ROTATIONAL NATURAL FREQUENCY IDENTIFICATION OF A ROTOR-SHAFT SYSTEM BY USING INERTIAL MEASUREMENT UNIT

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ROTATIONAL NATURAL FREQUENCY IDENTIFICATION OF A ROTOR-SHAFT SYSTEM BY USING INERTIAL MEASUREMENT UNIT

ABSTRACT

It is important to some plants and rotating machineries to identify the vibration characteristic of a structure to maintain their integrity. These rotating machinery/shaft while they are rotating has its own natural frequencies and mode shapes. Every rotating system have their own gyroscopic effect and this study is intended to use an inertial measurement unit directly to obtain system's natural frequency. The objectives of this study is to determine the natural frequencies of a rigid rotor-shaft test rig setting in the lab which consist of 3 point at each respective disc and to perform animation of the mode shapes obtained from the inertial measurement unit reading. Literature review has been done to numerous journals or studies on the usage of the inertial measurement unit. Most of the studies or experimental setup using the inertial measurement unit to measure movement and navigation of a vehicle ,robotic movement and movement of human limbs. This research project involves the usage of few software such as VibraScout 6D, DASYLab 10, Measurement and instrumentation Explorer (MAX) and ME'scope VES 5 to acquire six degree of freedom data from inertial measurement unit, the impact hammer and tachometer data and for the purpose of data processing and animation. There are three experiment performed first the inertial measurement unit is placed at each three points of the three rigid discs while the motor runs accelerating from 0Hz to 50 Hz to find the natural frequencies. Second, the motor runs at specified natural frequency then again the inertial measurement unit is placed at those three points before the data obtained animated in ME'scope VES 5 to observe the mode shapes at each natural frequency. The third experiment involves the usage of impact hammer to excite the system and the data of the movement is then recorded by the IMU. There are 4 natural frequencies identified, that are 5.5Hz, 8Hz, 15Hz and 26Hz. The mode shapes at 5.5Hz and 15Hz being animated in this study for the purpose of testing the data applicability for animation. It is concluded that the inertial measurement unit data can be used to obtain natural frequencies and mode shapes in the form of rotating vibration. However, the validity and errors of data obtained is not investigated which can be done in other study in the future.

Keywords: inertial measurement unit, natural frequency, rigid rotor-shaft test rig.

ABSTRAK

Pengenalpasti sifat getaran bagi sesebuah struktur merupakan sesuatu yang penting bagi sesebuah kilang atau perusahaan dan bahagian jentera yang berputar bagi menjalankan fungsinya bagi mengekalkan integriti jentera tersebut. Jentera-jentera yang berputar bagi menjalankan fungsinya setiapnya mempunyai frekuensi semulajadi dan bentuk pergerakan getaran pada frekuensi semulajadi masing-masing. Setiap benda yang berputar mempunyai kesan giroskop masing-masing semasa berputar dan kajian ini bertujuan untuk menggunakan alat pengukur inertia untuk mendapatkan frekuensi semulajadi. Objektif kajian ini adalah untuk mengenalpasti frekuensi semulajadi satu set aci pemutar tidak berputar iaitu pepasangan bagi tujuan kajian di makmal di mana sistem tersebut yang terdiri dari tiga cakera silinder dan mempunyai titik/tempat alat pengukur inertia ditempatkan. Setelah bacaan dan data diperolehi daripada alat pengukur inertia , data tersebut akan digunakan untuk membuat animasi bentuk pergerakan semasa getaran pada frekuansi semulajadi sistem berputar tersebut. Beberapa kajian literasi telah dijalankan berkaitan penggunaan alat pengukur inertia. Kebanyakkan kajian dengan menggunakan peralatan eksperimen di makmal menggunakan alat pengukur inertia untuk membuat pengukuran dan navigasi kenderaan, pergerakan rosot serta pengukuran pergerakan tangan atau kaki manusia. Kajian ini telah menggunakan beberapa jenis perisian seperti VibraScout 6D, DASYLab 10, Measurement and instrumentation Explorer (MAX) and ME'scope VES 5 untuk mendapatkan 6 jenis pergerakan dari data yang diperolehi daripada alat pengukur inertia. Di samping itu, data daripada penggunaan penukul dan tachometer juga diperolehi dan diproses untuk dibuat animasi. Terdapat tiga jenis aktiviti pengujian yang dijalankan iaitu pertama adalah alat pengukur inertia ditempatkan di ketiga-tiga cakera silinder (satu persatu) sambil motor dibiarkan berputar semakin laju dari 0 hingga 50Hz untuk mendapatkan frekuansi semulajadi. Aktiviti seterusnya adalah menjalankan motor pada frekuansi semulajadi dan alat pengukur inertia ditempatkan di ketiga-tiga cakera silinder (satu persatu) sebelum datanya diambil dan diproses di dalam perisian ME’scope VES 5 untuk animasi pergerakan sistem. Eksperimen ketiga adalah melibatkan penggunaan tukul impak sebagai alat untuk mengujakan pergerakan cakera tersebut dan getaran daripada pergerakan yang terhasil di ambil data di dalam IMU. Terdapat 4 frekuensi semulajadi yang diperolehi iaitu 5.5Hz, 8Hz, 15Hz dan 26Hz. Animasi terhadap bentuk pergerakan getaran pada frekuansi semulajadi hanya dijalankan ke atas 2 frekuensi semulajadi iaitu 5.5Hz dan 15Hz bagi menguji kebolehgunaan data dari alat pengukur inertia untuk kedua-dua objektif kajian ini. Sebagai kesimpulannya alat pengukur inertia ini boleh digunakan untuk mengenalpasti frekuensi semulajadi dan bentuk pergerakan getaran bagi sistem pergerakan putaran. Walaubagaimanapun kajian lanjut pada masa akan datang perlu dijalankan terhadap kesahihan atau validasi data serta peratusan kesilapan atau ralat dari bacaan sebenar.

Katakunci : Alat pengukur inertia, frekuensi semulajadi, rig ujian aci rotor tidak bergerak.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS AND ABBREVIATION

AC – Alternating current

ANSYS – Analysis System

ASCII – American Standard Code for Information Interchange

CSV – Comma-separated Values

degree/s – degree/second

FEM - Finite Element Model

FFT – Fast Fourier Transform

FRF – Frequency Response Function

Hz - hertz

IMU – inertial measurement unit

MEMS – Microelectromechanical System

mm - milimeter

mVolts/g – millivolts/gram

NI DAQ – National Instrument Data Acquisition

ODS – Operating Deflection Shape

PC – Personal Computer

TDMS – Technical Data Management Streaming

USB – Universal Serial Bus

UFF58 – Universal File Format 58

2kS/s.- Two kilo samples per second

6 DOF – Six degree of freedom

CHAPTER 1 : INTRODUCTION

The problem of resonance at natural frequency of a rotor-shaft system is becoming an important issue to the manufacturer and plant which involved massive and expensive assets for the economic benefit of the company. There are several methods to determine the natural frequency and the dynamic behavior of the system done on site ranging from route based walk around methods with single and dual channel data collectors to permanently installed long term condition monitoring system. Modal analysis is widely used to describe the dynamic behavior of non-rotating structures. The adaptation of conventional modal analysis and testing methods to the study of rotational machinery structures requires overcoming some important theoretical and practical limitations. Conventional modal analysis and testing methods are based on the principles of reciprocity, which apply to non-rotating, linear structures in general. The mass, damping and stiffness matrices that are used to represent the dynamic properties of these system are symmetric. However, the dynamic behavior of rotating machinery structures does not always abide by this principle. This is due to the effects of forces that originate on their rotating components, which may either be of the gyroscopic or the circulatory types (Gutierrez E.S 2003). A fundamental requirement for rotating machinery diagnostic is basic time and frequency domain measurement capabilities. Rotating machinery diagnostic analyzers must have the ability to measure RPM from tachometer. A tachometer input measures the machine speed concurrently with the normal acquisition of measurement signal. Practically, to monitor vibration, accelerometers or velocity pickups and proximity probes such as displacement sensors are used to perform rotor dynamic analysis including determining natural frequencies and/or mode shapes in rotating components. The trigger input channel received a periodic analog signal from tachometer probe monitoring the machine under test. Vibration data from rotor shaft system during test is presented in graph or mapping in the time/frequency variations of signals. Another common method for determining natural frequencies is by stimulation of the test object to vibrate at its resonance frequency. Commonly a modal hammer or a shaker will be used as the stimulating device which is difficult especially on to rotating components. (Nordmann, 1984) used impact hammer excitation to excite the flexible shaft of a pump supported in oil film bearing. This set up is convenient to apply but its drawback is that it is difficult to achieve repeatability and to hit a moving component with accuracy. Also, it applies an undesirable tangential component of excitation by friction which affects the response of the test piece. To overcome this problem, (Kessler, 1999) used a tri-axial force transducer to apply the excitation. In this way, he was able to obtain an estimation of the applied tangential force in order to correct the measured FRFs, although this is not straightforward.

This study however is mainly focusing on the usage of microelectronic measurement sensors inertial measurement unit (MEMS IMU) to capture the vibration measurement in terms of angular velocity and acceleration. The usage of IMU would also covers the problem faced by (Kessler, 1999) as an IMU is a tri-axial accelerometer as well as tri-axial gyroscope. The ability of an IMU to give tri-axial data measurement will also minimize the effect of the unstable whirling of rotating shaft, as IMU actually measures those whirling movement. An IMU is another alternative measurement device which also could provide the vibration measurement data as conventional method of modal analysis measurement data using accelerometer transducer.

1.1 Scope of the study

This study is confined to the usage of an IMU and type of data that can be provided by the equipment in determining of the natural frequencies and their mode shapes of the rotor-shaft system during the run-up test of the test rig in the lab. The induction motor is set to be rotating from zero to maximum frequency limit of the inverter and accelerate for a period of time. The IMU used to acquire measurement data from the points of measurement where the movement of the disc is captured while the induction motor rotates. The frequency at where the disc moves with high amplitude indicates resonance at the natural frequency of the system. The findings of the natural frequencies of the system is then compared to the other method of determining the natural frequency from stimulation force from the impact hammer. The emphasis is placed on the usability of the IMU itself in providing reliable data to study the dynamic behavior of rotating structures. The type of data acquired from the IMU is in 6 degree of freedom of angular velocity and acceleration.

1.2 Objectives of the study

The objectives of the study are :-

1) To determine the natural frequencies of the rotating shaft system with IMU by performing the transient response analysis from 0 Hz to 50 Hz.
2) To obtain the mode shapes of the system which is operating at its respective natural frequencies (i.e. known as steady state response in the analysis).
3) To develop a rotational modal analysis involving impact hammer excitation and IMU for the identification of the natural frequency.

