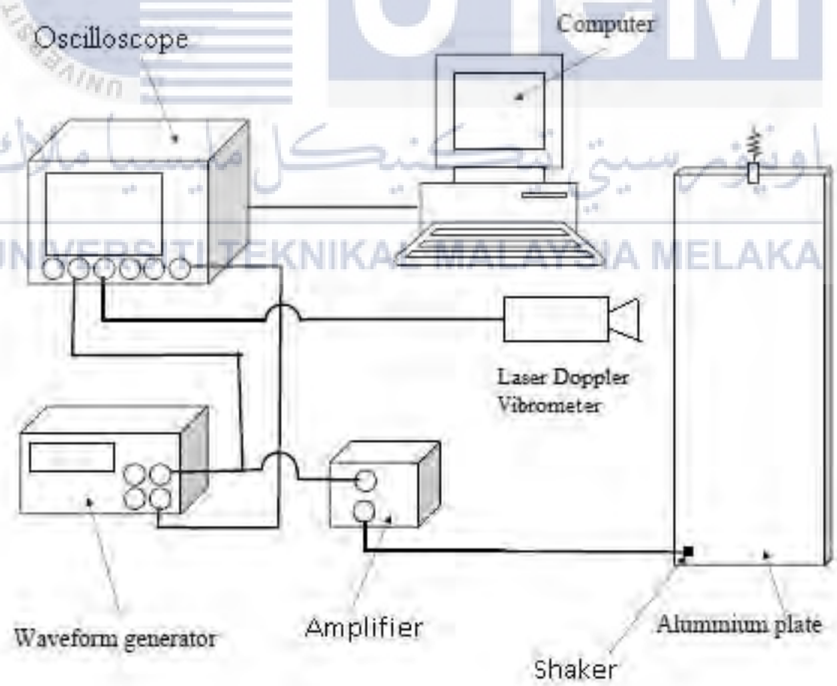
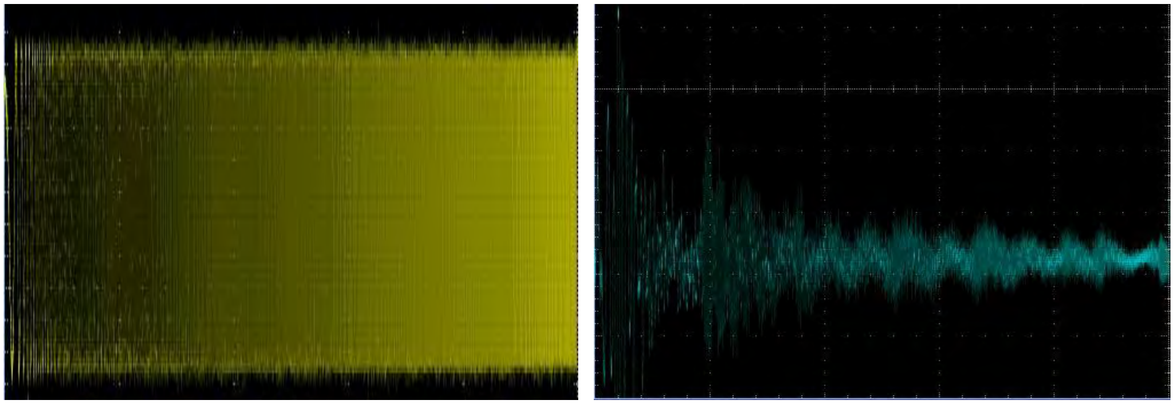


Figure 3-6: Experimental setup and arrangement for the experimental modal test.



(a) (b)

Figure 3-7: Input signal (a) and output signal (b) in time domain.

Then, the data will be import into Matlab software. The data analysed using Transfer function estimation in Matlab to generate the frequency response function (FRF). The coding is provided in ***Appendix A***.

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3.4 Vibro-acoustic Test

In vibro-acoustic test, the experimental arrangements and equipment were similar as Figure 3-5. The cracked aluminium plate was hanged using a thread to prevent nonlinearities from boundaries. Low frequency vibration and high frequency ultrasonic signal excited simultaneously to the plate. PZT transducer used to introduce high frequency ultrasonic signal of 60 kHz sine wave as a high frequency input. Electrodynamics vibration shaker act as low frequency exciter which will modally excite with selected low frequency to the plate. Different amplitudes of low frequency excitation were used varied from 0.75V to 4.0V. Low frequency exciter was located at the right corner of the plate. Low frequency which was selected divided into two groups: resonance frequency and non-resonance frequency. Both low frequency and high frequency excitation signals were generated by Tektronix AFG3022C Arbitrary Function Generator. Data and output signal measured using Laser Doppler Vibrometer. The point of measurement for output signal is located 30 mm above the notch line while the high frequency excitation located 30mm below the notch line. Laser Doppler Vibrometer is a non-contact vibration measurement with high resolution which significantly improves the accuracy and precision of the test. Response signals obtained will apply Fourier analysis by using Matlab software. Through the Fourier analysis, power spectra will be generated. Figure 3-8 shows the layout of PZT transducer, shaker and Laser Doppler Vibrometer.