1.3 Structure of the study

This study is mainly to determine natural frequencies and mode shapes of the rotating system by using an IMU. The experiment of the usage of the IMU has been conducted at test rig consist of an induction motor connecting to 3 non-rotating shafts. The linear movement of the rotating induction motor transferred by a plastic cable. This report will show how the equipment and the instrumentations used in this study including a few software involved in data acquisition and processing which will be discussed in Chapter 3. The procedure of the transient response test performed at all the 3 points of discs is also briefly explained in Chapter 3: Methodology. The data acquisition and analyzing process using DASYlab 10 and ME'scope VES 5 will show the results of the natural frequencies obtained. After that the motor will be made run at natural frequency where IMU being placed at all the three points. The data obtained will be processed in ME'scope VES 5 software to animate the movement of the three disc showing different mode shapes at a different natural frequencies. The third objective is also performed by using impact hammer excitation while the dynamic behavior data during impact force acquired by IMU. The results and discussion is shown and explained in Chapter 4. The conclusion and potential of improvement to this study is stated in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

2.1 Modal Analysis

It is important to determine the fundamental frequency especially in rotating structures to avoid resonance problems which would lead to disastrous event of any machinery or plant. Natural frequency is the frequency or frequencies at which an object tends to vibrate with when hit, struck, plucked, strummed or somehow disturbed (Subramaniam, 2018). Mechanical resonance is the tendency of a mechanical system to respond at greater amplitude when the frequency of its oscillations matches the system's natural frequency of vibration than it does at other frequencies. Resonance vibration in mechanical structures such as pumps, turbines and motors occurs when a natural frequency is at or close to a forcing frequency such as rotor speed. A mode shape is however, a pattern of vibration executed by a mechanical system at a specific frequency. Different mode shapes will be associated with different natural frequencies. Rotating machinery structures are continuous systems and has an infinite number of degree of freedom. However, in practice, dynamic studies are focused on the behavior only within a limited frequency interval. Within this interval, some of the vibration modes dominate the dynamic behavior whereas others might only have a small influence. The experimental techniques of modal analysis discover these mode shapes and the frequencies.

Most of the modal identification methods and conventional procedures of modal analysis deal with structures with assumed linear behavior. Rotating machines have an inherent nonsymmetric nature, due to rotation-related factors, such as gyroscopic effects. All dynamic phenomena occurring during the performance of a rotating machine are closely related to the rotation motion of the rotor. Rotor are constraint into two lateral directions which is called vertical and horizontal (two-orthogonal lateral components). Normally during an impulse testing applied to a rotating system, results in a response containing vertical and horizontal components and undetermined tangential input and output force component. When measuring rotating machines vibration, it is important to identify each vibrational frequency component whether it is forward or backward (Agnes, 1995). This effect may be difficult to address with conventional methods of modal testing

Many studies have been done to determine the natural frequency and mode shape of machinery or part of it in experimental laboratory setup. The detection of natural frequencies and mode shapes of a rotating frame has been studied experimentally surrounded by heavy fluid and compared to numerical results and Finite Element Model (FEM).(Alexandre Presas, 2015). The study has also being compared to other studies that determine natural frequency under different medium and the interaction between the disc and with the surrounding media. A study of the natural frequencies of steel shaft & composite shaft have been reported with boundary condition and comparison between theoretical, numerical which is by ANSYS workbench and experimental method which is done by impact hammer and the resulting vibration of the shaft is measured by accelerometer(Prof. Bhirud Pankaj, 2016). Issues regarding modal testing for rotating system has being address by a few researcher and the need to acquire all parameter of movement of rotational system other than only vertical and horizontal or reciprocal movement of the system. However any studies using IMU MEMS as measurement equipment to obtain frequencies has not being found.

2.2 Inertial Measurement Units (MEMS)

In this study, the detection of the natural frequencies and mode shapes of an induction motor rotating at the frequency 0 Hz and accelerate to 50 Hz is done by using an IMU (inertial measurement unit). An IMU is an electronic device that measures and reports a body's specific force and angular rate, using a combination of accelerometers and gyroscopes. A 3-axis accelerometer measures acceleration along the X, Y and Z axes of the IMU and a 3-axis gyroscope measures angular velocity about X, Y and Z axes of the IMU.(Valentina Zega, 2018) as illustrated in Figure 2.1. The small size 6DOF (6 degree of freedom) shows as in Figure 2.2 is mainly used to determine the location of the center of rotation of a rigid body inside space.

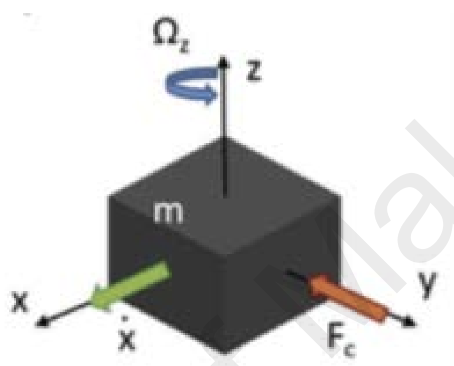


Figure 2.1 : The schematic of three axis inertial measurement unit.

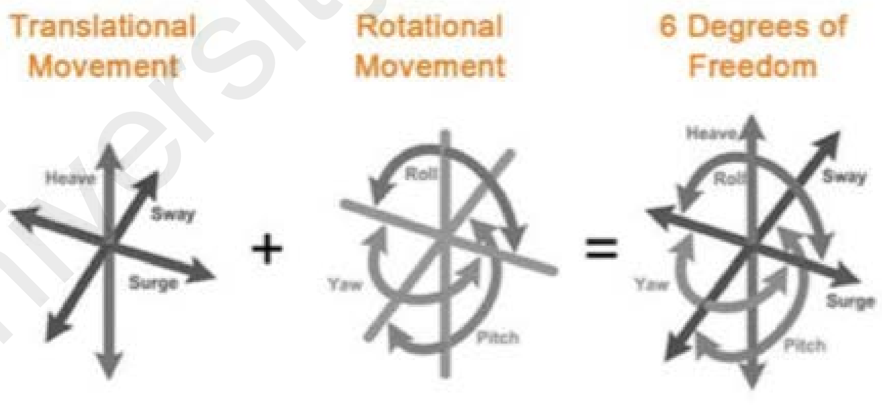


Figure 2.2 : The 6 DOF (degree of freedom) that can be measured by an inertial measurement unit(D. I. Inc, 2017).

We can use the right hand rule to determine the rotational direction of angular velocity of each X ,Y and Z axis. Direction of the thumb is the positive direction of angular velocity as illustrated in the Figure 2.3 below:-

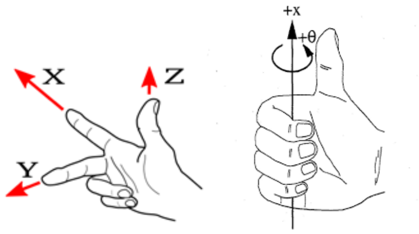


Figure 2.3 : The positive direction of angular velocity.

The IMU being used (or basically all accelerometers) share a basic structure consisting of an inertial mass suspended from a spring. The difference is the sensing of the relative position of the inertial mass as it displaces under the effect of external acceleration. Common sensing method is capacitive in which the use of special electronic circuits to detect minute changes in capacitance and to translate them into an amplified output voltage. There are some IMU method uses piezoresistors to sense the internal stress induced in the spring or in some method the spring is piezoelectric or contains a piezoelectric thin film, providing a voltage in direct proportion to the displacement. (Nadim Maluf, 2004).

A rigid body has six degree of freedom as illustrated in Figure 2.2. Accelerometers measure linear motion whereas gyroscopes measure angular motion. Gyroscope is the most important features in MEMS. The working principles of a gyroscope is given as an example of a wheel (rotor) rotates at a high angular speed about its axis. When the orientation of the frame changes, the gyroscopic effect causes the gimbals (for example a simplified gyrocompass) to rotate so that the direction of the spinning axis remains fixed with respect to the inertial frame. This is called conservation of angular momentum which will give rise to varies forces. One of it is the Coriolis force that is the principle of mechanical gyroscope including the inertial measurement unit. Vibratory gyroscope is biologically inspired for example the housefly which has a pair of balancers attached to each side of its thorax. The balancers vibrate in a plane perpendicular to the fly's axis. As the insect's flight changes direction, the tips of the balancers experience a Coriolis force. Without them, the fly is incapable of controlling the flight.(Thomas B.Jones, 2013)

There are a few studies using the IMU in their research, the determination angular velocity and positioning of the main body of experiment are done by using the micro-electro-mechanical system based inertial system with rotating accelerometer and gyroscopes (MEMS IMU). There are a few studies and research recently using IMU MEMS. A study using a wireless IMU which was design for biomechanics motion capture applications putting on a footbridge and the experiment has proven that the IMU is useful for evaluation of vibration serviceability(Brownjohn J.M.W, 2016). The usage of IMU if further validated by (Leah Taylor, 2017) where commercially available IMU has excellent utility and reliability with exceptional accuracy and precision and for angular velocity it shows a good accuracy and precision.

The potential of modern MEMS devices has been studied extensively. MEMS devices also have the potential of becoming gyroscopic generators which can enhance the attainable power level of energy scavengers and offers a promising future for practical implementation.(Yeatman, 2006).

IMU is found to be a potential multi parameter measurement device especially to a system with multi axial movement to be measured to make sure the problem of vibration in rotational system is being considered as the whole and realistic to the problem.

CHAPTER 3 : METHODOLOGY

3.1 Equipment and instrumentation

The determination of rotational natural frequency of an induction motor by using the inertial measurement unit consists of a lab experimental setup. The setup consists of 3 disk in series connected each by a rigid non-rotating shaft. A flexible nylon tape connecting the AC induction motor to the series of discs. When the motor is rotating, the excitation performed by the rotating motor is send to the 3 disk by the flexible nylon tape. The setup is as it is to convert rotational motion to linear impact motion.

The set up diagram (layout plan) are as shown below :-

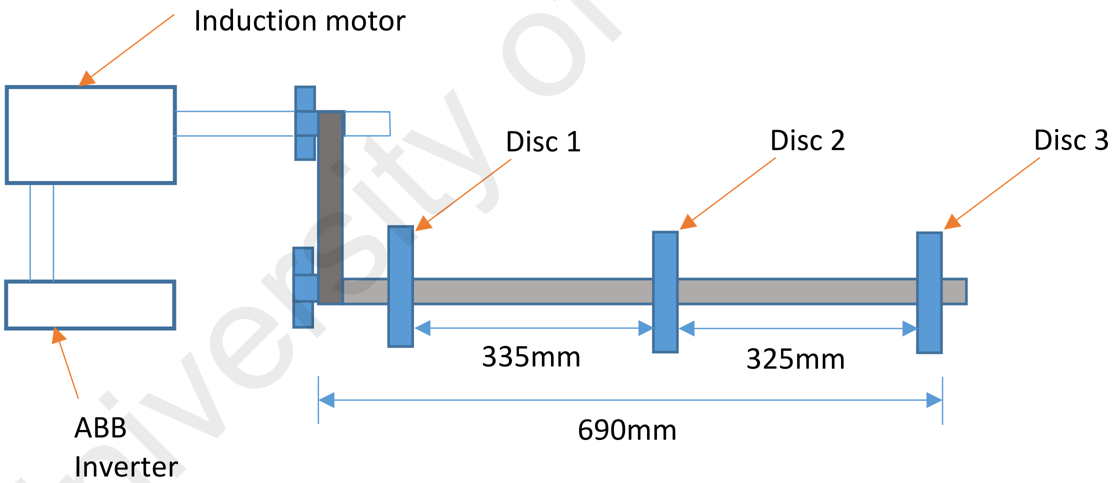


Figure 3.1 : Experimental set-up of induction motor vibration

There are two test performed in this research project to determine the natural frequencies and the mode shapes of the induction motor namely:

1) Transient response analysis, which measures the response of a system to load (where in this study a run-up test performed and induction motor runs from 0-50 Hz for a period of time) by using IMU to acquire the data.

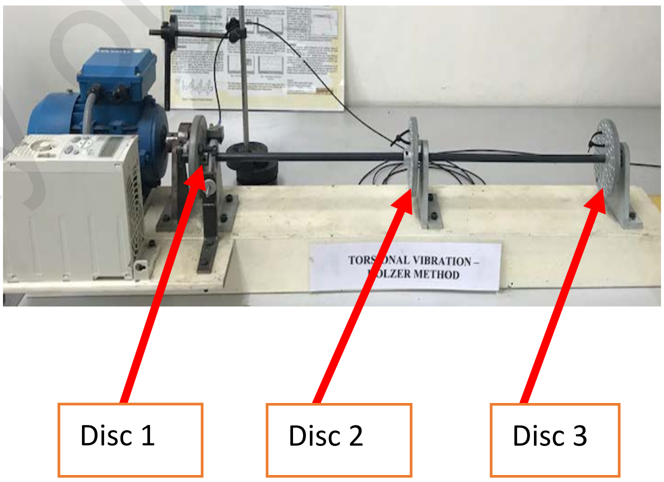
2) Steady state response analysis where the induction motor runs at natural frequency obtained while the IMU being placed at each disc (1, 2 and 3) to take response data.

3) Performing modal analysis through impact hammer excitation to determine natural frequencies and if possible make the comparison with the run-up test.

3.1.1 Test rigs and signal instrumentation

The test rigs consist of the following components as in Table 3.1:-

Table 3.1: Test rig and instrumentations

No.	Items	Figures
1.	Disk - The disk is made of stainless steel of diameter 100mm and 10mm thickness (cylindrical) for disc 1 and diameter 100mm and 8mm thickness (cylindrical) for disc 2 and 3. These disc are connected along its axis by a rigid and non-rotating shaft. The distance from disc 1 to disc 2 is 335mm and the distance between disc 2 and disc 3 is 325mm.	

2	Motor – The motor is Simex Three Phase Induction Motor Type SA 632-2 , 220-240V which is controlled by an inverter.	
3	Inverter - ABB Frequency Drives ACS-150-01E-02A4-2, 200-240V single phase input.	
4	The Dytran 7546A USB Digital 6 degrees of Freedom transducer combines a 3-axes MEMS accelerometer, 3-axes gyroscope and temperature sensor with a microcontroller. (temperature reading is not capture in this research	

	project). Software: Dytran VibraScout 6D.	
5	Impulse Force Test Hammer ICP Model: PCB 086C03 with tip.	
6	National Instrument NI 9234 four channel dynamic signal acquisition module.	

7	Tachometer	

There are four software are used in this study as in Table 3.2.

Table 3.2: Software and description

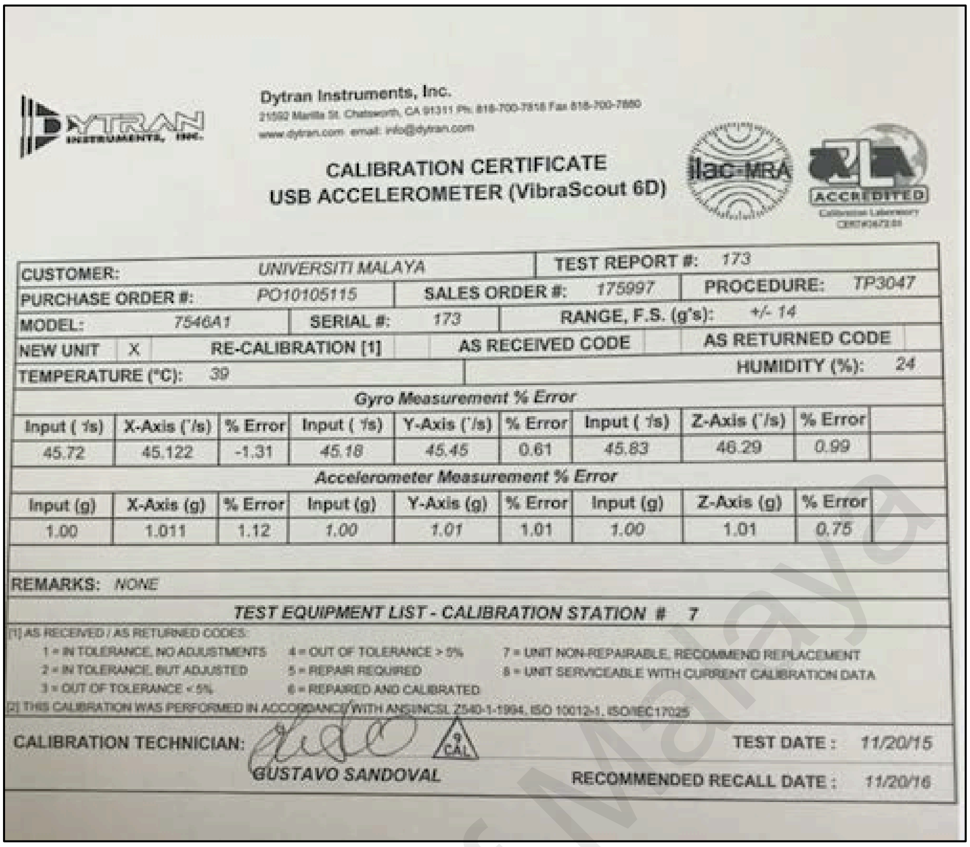
No.	Software	Usage/description
1.	Measurement & Automation Explorer (NI MAX) for (the impact hammer and tachometer)	Provide access to NI DAQ to configure the hardware , to create and edit channels and to view devices and instruments connected to system being used.
2.	9006 VibraScout 6D Software (for IMU reader)	Provide real time display of acceleration, gyro and temperature data, embedded post processor for data export to ASCII CSV, UFF58, Matlab compatible and also can overlays for channel to channel comparison.
3.	DASYLab 10	Interactive developed PC-based data acquisition applications by attaching functional icon. It also

		have real-time analysis and control and ability to custom GUIs.
4.	ME'scope VES Visual Engineering Series	The experimental or analytical data can be imported or directly acquire multi-channel time or frequency data from a machine or structure and post-process it.

3.1.2 Equipment limitation, requirement and calibration

The Dytran 7546A USB Digital 6 degree of freedom transducer (combines a 3-axes MEMS accelerometer, 3-axes gyroscope and temperature sensor). Maximum sampling rate for accelerometer (manufacturing specification) for all three channels X, Y and Z direction is 3200Hz. Maximum sampling rate for gyro (manufacturing specification) all three channel X, Y and Z direction is 2000Hz. Maximum bandwidth is VibraScout 6D is set to be 1600Hz , the true bandwidth of the accelerometer is 1600Hz but the gyro bandwidth is limited to 2000Hz (in this case the limit is 1600Hz).
NI 9234 data acquisition device has the data range using internal master time base where the minimum is 1.652kS/s and maximum is 51.2kS/s. The sampling rate is set to be at 1600 Hz same as in DASYlab 10.

The IMU is the critical measurement device that is being used in this study. Figure 3.2 shows the calibration certificate of the USB Accelerometer (VibraScout 6D). The size of 21.8mm X 21.8mm and design specification of the IMU as shown in technical drawing attached in Figure 3.3.



Dytran Instruments, Inc.
21592 Marilla St. Chatsworth, CA 91311 Ph: 818-700-7818 Fax 818-700-7880
www.dytran.com email: info@dytran.com

CALIBRATION CERTIFICATE
USB ACCELEROMETER (VibraScout 6D)

CUSTOMER:	UNIVERSITI MALAYA			TEST REPORT #:	173
PURCHASE ORDER #:	PO10105115	SALES ORDER #:	175997	PROCEDURE:	TP3047
MODEL:	7546A1	SERIAL #:	173	RANGE, F.S. (g's):	+/- 14
NEW UNIT	X	RE-CALIBRATION [1]	AS RECEIVED CODE		AS RETURNED CODE
TEMPERATURE (°C):	39			HUMIDITY (%):	24

Gyro Measurement % Error

Input (°/s)	X-Axis (°/s)	% Error	Input (°/s)	Y-Axis (°/s)	% Error	Input (°/s)	Z-Axis (°/s)	% Error
45.72	45.122	-1.31	45.18	45.45	0.61	45.83	46.29	0.99

Accelerometer Measurement % Error

Input (g)	X-Axis (g)	% Error	Input (g)	Y-Axis (g)	% Error	Input (g)	Z-Axis (g)	% Error
1.00	1.011	1.12	1.00	1.01	1.01	1.00	1.01	0.75

REMARKS: NONE

TEST EQUIPMENT LIST - CALIBRATION STATION # 7

[1] AS RECEIVED / AS RETURNED CODES:
1 = IN TOLERANCE, NO ADJUSTMENTS
2 = IN TOLERANCE, BUT ADJUSTED
3 = OUT OF TOLERANCE < 5%
4 = OUT OF TOLERANCE > 5%
5 = REPAIR REQUIRED
6 = REPAIRED AND CALIBRATED
7 = UNIT NON-REPAIRABLE, RECOMMEND REPLACEMENT
8 = UNIT SERVICEABLE WITH CURRENT CALIBRATION DATA
[2] THIS CALIBRATION WAS PERFORMED IN ACCORDANCE WITH ANSI/NCSL Z540-1-1994, ISO 10012-1, ISO/IEC17025

CALIBRATION TECHNICIAN: GUSTAVO SANDOVAL
TEST DATE : 11/20/15
RECOMMENDED RECALL DATE : 11/20/16

Figure 3.2 : The snapshot of Certificate of Calibration of USB Accelerometer (IMU)

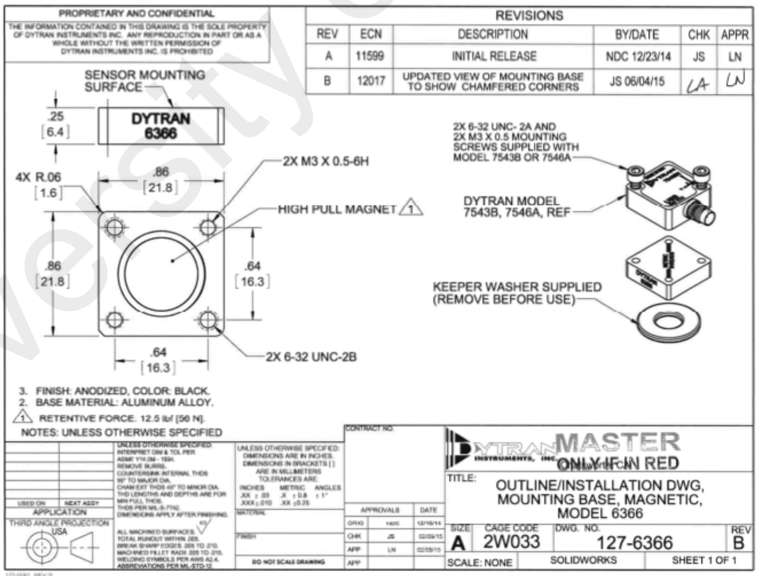


Figure 3.3 : The design drawing of the IMU

3.2 Transient Response Analysis Procedures

The test procedure are divided into two method which are :-

1) The run-up test to determine natural frequency of the system.
2) The determination of mode shapes of each natural frequency by performing simulation for observation.