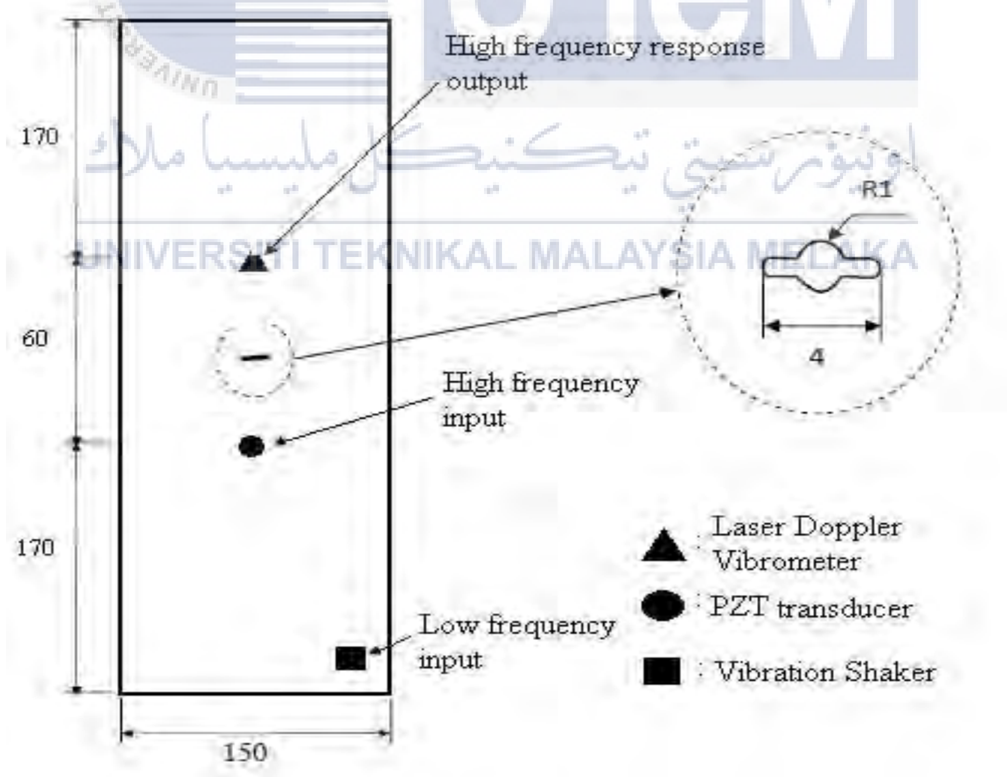

Figure 3-8: Layout of PZT transducer, shaker and Laser Doppler Vibrometer.

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Amplitude modulation will be obtained in power spectra. Power spectra obtained as shown in Figure 3-9. From the power spectra, intensity of modulation R-value obtained by using this method:

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

Where A_o is amplitude of the high-frequency component and $A_{1,2}$ are amplitude of first sideband on the left and right of the high-frequency component.

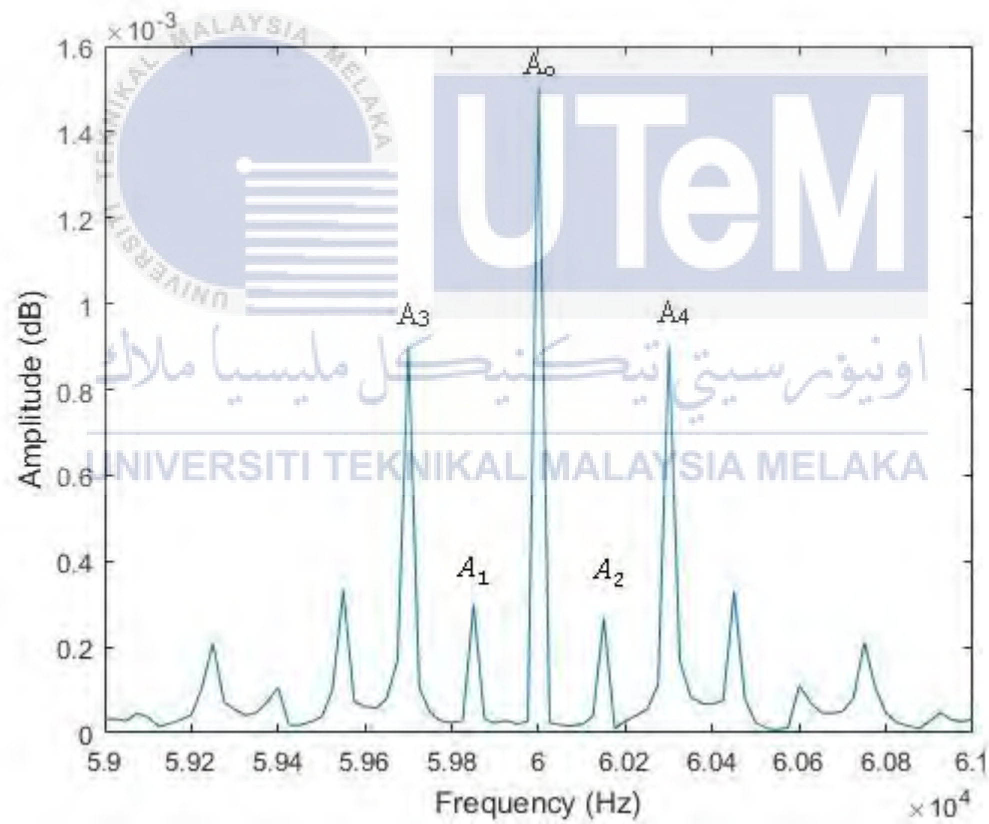

Figure 3-9: Power spectra obtained from Fourier analysis.

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In order to obtain better result, first few pairs of sidebands need to considered in calculation the R index [47] and the calculation on the combination of pairs of modulation sidebands has been done using formula as written:

$$R = \frac{\sum_{i=1}^{n}(A_{LSB}^{i} + A_{RSB}^{i})}{A_o}$$

Where A_o is the amplitude of high frequency component while A_{LSB}^{i} and A_{RSB}^{i} are amplitude of i^{th} pair of modulation sideband on the left and right of the high-frequency component.

The graph of intensity of modulation R-value versus low frequency was plotted. Analysis has been done on low frequency versus intensity of modulation graph to determine effect of low frequency on intensity of modulation R-value.

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CHAPTER 4

RESULT AND DISCUSSION

4.1 Modal Test Analysis

In modal test analysis, aluminium plate was excited by sweep frequency between 1 to 2000Hz to obtain the natural frequency of the plate. The sample of output response signal is shown in Figure 4-1. The data was exported from Tektronix DPO4032 Oscilloscope for analysis using Matlab software. Five set of data was obtained to increase the accuracy of the result.

Figure 4-1: Output response signal

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Vibro-acoustic analysis. The frequencies included 83.16Hz, 105.3Hz, 116.7Hz, 151.8Hz, 204.5Hz and 236.5Hz.

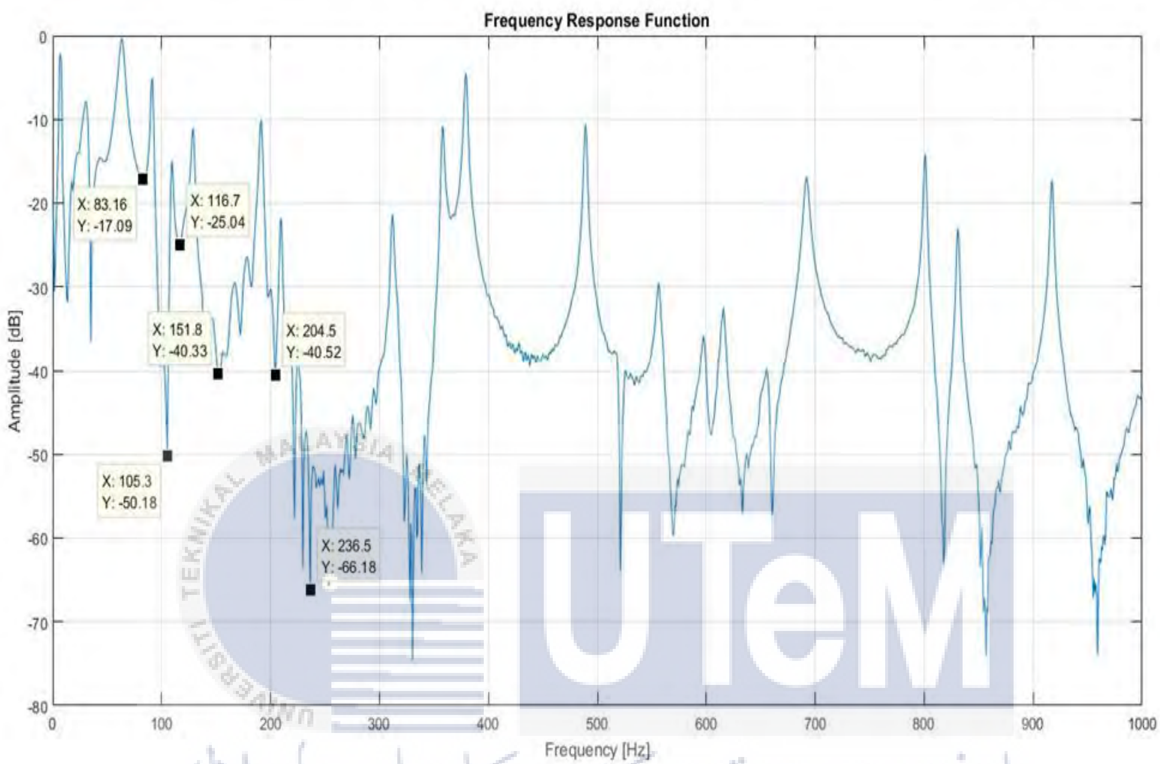

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Figure 4-3: First 6 selected non-resonance frequencies for Vibro-acoustic analysis.

4.2 Vibro-acoustics Test Analysis

This section shows the vibro-acoustics test analysis result. In the experiment, PZT transducer used to produce 60 kHz high frequency signal while shaker act as low frequency exciter which excite resonance and non-resonance frequencies of the aluminium plate. By exciting the high and low frequency signal simultaneously, the output result which measured by laser vibrometer is displayed on the Tektronix DPO4032 Oscilloscope. The data captured from Tektronix DPO4032 Oscilloscope was exported and analysed by Matlab software.

4.2.1 Resonance Frequency

First six resonance frequencies of aluminium plate was use as low frequency exciter in the experiment. The six frequencies which used as exciter are 63.32Hz, 91.55Hz, 109.1Hz, 128.9Hz, 191.5Hz and 209.8Hz. The signals output which obtained form Tektronix DPO4032 Oscilloscope are exported and analysed using Fast Fourier Transform method in Matlab software to produce spectrum. The sample of spectrum produce is shown in Figure 4-4 and the Figure 4-5 show the spectra zoomed around the high frequency wave for every resonance low frequency excitation.

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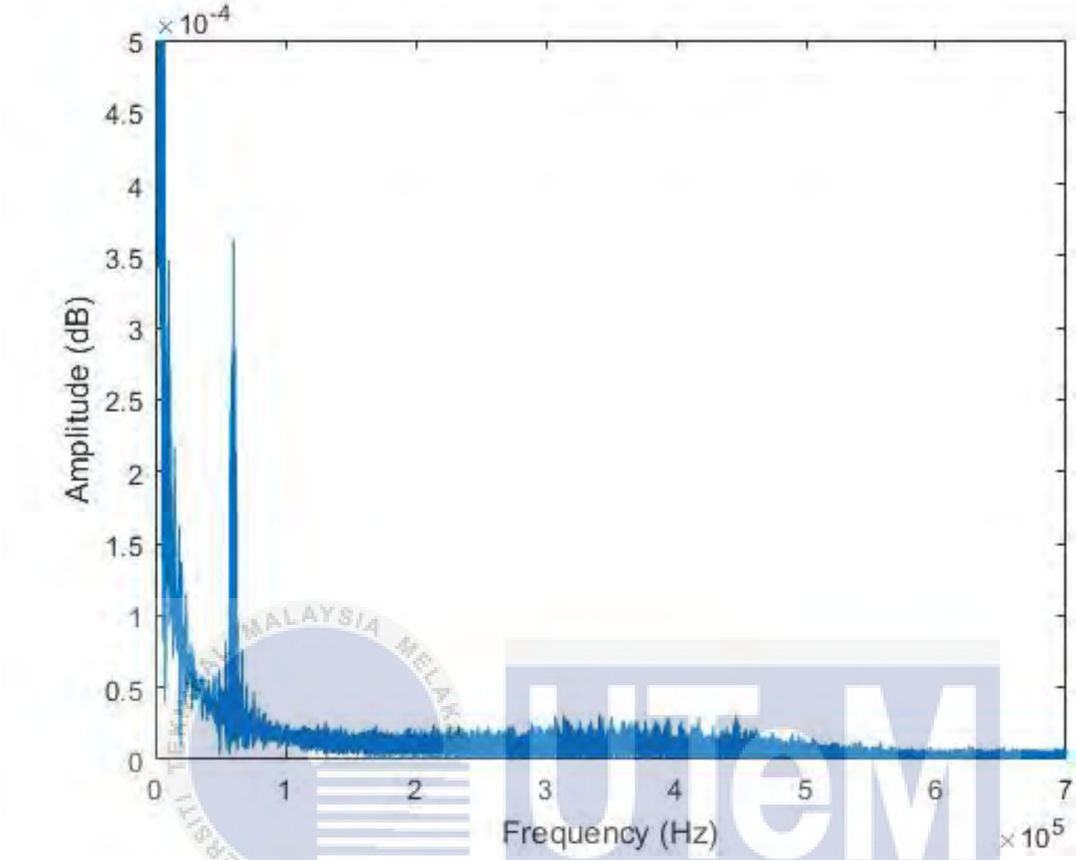

Figure 4-4: Amplitude Spectrum produced by using FFT method in Matlab software.