3.2.1 Setting the inverter

In preparation to do measurement of frequency response using IMU, the inverter that drives the induction motor have to be set with keypad to be running 0-50Hz with acceleration time of 300 seconds with the procedure as below and the location of the keys are as shown in Figure 3.4 (Pari, 2009):-

1) Set the local frequency reference with keypad by setting it in parameter 1109 LOC REF SOURCE to 1 (KEYPAD) so that the keys and can be used to set the local reference.
2) Press the key and until "rEF' is seen and then press . Now the display shows the current reference value with SET under the value. To increase the reference value, press and to decrease the reference value, press . Press until the value reaching 50 Hz in the display.
3) Next, the acceleration time is set that is the time required for the speed to change from 0 to the speed (50Hz) defined in step 2. This can be done by press until 

appear. Press and until the parameter 2202 appeared and press and until the 300 s.

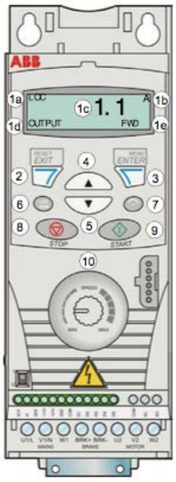


Figure 3.4 : Layout of the keypad of the inverter (ABB Frequency Drives)

3.2.2 Setting up the connection of tachometer and impact hammer

The tachometer in this study are used to take real-time data of rotation and the frequency of the rotating induction motor even an inverter is being used. The inverter working principle is the attempt to maintain consistent voltage and frequency output regardless of current output as opposed to varying voltage and frequency with generally consistent current output to speed up or slow down a motor load. So the frequency at any one time shown at inverter is not exactly the frequency of the real time rotation of the induction motor. The usage of tachometer to measure frequency and real time rotational of the induction motor is done at every point of measurement of the IMU. This is to make sure as if the data from IMU being taken simultaneously from all the three points in this study. A non-contact tachometer generally uses infrared light to measure the speed of rotation of a rotor. A reflector tape acting like a marker for the being put on the rotor of the induction motor so that the when the rotor rotates, the infrared light from the tachometer will fall on the reflector and reflected again to the detector on the tachometer. The number of frequency changes per unit time gives the speed of the rotation of the rotor.

The impact hammer Impulse Force Test Hammer ICP Model : PCB 086C03 with tip is being used in this study as a triggering signal (Piezoelectronics, 2010) to make sure that the real-time data acquisition taken in DASYLab 10 (such as tachometer and the impact hammer) and IMU data in VibraScout 6D software is being read by both software simultaneously and at the same time pace. These two instrument (tachometer and impact hammer) is connected to NI 9234 a four-channel dynamic signal acquisition module to simultaneously acquire signals before being read by DASYLab 10 software.(*NI 9234*).

The setup of both tachometer and the impact hammer is being done in the NI's Measurement & Automation Explorer (MAX) to provide access to NI instrument DAQ devices. MAX is a software that automatically installs the NI software and devices. The steps of installing the devices are as follows:-

1) Connect the USB DAQ device to the PC.
2) Connect the tachometer to analog input channel 0 (ai0) terminal of the NI 9234.
3) Connect the Impulse Force Test Hammer ICP Model : PCB 086C03 to analog input channel 1 (ai1) terminal of NI 9234.
4) Double click on MAX software.
5) Click at Devices and Interfaces and make sure NI USB-9234 is detected as in Figure 3.5.

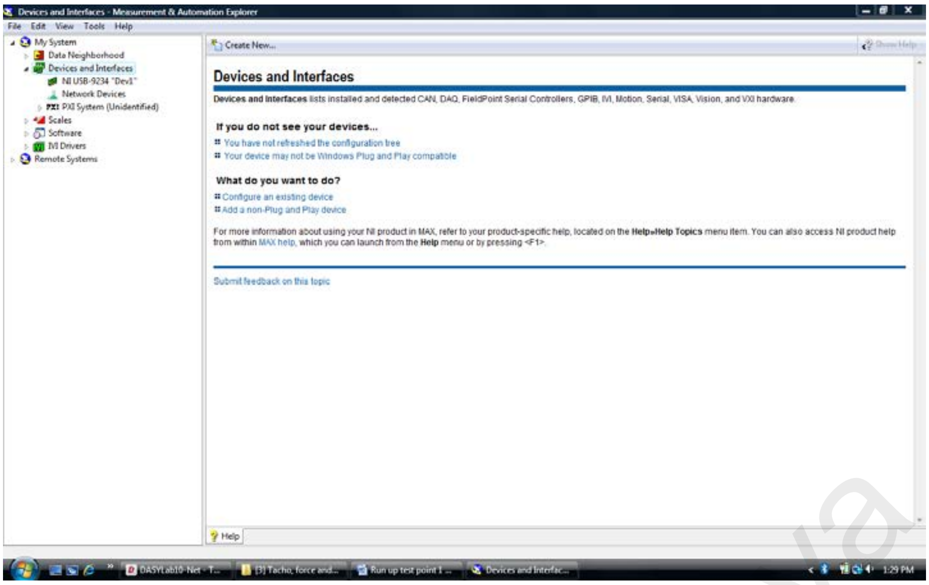


Figure 3.5 : The NI MAX set-up window

6) Click at NI USB-9234 Dev1 and click Create Task. Name the Task that will be performed (which is the tachometer and impact hammer). Figure 3.6

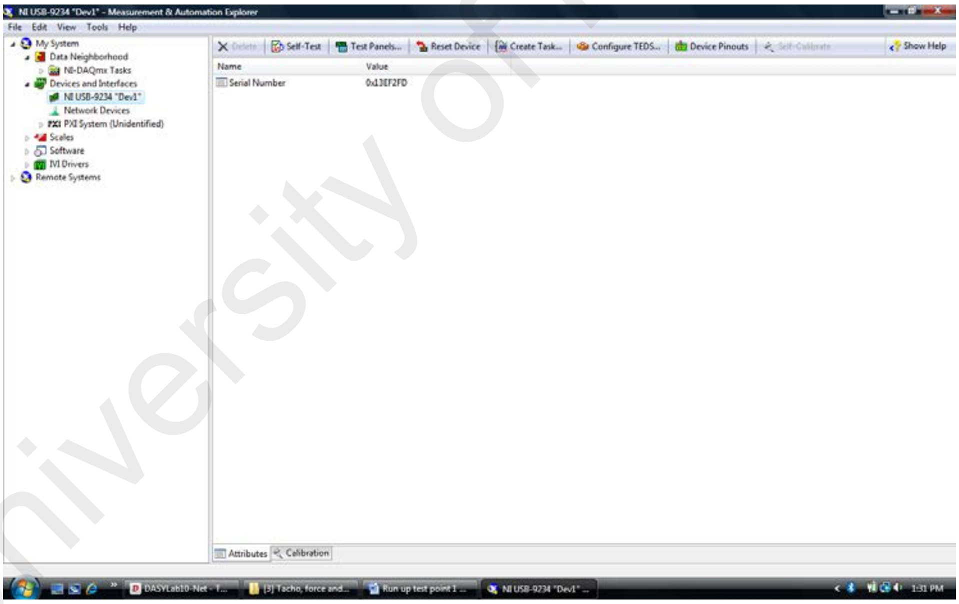


Figure 3.6 : The NI MAX NI USB-9234 window

7) The task 'Force 20avg' created and the setup is ready to be completed by putting the impact force hammer which is 'Acceleration' channel setting to be the sensitivity of 2.25 mVolts/g as stated in the instrument certificate (Figure 3.8). Please refer Figure 3.7 for the MAX interface.

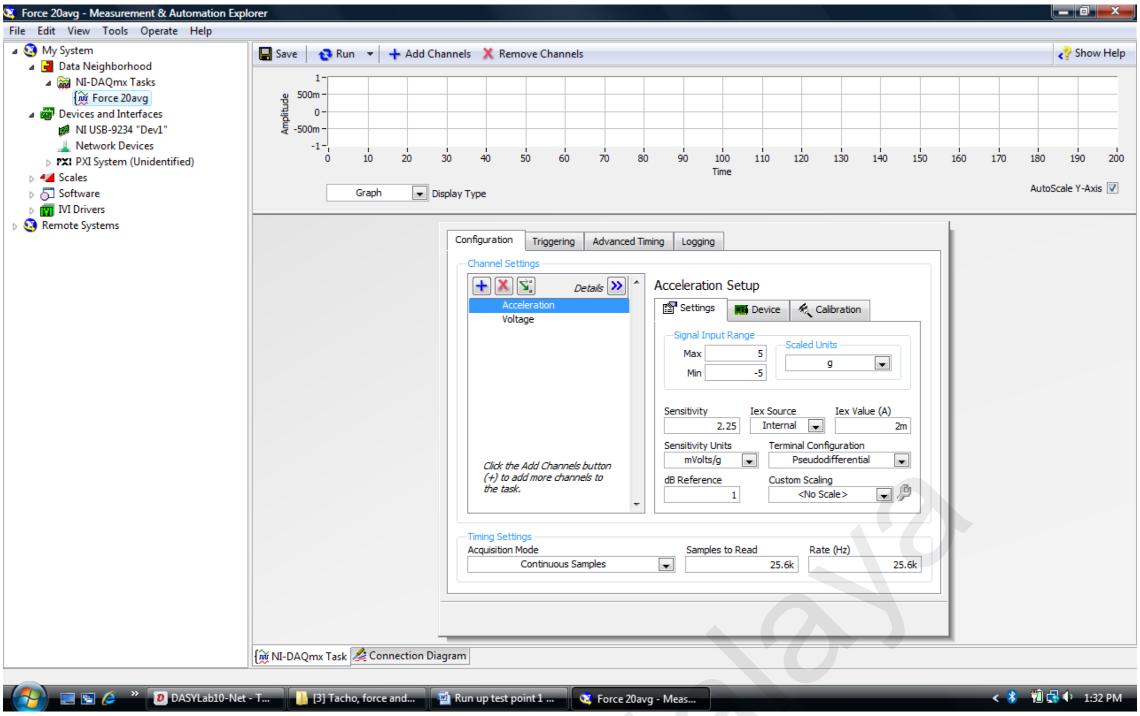
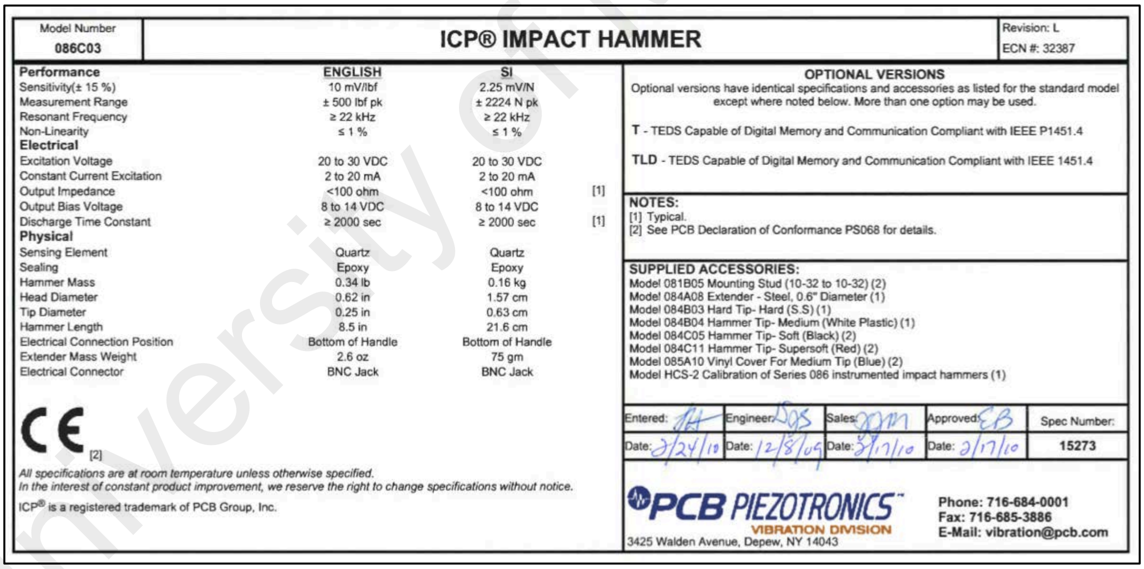