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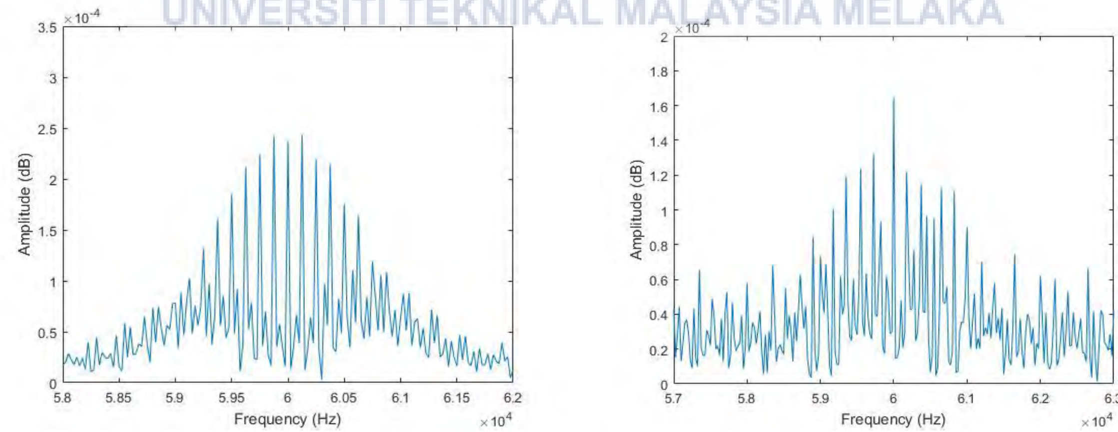
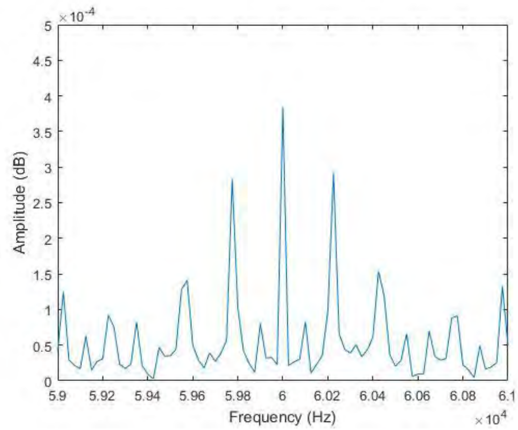
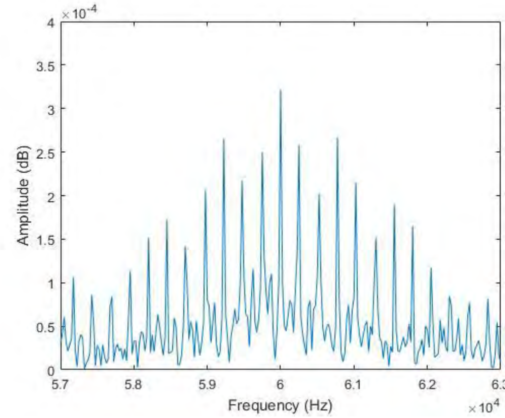


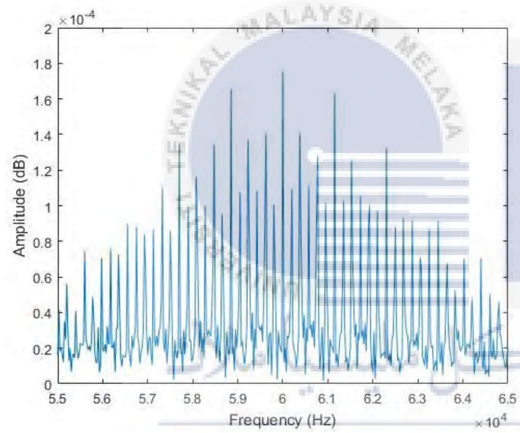
(a) (b)

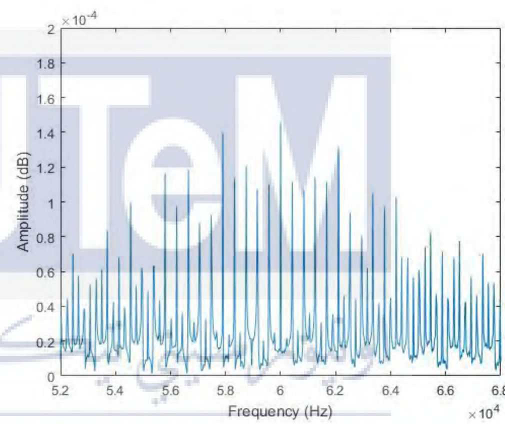


(c)



(d)





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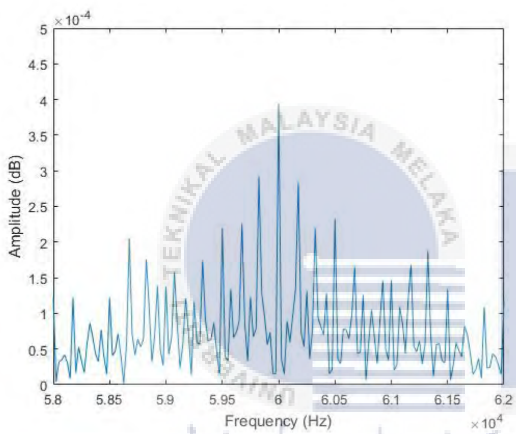
(e)

(f)

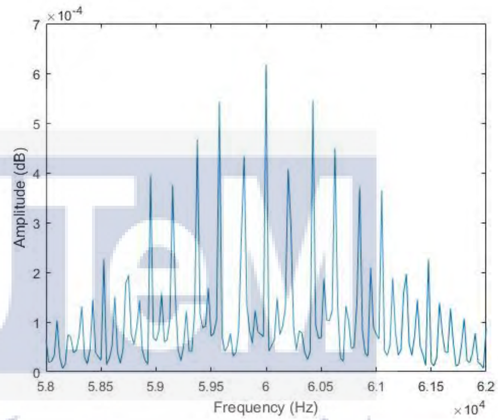
Figure 4-5: Zoomed spectra when resonance frequency 63.32Hz (a), 91.55Hz (b), 109.1Hz (c), 128.9Hz (d), 191.5Hz (e) and 209.8Hz (f) as low frequency exciter.

4.2.2 Non-resonance Frequency

From modal analysis, six non-resonance frequencies were selected for this experiment to determine the effect of non-resonance frequencies compared to resonance frequencies. The non-resonance frequencies which included 83.16Hz, 105.3Hz, 116.7Hz, 151.8Hz, 204.5Hz and 236.5Hz. Figure 4-6 shows the zoomed spectra which obtained from data analysed by using Matlab software.



(a)



(b)

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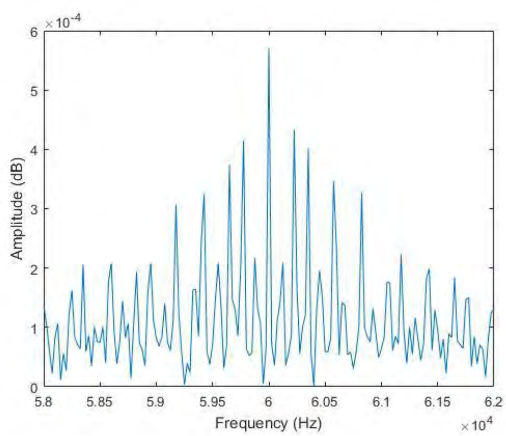
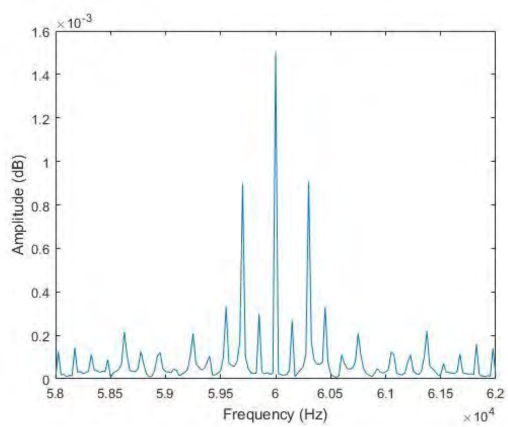
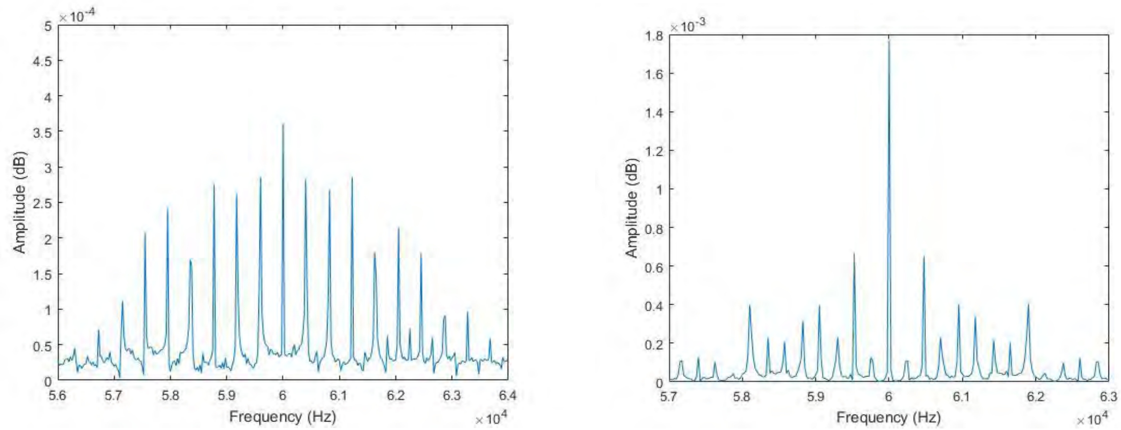


(c)



(d)



(e) (f)

Figure 4-6: Zoomed spectra when non-resonance frequency 83.16Hz (a), 105.3Hz (b), 116.7Hz (c), 151.8Hz (d), 204.5Hz (e) and 236.5Hz (f) as low frequency exciter.

4.2.3 Modulation Intensity (R-Value)

From the spectra obtained from Fourier analysis in Matlab software, modulation intensity R-value calculated as ratio between sum of amplitude of i^{th} pairs of sideband and the amplitude of high frequency, i.e.,

$$R = \frac{\sum_{i=1}^{n}(A_{LSB}^{i} + A_{RSB}^{i})}{A_o}$$

4.2.3.1 R-value versus Resonance Frequencies

By using the formula, the R-value for first few pair of amplitude modulation sideband has been obtained and graph of modulation intensity versus resonance frequencies has been plot as shown in Figure 4-7. The first 6 resonance frequencies included 63.32Hz, 91.55Hz, 109.1Hz, 128.9Hz, 191.5Hz and 209.8Hz. Figure 4-8 show the result of averaging the first 2 pairs of modulation sidebands when the plate is being excited by first 6 resonance frequencies.