Figure 3.7 : The NI MAX device 'Acceleration' setup window



Model Number 086C03	ICP® IMPACT HAMMER		Revision: L ECN #: 32387
Performance	**ENGLISH**	**SI**	
Sensitivity(± 15 %)	10 mV/lbf	2.25 mV/N	
Measurement Range	± 500 lbf pk	± 2224 N pk	
Resonant Frequency	≥ 22 kHz	≥ 22 kHz	
Non-Linearity	≤ 1 %	≤ 1 %	
Electrical			
Excitation Voltage	20 to 30 VDC	20 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	<100 ohm	<100 ohm	[1]
Output Bias Voltage	8 to 14 VDC	8 to 14 VDC	
Discharge Time Constant	≥ 2000 sec	≥ 2000 sec	[1]
Physical			
Sensing Element	Quartz	Quartz	
Sealing	Epoxy	Epoxy	
Hammer Mass	0.34 lb	0.16 kg	
Head Diameter	0.62 in	1.57 cm	
Tip Diameter	0.25 in	0.63 cm	
Hammer Length	8.5 in	21.6 cm	
Electrical Connection Position	Bottom of Handle	Bottom of Handle	
Extender Mass Weight	2.6 oz	75 gm	
Electrical Connector	BNC Jack	BNC Jack	

CE [2]

All specifications are at room temperature unless otherwise specified.
In the interest of constant product improvement, we reserve the right to change specifications without notice.
ICP® is a registered trademark of PCB Group, Inc.

OPTIONAL VERSIONS
Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.

T - TEDS Capable of Digital Memory and Communication Compliant with IEEE P1451.4

TLD - TEDS Capable of Digital Memory and Communication Compliant with IEEE 1451.4

NOTES:
[1] Typical.
[2] See PCB Declaration of Conformance PS068 for details.

SUPPLIED ACCESSORIES:
Model 081B05 Mounting Stud (10-32 to 10-32) (2)
Model 084A08 Extender - Steel, 0.6" Diameter (1)
Model 084B03 Hard Tip- Hard (S.S) (1)
Model 084B04 Hammer Tip- Medium (White Plastic) (1)
Model 084C05 Hammer Tip- Soft (Black) (2)
Model 084C11 Hammer Tip- Supersoft (Red) (2)
Model 085A10 Vinyl Cover For Medium Tip (Blue) (2)
Model HCS-2 Calibration of Series 086 instrumented impact hammers (1)

Entered: JH	Engineer: JDS	Sales: JJM	Approved: CB	Spec Number:
Date: 2/24/10	Date: 12/8/09	Date: 3/17/10	Date: 2/17/10	15273

PCB PIEZOTRONICS
VIBRATION DIVISION
3425 Walden Avenue, Depew, NY 14043
Phone: 716-684-0001
Fax: 716-685-3886
E-Mail: vibration@pcb.com

Figure 3.8 : The Impact Hammer certificate

8) Set the tachometer at 'Channel Setting' as 'Voltage' as in Figure 3.9. Make sure 'Acquisition Mode' in 'Timing Settings' is 'Continuous Samples'.

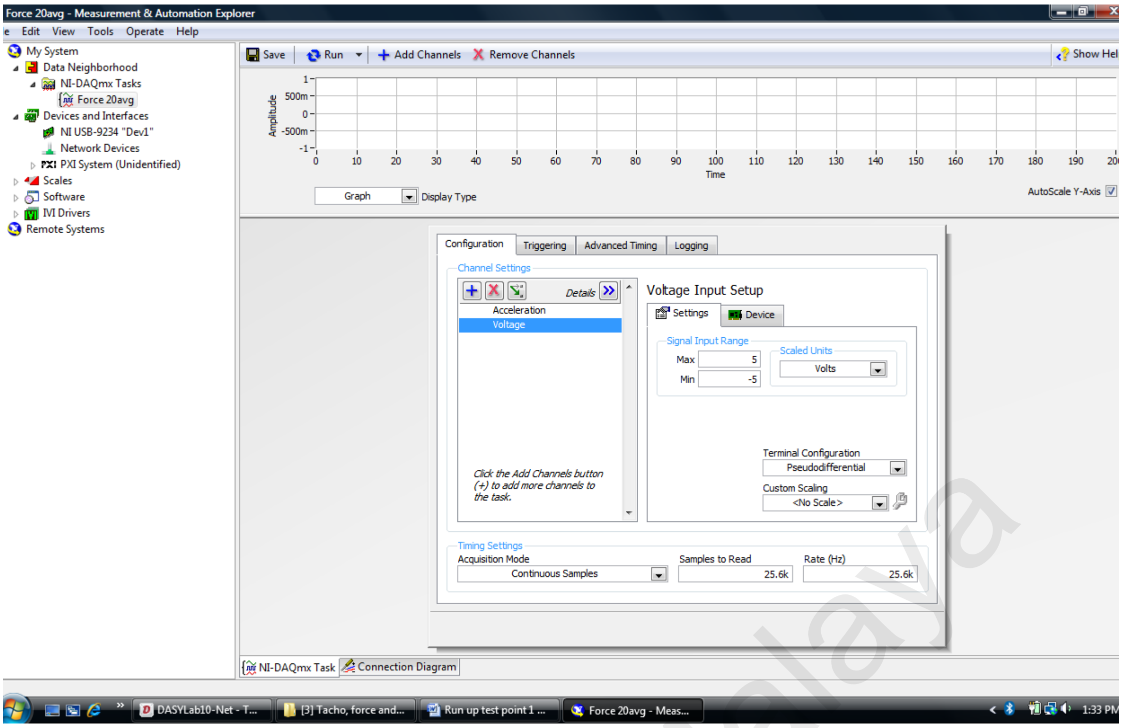


Figure 3.9 : The NI MAX device 'Voltage' setup window

9) Click 'Save' and exit MAX.

3.2.3 Setting up the IMU and VibraScout 6D Software

The IMU is fixed to the disc by attaching the IMU to the base magnet to enable it to be positioned on a 25mm X 18mm bracket. The bracket is fixed to the disc by strong glue so that the IMU is placed rigidly along the radial direction of the disc. The Dytran VibraScout 6D software is connected by 6330A 4-pin to USB cable to the IMU. The induction motor was set to be running from 0 to 50Hz with acceleration time of 300 seconds while IMU being placed at point disc 1. The position of the IMU is set to be easily accessible as the IMU need to be connected via USB cable to the computer as shown in the Figure 3.10.

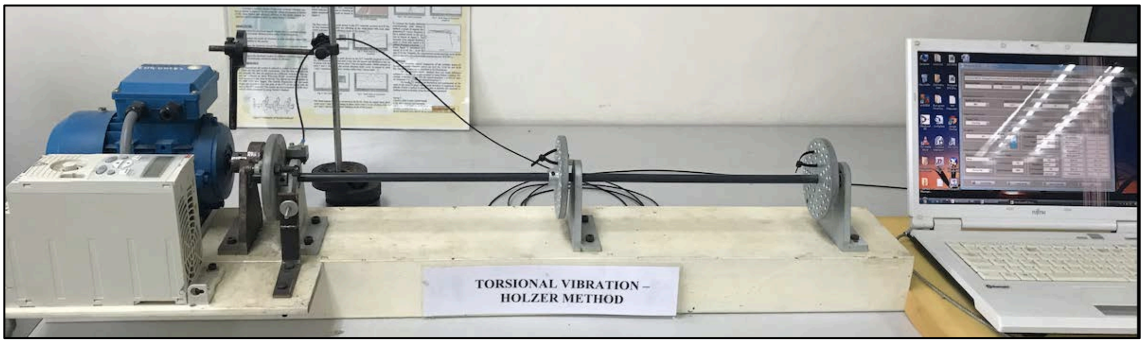


Figure 3.10 : The setup and positioning of the IMU (at disc 1).

Note that the direction of X, Y and Z axis need to be identify and understood. The positioning and the 3 axis direction are as Figure 3.11 as follows:-

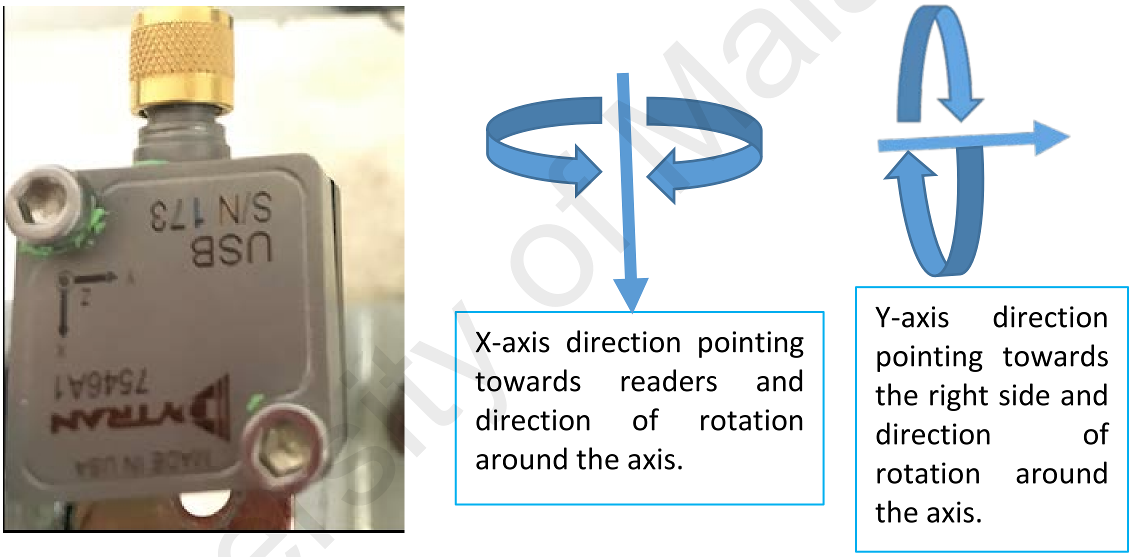


Figure 3.11 : The orientation of the IMU and direction of movement

And same principle apply to the Z-axis pointing up facing out of this paper and the direction of rotation is around the axis.