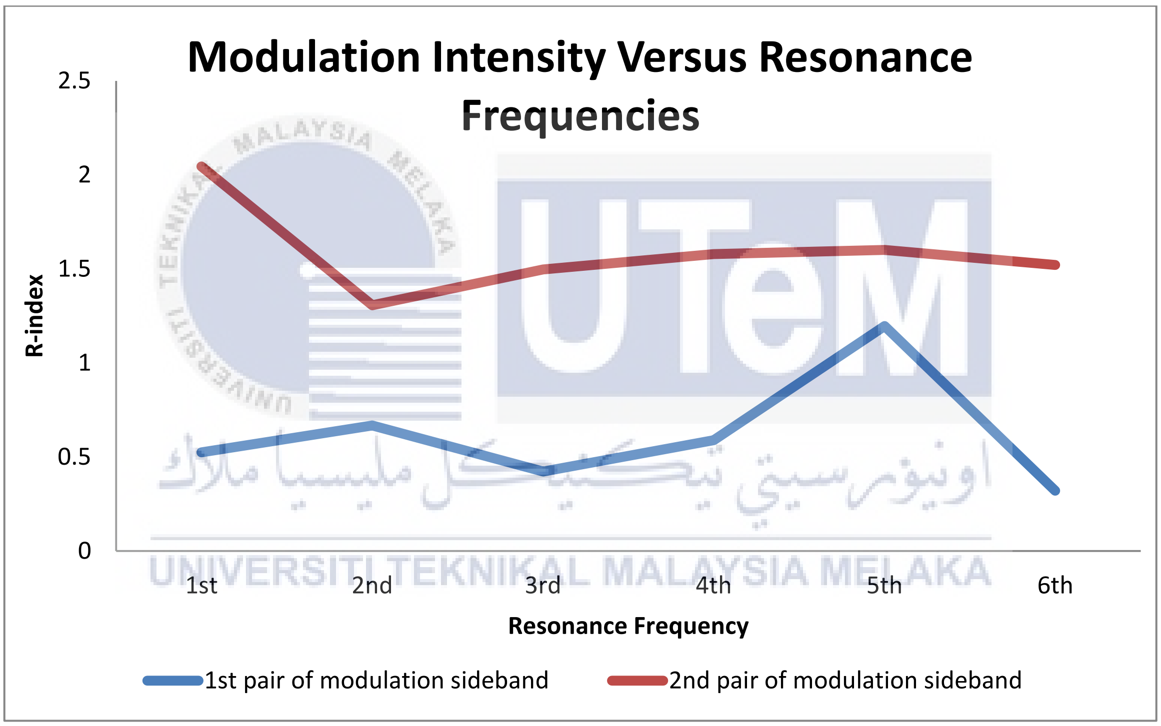


Figure 4-7: R-value calculated for first 2 pairs of modulation sidebands of first 6 resonance frequencies.

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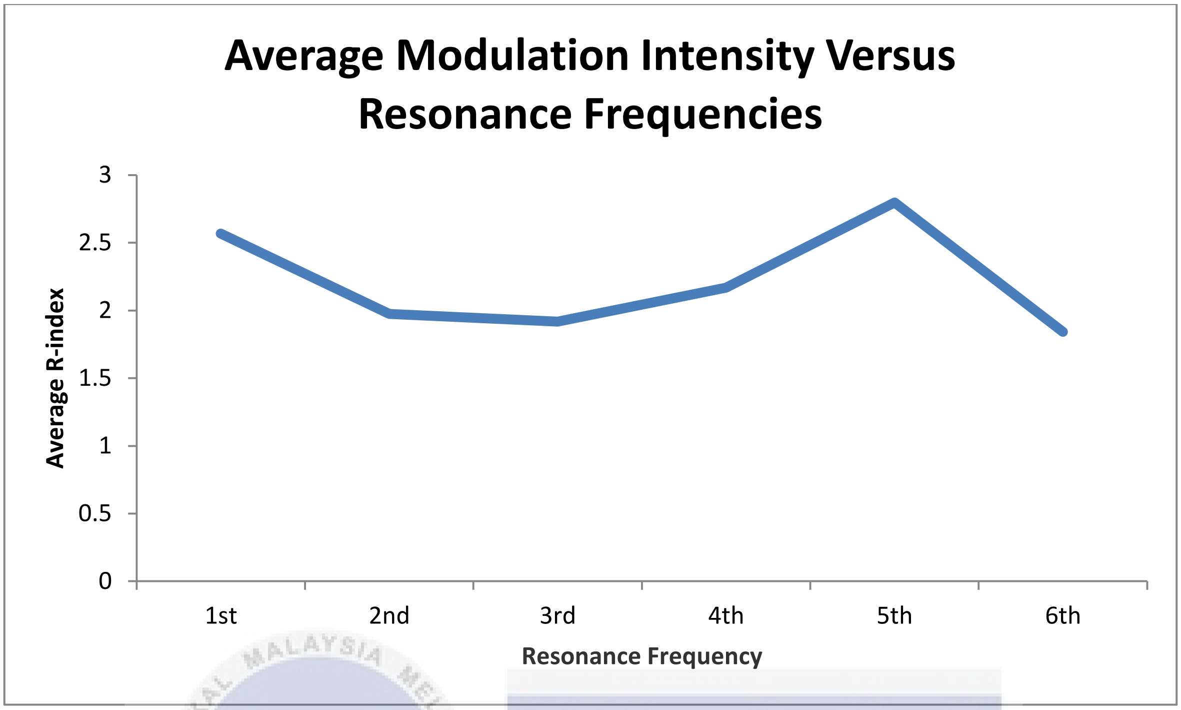

Figure 4-8: Average R-value of modulation sidebands for first 6 resonance frequencies.

From Figure 4-7, 2nd pair of modulation of six resonance frequencies shows higher R-index value compare to the 1st pair of modulation. For 1st pair of modulation, the highest R-value obtained when the plate is excited using 5th resonance frequency which is 191.5 Hz while the highest R-value for 2nd pair of modulation produced when excitation of 1st resonance frequency which is 63.32 Hz.

From the result of average R value of the plate when the plate excited by first six resonance frequencies, 5th resonance frequency produced highest modulation intensity during the excitation where R value is equal to 2.796 and followed by 1st resonance frequency which produce R-value of 2.568. The 6th resonance frequency shows most insignificant effect of modulation because the R value is only 1.842.

4.2.3.2 R-value versus Non-resonance Frequencies

Two pairs of amplitude modulation sideband has been calculate using the formula and graph of modulation intensity versus non-resonance frequencies has been plot as shown in Figure 4-9. This six non-resonance frequencies correspond to 83.16Hz, 105.3Hz, 116.7Hz, 151.8Hz, 204.5Hz and 236.5Hz. The result of averaging the first 2 pairs of modulation sidebands when the plate is being excited by first 6 non-resonance frequencies is shown in Figure 4-10.

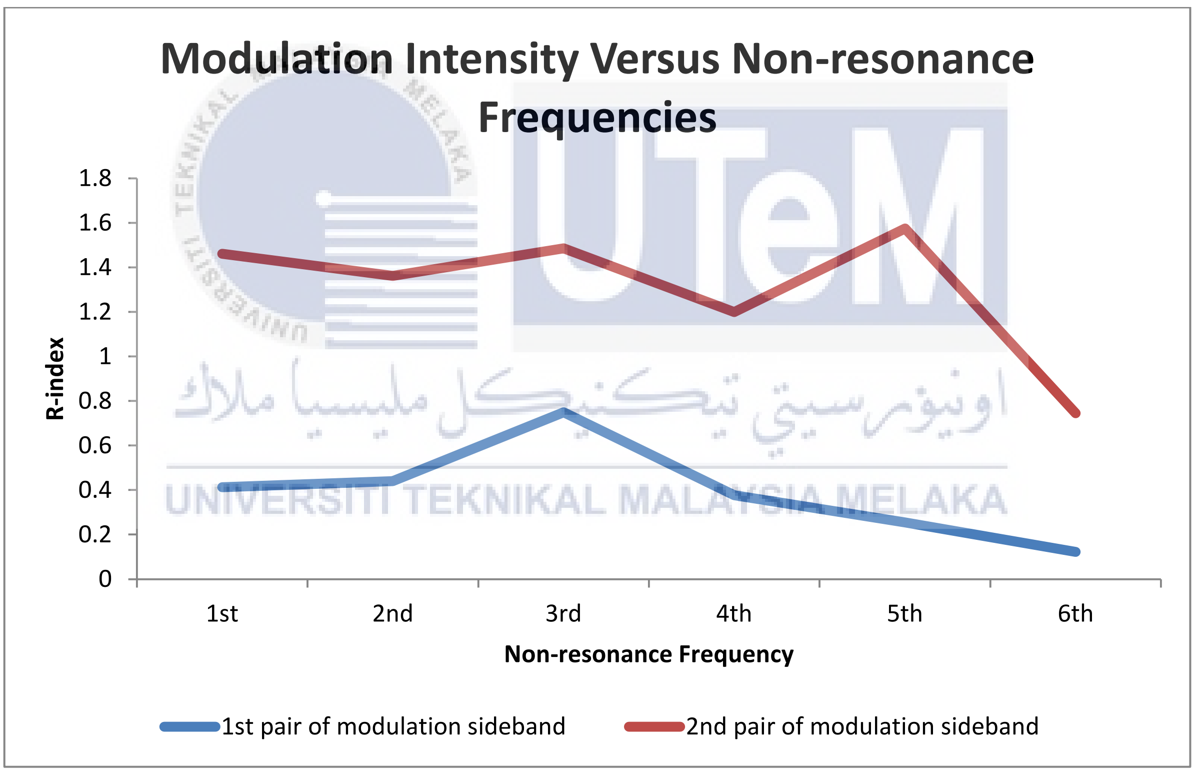

Figure 4-9: R-value calculated for first 2 pairs of modulation sidebands of 6 non-resonance frequencies.

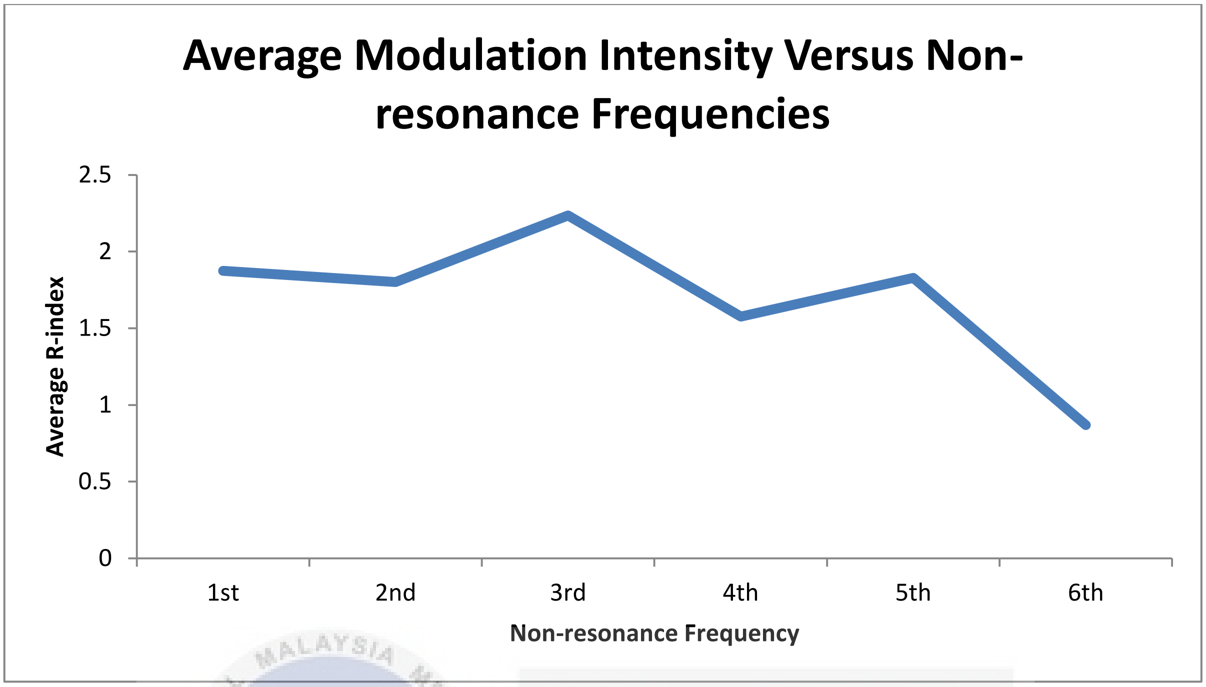

Figure 4-10: Average R-value of modulation sidebands for 6 non-resonance frequencies.

From Figure 4-9, 2nd pair of modulation sideband shows higher R-index compared to 1st pair of modulation sideband. When the plate excited with 3rd non-resonance frequency, 1st pair of modulation sideband shows the highest R-index which is equal to 0.749. When the plate excited with 5th non-resonance frequency, the R-value is equal to 1.57 which is the highest among the six non-resonance frequency.

After averaging, the highest R-value 2.234 occurs when 3rd non-resonance frequency excited to the plate and followed by 5th non-resonance frequency where the R-index is equal to 1.829. Similar to the result of resonance frequency, its show the least significant effect of modulation during the plate excited with 6th non-resonance frequency 236.5 Hz.

4.2.3.3 Summary

R-value of both resonance and non-resonance is tabulated in Table 4-1. In order to compare the effect of modulation, graph of modulation intensity against low frequency was plot as shown in Figure 4-11.

Table 4-1: R-value calculated for first 2 pairs of modulation sidebands.