Below are the parameter setup of IMU in VibraScout 6D:-

1) Bandwidth (Hz) = 800 as the sampling frequency for the system is 2 X Bandwidth (equals to 1600Hz) which is the maximum sampling rate for gyro.
2) Update rate (seconds) = 1
3) Recording duration (seconds) = 300

4) GyroRange (degree/s) = 1000

5) Acceleration is set to be of the unit m/s^2 and angle to be the unit of radian and temperature is Celsius.

Click on the Setup button to set up for the test as in Figure 3.12. The window in Figure 3.12 will displayed and allows the user to define the parameters needed.

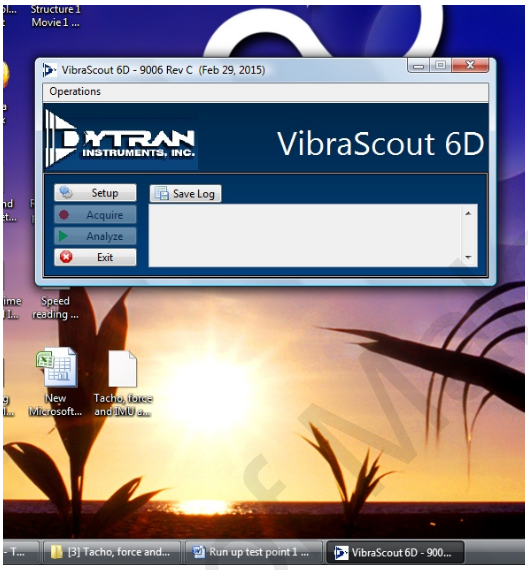


Figure 3.12 : VibraScout 6D interface

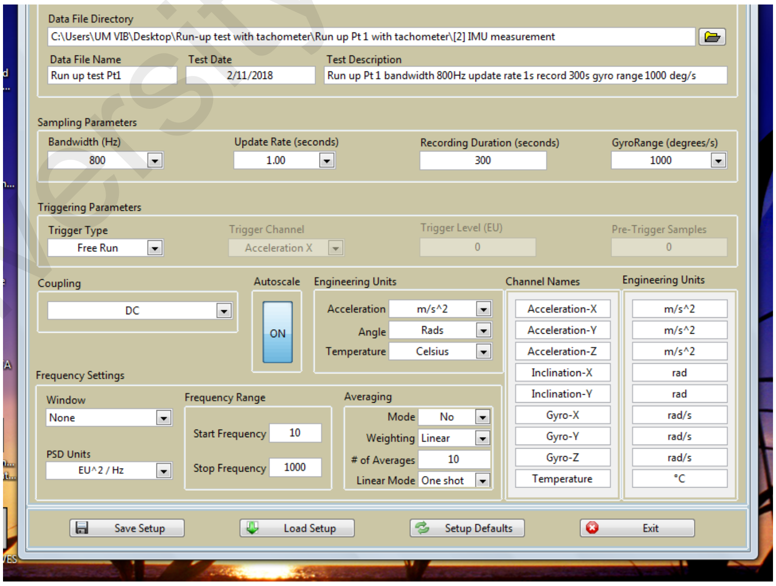


Figure 3.13 : VibraScout 6D Test Setup window

Once completed the setup as in Figure 3.13, Save the setup and click Exit.

Click on the Acquire button at VibraScout 6D main window to start real time acquisition. Choose Multi Channel View to display all 9 channels of data on a single window as in Figure 3.14.

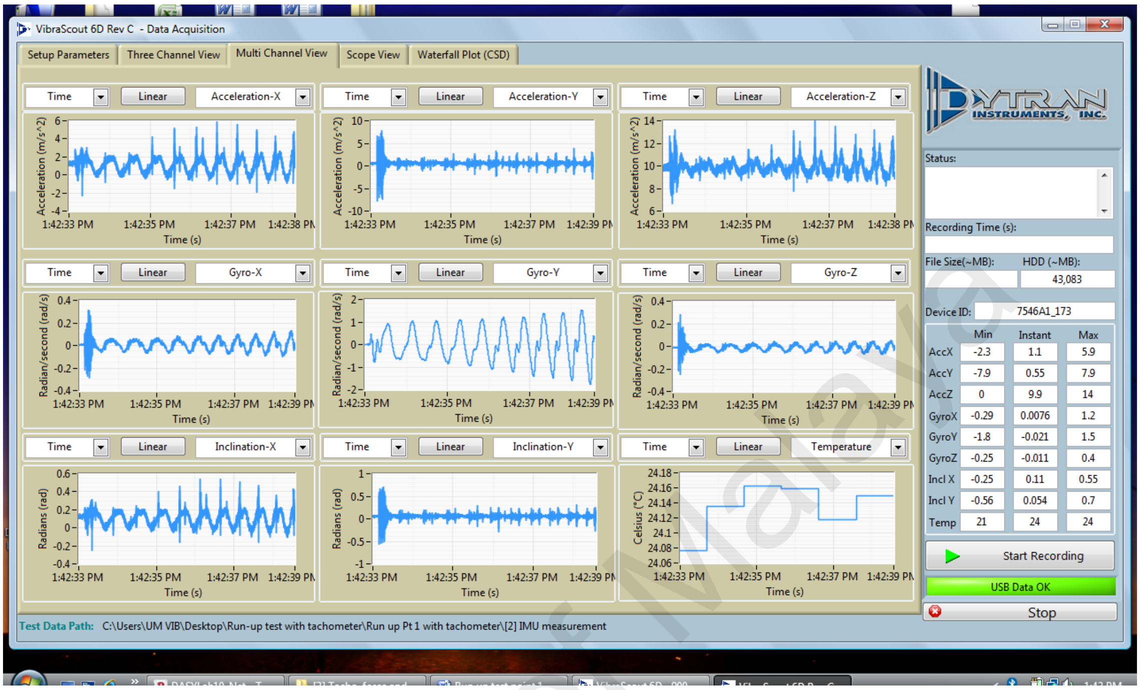


Figure 3.14 : VibraScout 6D Data Acquisition display

3.2.4 Setting up DASYLab 10 (with both USB NI 9234 and USB VibraScout 6D connected) to the PC.

In DASYLab 10, the three data being process and is placed in the ASCII file format. The DASYLab 10 worksheet are as in Figure 3.15.

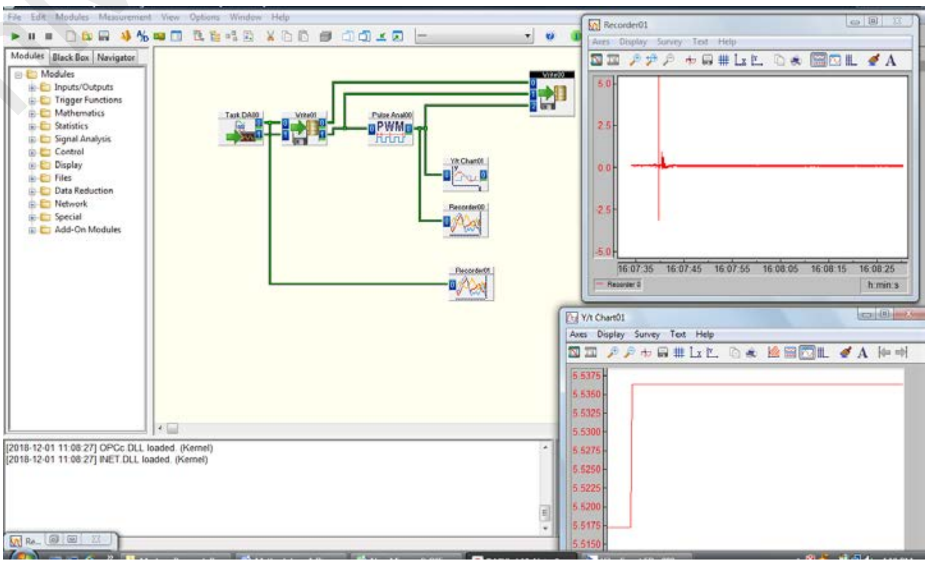


Figure 3.15 : DASYLab worksheet of Force and Tachometer reading

3.3 Performing Transient Response Test

Once the impact hammer and the tachometer data acquisition worksheet being set, the IMU being ready to be used and the laser light of tachometer is pointing to the reflector tape at induction motor rotor, the test rig set up are ready to be used. The steps are as below:-

1) Press play in DASYLab 10 window as shown in Figure 3.14.
2) Press 'Start Recording' in VibraScout 6D window as in Figure 3.13.
3) Knock once using the impact hammer on the surface of IMU as in –Z direction.
4) Put down the impact hammer and start up/run the inverter (induction motor been set to run from 0-50Hz with acceleration time of 300 sec before).
5) After 300 seconds, the VibraScout 6D will stop recording automatically and press at DASYLab 10 window to also stop acquiring data from the impact hammer and tachometer.

The data acquired and being written in ASCII file format are as shown in Figure 3.16 from the impact hammer and the tachometer.

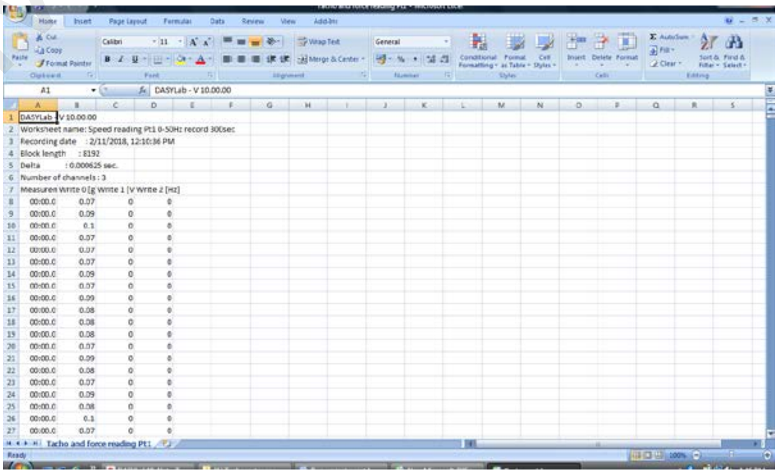


Figure 3.16 : ASCII file format of Force and Tachometer data

Data from the IMU will be acquired and save in TDMS format file as shown in Figure 3.17 and Figure 3.18 that can be open via Microsoft Excel. The data of 6 degree of freedom from accelerometer X, Y and Z axis each and gyroscope X, Y and Z axis. (The data of pitch, roll and temperature will not be a part of analysis for this study).

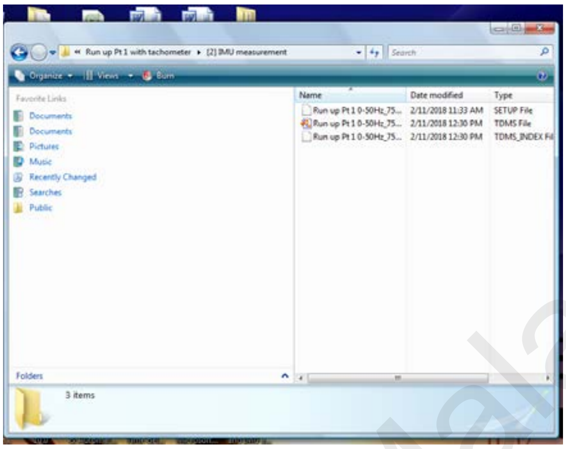


Figure 3.17 : The types of file acquired from IMU, TDMS file is the data from IMU.