Resonance Frequencies	**R-value For 1st pair**	**R-value For 2nd pair**	**Average R-value**	**Non-resonance Frequencies**	**R-value For 1st pair**	**R-value For 2nd pair**	**Average R-value**
63.32	0.5238	2.0443	2.5680	**83.16**	0.4129	1.4612	1.8742
91.55	0.6665	1.3067	1.9732	**105.3**	0.4401	1.3621	1.8022
109.1	0.4224	1.4962	1.9186	**116.7**	0.7493	1.4857	2.2350
128.9	0.5895	1.5780	2.1675	**151.8**	0.3772	1.1994	1.5766
191.5	1.1953	1.6008	2.7961	**204.5**	0.2547	1.5741	1.8288
209.8	0.3207	1.5213	1.8420	**236.5**	0.1228	0.7454	0.8682

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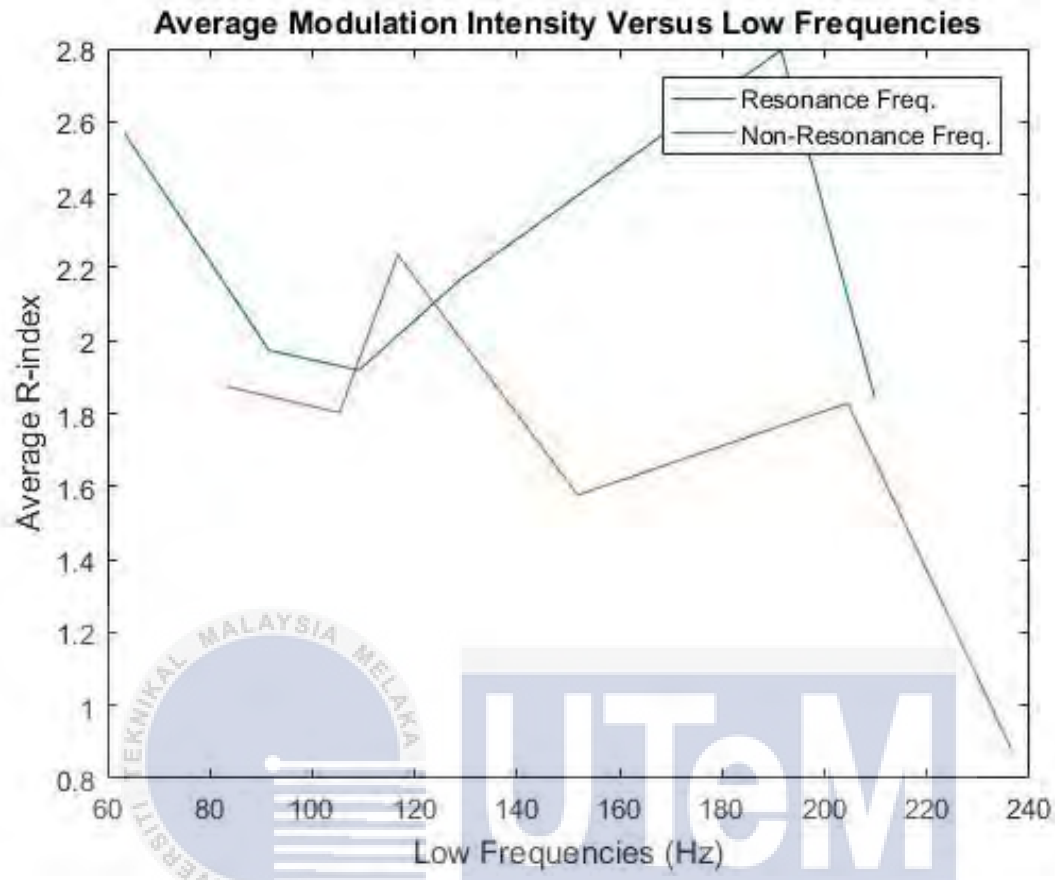

Figure 4-11: Average R-value of modulation sidebands for low frequencies.

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From the result, most significant of amplitude modulation effect shows when the plate excited with 191.5Hz low frequency which is 5th resonance frequency of the plate. For non-resonance frequency, 116.7Hz contributed most to the amplitude modulation effect.

From the above findings, resonance frequency shows more significant effect on modulation effect compared to non-resonance frequency. Mostly the R value of resonance frequency is higher than non-resonance frequency. This is due to resonance frequency excitation will generate more energy and cause friction at the crack which produces heat and caused amplitude dissipation. Thus, resonance frequencies are more suitable for vibro-acoustic analysis for crack detection.

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CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In a nutshell, selection of low-frequency for vibro-acoustic analysis is very important to obtained better nonlinear modulation effect for detection of damaged structure. The results show that resonance frequency is a better frequency for excitation when compared to non-resonance frequency. This is due to the damage detection of the structure is strongly depends on the modulation intensity. These resonance frequencies of the plate can be determined using modal analysis.

The results of the experiment show that when the plate was excited by 191.5 Hz of low frequency, the most significant of modulation effect can be observed. This is due to resonance frequency excitation will generate more energy and cause friction at the crack which produces heat and caused amplitude dissipation.

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Besides low frequency excitation, high frequency excitation is also an important parameter for damaged detection when using vibro-acoustic analysis. Different high frequency excitation may take affect when detecting the length more accurately. In order to detect the location of crack precisely, the location of both high frequency and low frequency signal might contribute to the result. Future work on verification these parameters are required to get better vibro-acoustic analysis for crack detection.

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APPENDIX A

```
% Extract data from xlsx file

input = xlsread('input.xlsx');

output = xlsread('output.xlsx');

t = xlsread('time.xlsx');

input1 = input(:,1) ;

input2 = input(:,2) ;

input3 = input(:,3) ;

input4 = input(:,4) ;

input5 = input(:,5) ;

output1 = output(:,1) ;

output2 = output(:,2) ;

output3 = output(:,3) ;

output4 = output(:,4) ;

output5 = output(:,5) ;


% Sampling Frequency

dt = mean (diff(t));

Fs = 1/dt;



% Finds a transfer function estimate, txy, given an input signal and an
output signal

[TF1,f1]=tfestimate(input1,output1,[],[],[],Fs);

[TF2,f2]=tfestimate(input2,output2,[],[],[],Fs);
```

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```
[TF3,f3]=tfestimate(input3,output3,[],[],[],Fs);

[TF4,f4]=tfestimate(input4,output4,[],[],[],Fs);

[TF5,f5]=tfestimate(input5,output5,[],[],[],Fs);



% Averaging data

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

Favg=(f1+f2+f3+f4+f5)/5;



% Plot and labeling graph

plot(Favg,20*log10(abs(TFavg)));

xlabel('Frequency [Hz]');

ylabel('Amplitude [dB]');

title('Frequency Response Function');

grid on;

xlim([0,2000]);
```

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