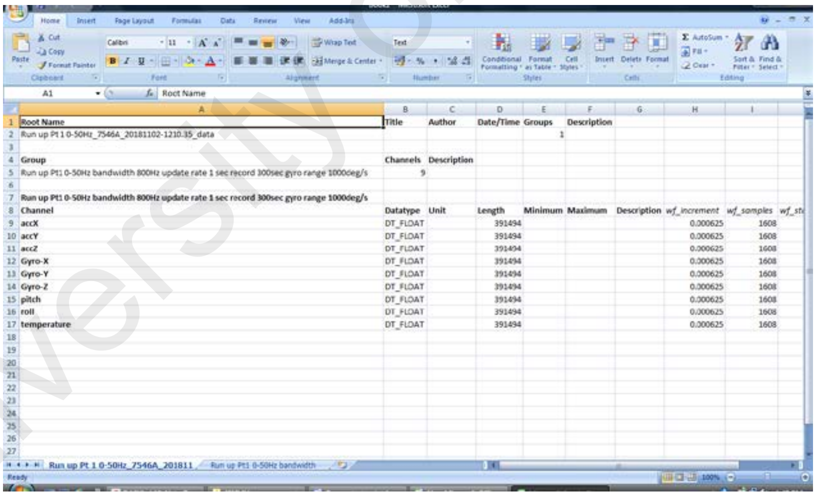
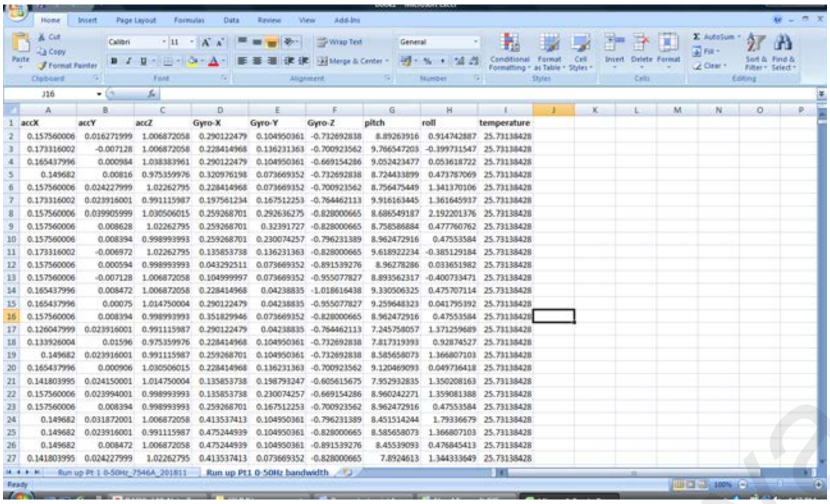


Figure 3.18 : Types of data acquired in TDMS file of IMU

The format of the data are as below as in Figure 3.19:-



	A	B	C	D	E	F	G	H	I
1	accX	accY	accZ	Gyro-X	Gyro-Y	Gyro-Z	pitch	roll	temperature
2	0.157560006	0.016271999	1.006872058	0.290122479	0.104950361	-0.732692838	8.89263916	0.914742887	25.73138428
3	0.173316002	-0.007128	1.006872058	0.228414968	0.136231363	-0.700923562	9.766547203	-0.399731547	25.73138428
4	0.165437996	0.000984	1.038383961	0.290122479	0.104950361	-0.669154286	9.052423477	0.053618722	25.73138428
5	0.149682	0.00816	0.975359976	0.320976198	0.073669352	-0.732692838	8.724433899	0.473787069	25.73138428
6	0.157560006	0.024227999	1.02262795	0.228414968	0.073669352	-0.700923562	8.756475449	1.341370106	25.73138428
7	0.173316002	0.023916001	0.991115987	0.197561234	0.167512253	-0.764462113	9.916163445	1.361645937	25.73138428
8	0.157560006	0.039905999	1.030506015	0.259268701	0.292636275	-0.828000665	8.686549187	2.192201376	25.73138428
9	0.157560006	0.008628	1.02262795	0.259268701	0.32391727	-0.828000665	8.758586884	0.477760762	25.73138428
10	0.157560006	0.008394	0.998993993	0.259268701	0.230074257	-0.796231389	8.962472916	0.47553584	25.73138428
11	0.173316002	-0.006972	1.02262795	0.135853738	0.136231363	-0.828000665	9.618922234	-0.385129184	25.73138428
12	0.157560006	0.000594	0.998993993	0.043292511	0.073669352	-0.891539276	8.96278286	0.033651982	25.73138428
13	0.157560006	-0.007128	1.006872058	0.104999997	0.073669352	-0.955077827	8.893562317	-0.400733471	25.73138428
14	0.165437996	0.008472	1.006872058	0.228414968	0.04238835	-1.018616438	9.330506325	0.475707114	25.73138428
15	0.165437996	0.00075	1.014750004	0.290122479	0.04238835	-0.955077827	9.259648323	0.041795392	25.73138428
16	0.157560006	0.008394	0.998993993	0.351829946	0.073669352	-0.828000665	8.962472916	0.47553584	25.73138428
17	0.126047999	0.023916001	0.991115987	0.290122479	0.04238835	-0.764462113	7.245758057	1.371259689	25.73138428
18	0.133926004	0.01596	0.975359976	0.228414968	0.104950361	-0.732692838	7.817319393	0.92874527	25.73138428
19	0.149682	0.023916001	0.991115987	0.259268701	0.104950361	-0.732692838	8.585658073	1.366807103	25.73138428
20	0.165437996	0.000906	1.030506015	0.228414968	0.136231363	-0.700923562	9.120469093	0.049736418	25.73138428
21	0.141803995	0.024150001	1.014750004	0.135853738	0.198793247	-0.605615675	7.952932835	1.350208163	25.73138428
22	0.157560006	0.023994001	0.998993993	0.135853738	0.230074257	-0.669154286	8.960242271	1.359081388	25.73138428
23	0.157560006	0.008394	0.998993993	0.259268701	0.167512253	-0.700923562	8.962472916	0.47553584	25.73138428
24	0.149682	0.031872001	1.006872058	0.413537413	0.104950361	-0.796231389	8.451514244	1.79336679	25.73138428
25	0.149682	0.023916001	0.991115987	0.475244939	0.104950361	-0.828000665	8.585658073	1.366807103	25.73138428
26	0.149682	0.008472	1.006872058	0.475244939	0.104950361	-0.891539276	8.45539093	0.476845413	25.73138428
27	0.141803995	0.024227999	1.02262795	0.413537413	0.073669352	-0.828000665	7.8924613	1.344333649	25.73138428

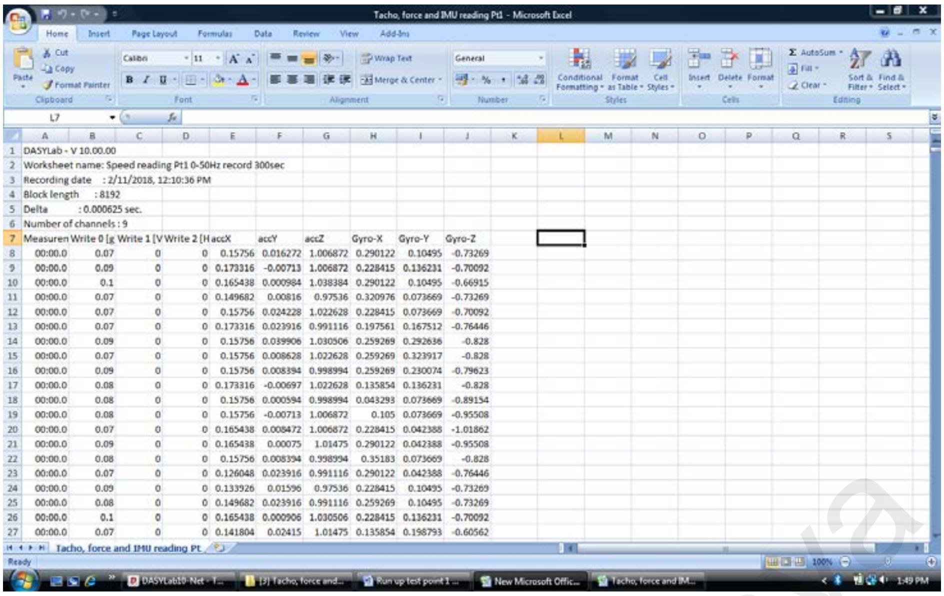
Figure 3.19 : Example of data captured from IMU in TDMS file

This whole process will be repeat at IMU being positioned at Point 2 and Point 3 following the same procedure.

3.4 Data Processing of Transient Response Test

3.4.1 Combining all parameter data

Both of these sets of data are combined in ASCII file format with 9 parameters combined as in Figure 3.20. Note that out of these 9 parameters, 3 parameters that are Force signal (column B), tachometer signal (pulse reading where the infra-red light detect the reflector tape at induction motor)(column C) and frequency data of tachometer (column D) and the other 6 parameter (as in column E till J) such as acceleration X-axis, acceleration Y-axis, acceleration Z-axis, angular velocity X-axis, angular velocity Y-axis and angular velocity Z-axis readings are from different software that is the VibraScout 6D.



DASYLab - V 10.00.00
Worksheet name: Speed reading Pt1 0-50Hz record 300sec
Recording date : 2/11/2018, 12:10:36 PM
Block length : 8192
Delta : 0.000625 sec.
Number of channels : 9

Measuren	Write 0 [g	Write 1 [V	Write 2 [H	accX	accY	accZ	Gyro-X	Gyro-Y	Gyro-Z
00:00.0	0.07	0	0	0.15756	0.016272	1.006872	0.290122	0.10495	-0.73269
00:00.0	0.09	0	0	0.173316	-0.00713	1.006872	0.228415	0.136231	-0.70092
00:00.0	0.1	0	0	0.165438	0.000984	1.038384	0.290122	0.10495	-0.66915
00:00.0	0.07	0	0	0.149682	0.00816	0.97536	0.320976	0.073669	-0.73269
00:00.0	0.07	0	0	0.15756	0.024228	1.022628	0.228415	0.073669	-0.70092
00:00.0	0.07	0	0	0.173316	0.023916	0.991116	0.197561	0.167512	-0.76446
00:00.0	0.09	0	0	0.15756	0.039906	1.030506	0.259269	0.292636	-0.828
00:00.0	0.07	0	0	0.15756	0.008628	1.022628	0.259269	0.323917	-0.828
00:00.0	0.09	0	0	0.15756	0.008394	0.998994	0.259269	0.230074	-0.79623
00:00.0	0.08	0	0	0.173316	-0.00697	1.022628	0.135854	0.136231	-0.828
00:00.0	0.08	0	0	0.15756	0.000594	0.998994	0.043293	0.073669	-0.89154
00:00.0	0.08	0	0	0.15756	-0.00713	1.006872	0.105	0.073669	-0.95508
00:00.0	0.07	0	0	0.165438	0.008472	1.006872	0.228415	0.042388	-1.01862
00:00.0	0.09	0	0	0.165438	0.00075	1.01475	0.290122	0.042388	-0.95508
00:00.0	0.08	0	0	0.15756	0.008394	0.998994	0.35183	0.073669	-0.828
00:00.0	0.07	0	0	0.126048	0.023916	0.991116	0.290122	0.042388	-0.76446
00:00.0	0.09	0	0	0.133926	0.01596	0.97536	0.228415	0.10495	-0.73269
00:00.0	0.08	0	0	0.149682	0.023916	0.991116	0.259269	0.10495	-0.73269
00:00.0	0.1	0	0	0.165438	0.000906	1.030506	0.228415	0.136231	-0.70092
00:00.0	0.07	0	0	0.141804	0.02415	1.01475	0.135854	0.198793	-0.60562

Figure 3.20 : Example of TDMS file data from IMU being assemble with Force and Tachometer data in ASCII file format

As explained earlier that the 9 parameter data comes from 2 different software and synchronizing the timing of acquired data is so critical. Again the 9 parameter data need to be process to make sure the same time sequence represent the test being performed to the test rig. The worksheet in DASYLab 10 organized to do delaying of IMU data timing as shown in Figure 3.21.

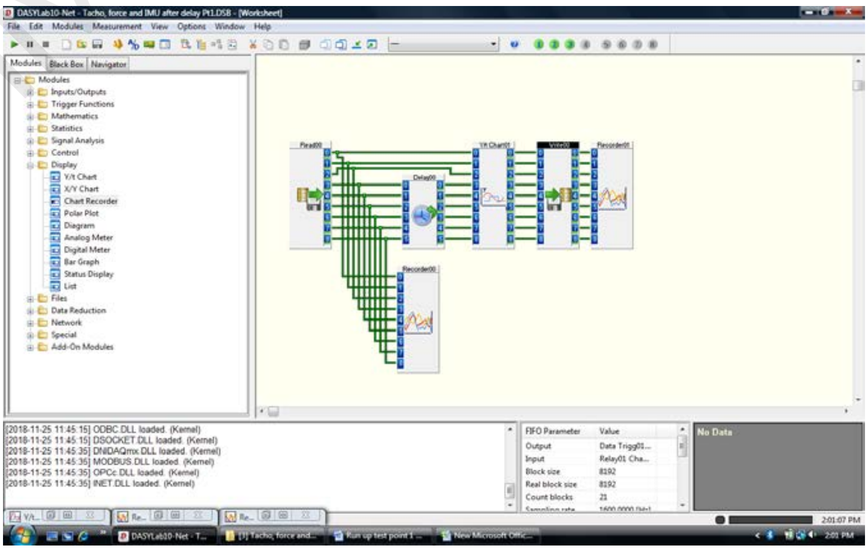


Figure 3.21 : DASYLab worksheet for delaying IMU data

Figure 3.22 shows how the raw data of those 9 parameters acquired in the test and compared to the data after delay. Figure 3.22 is a recorder graph plotted in DASYlab showing the signal of both impact force signal and the IMU response data. Delaying of IMU response data is to make sure that the measurement data acquired by NI 9234 and the IMU measurement data are read and processed synchronously by DASYlab 10. NI 9234 may have elapsed time as being mentioned in the equipment manual. The different time of the impact hammer applied and the IMU response to the impact is done by putting the DASYlab cursor between the starting of the two signal. The time difference (dt) shown in Recorder 1 window is the different of time start of force and IMU response that need to be delay. As shown in Figure 3.22 the different time is 3.10562 seconds.

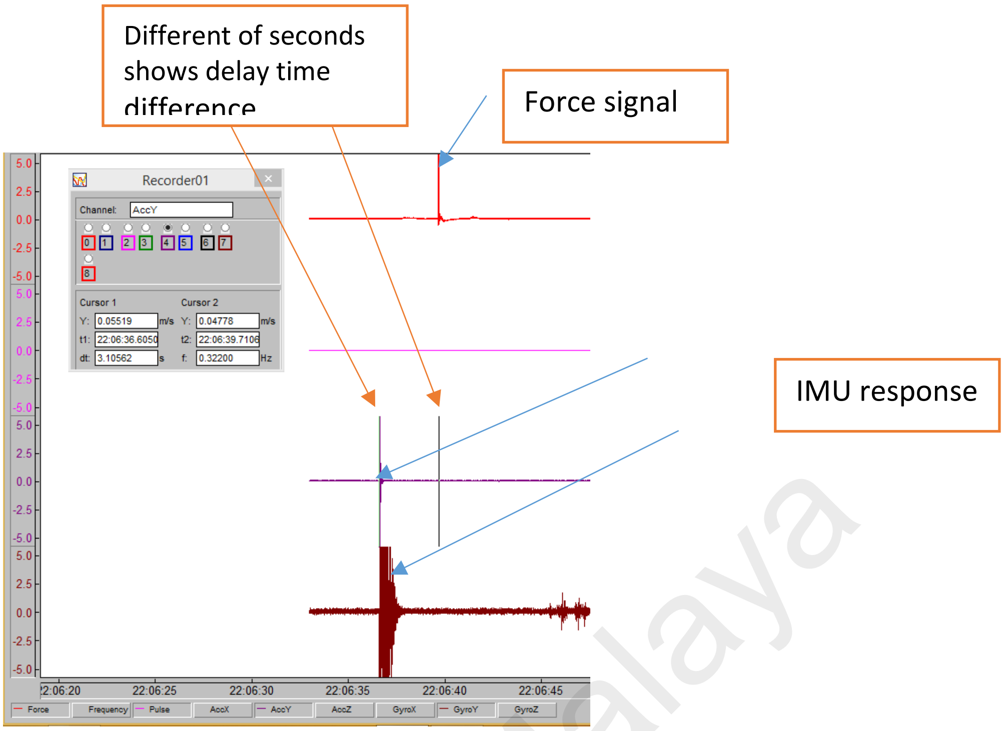
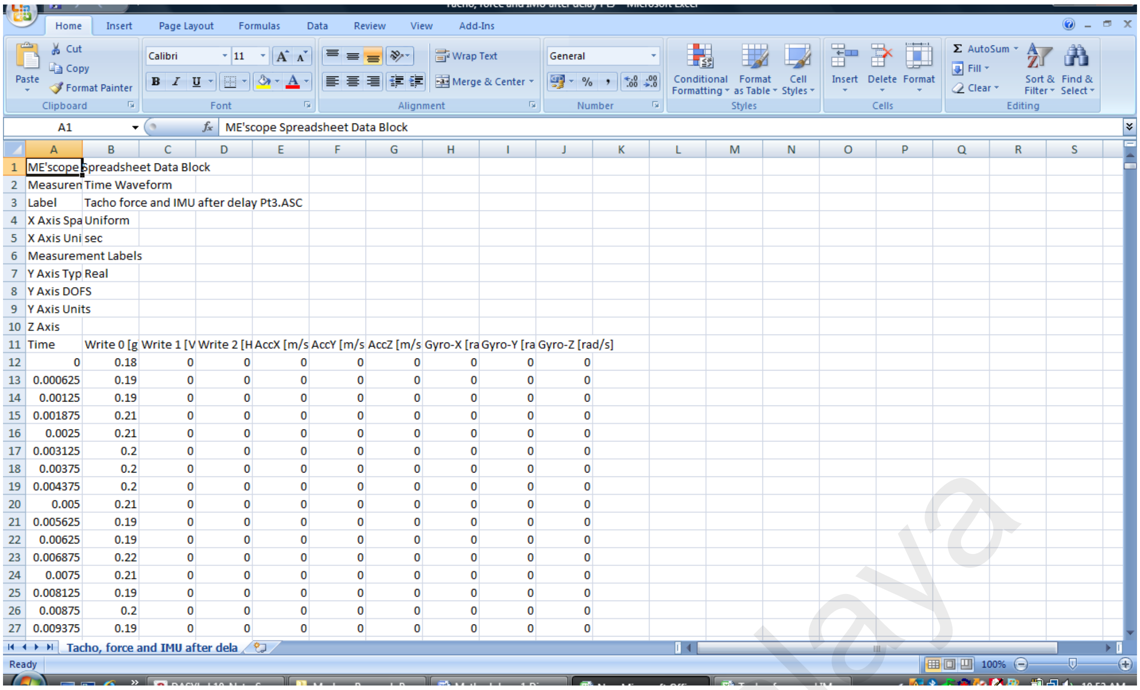


Figure 3.22 : Left window is before delay (raw data) whereas right window is after delay.

The signals represent the following data (sequence from top to bottom):-

1) Force from impact hammer signal.(red)
2) Rotation signal from tachometer.(navy blue)
3) Frequency reading (note that the frequency is increasing as time increase)(pink).
4) Acceleration X-axis (green)
5) Acceleration Y-axis (purple)
6) Acceleration Z-axis (blue)
7) Angular velocity X-axis (black)
8) Angular velocity Y-axis (dark red)
9) Angular velocity Z-axis (red)

The data of the time data synchronous are as shown in Figure 3.23.



	A	B	C	D	E	F	G	H	I	J
1	ME'scope Spreadsheet Data Block									
2	Measuren	Time Waveform								
3	Label	Tacho force and IMU after delay Pt3.ASC								
4	X Axis Spa	Uniform								
5	X Axis Uni	sec								
6	Measurement Labels									
7	Y Axis Typ	Real								
8	Y Axis DOFS									
9	Y Axis Units									
10	Z Axis									
11	Time	Write 0 [g	Write 1 [V	Write 2 [H	AccX [m/s	AccY [m/s	AccZ [m/s	Gyro-X [ra	Gyro-Y [ra	Gyro-Z [rad/s]
12	0	0.18	0	0	0	0	0	0	0	0
13	0.000625	0.19	0	0	0	0	0	0	0	0
14	0.00125	0.19	0	0	0	0	0	0	0	0
15	0.001875	0.21	0	0	0	0	0	0	0	0
16	0.0025	0.21	0	0	0	0	0	0	0	0
17	0.003125	0.2	0	0	0	0	0	0	0	0
18	0.00375	0.2	0	0	0	0	0	0	0	0
19	0.004375	0.2	0	0	0	0	0	0	0	0
20	0.005	0.21	0	0	0	0	0	0	0	0
21	0.005625	0.19	0	0	0	0	0	0	0	0
22	0.00625	0.19	0	0	0	0	0	0	0	0
23	0.006875	0.22	0	0	0	0	0	0	0	0
24	0.0075	0.21	0	0	0	0	0	0	0	0
25	0.008125	0.19	0	0	0	0	0	0	0	0
26	0.00875	0.2	0	0	0	0	0	0	0	0
27	0.009375	0.19	0	0	0	0	0	0	0	0

Figure 3.23 : Example of raw data of Force, Tachometer and IMU after delay in ASCII file format

Note that the data for IMU has been delayed as it was moved forward. This delayed raw data will be saved in ASCII format file to be further analyzed in ME'scope VES 5.

3.4.2 Setting up ME'scope VES 5 files

As described in details in 3.1, ME'scope VES 5 is used in this study so that all data needed from the IMU and tachometer could be overlayed, draw structure and animate at the frequency of the data acquired. First double click on the ME'scope VES 5 icon and the window appeared as in Figure 3.24.

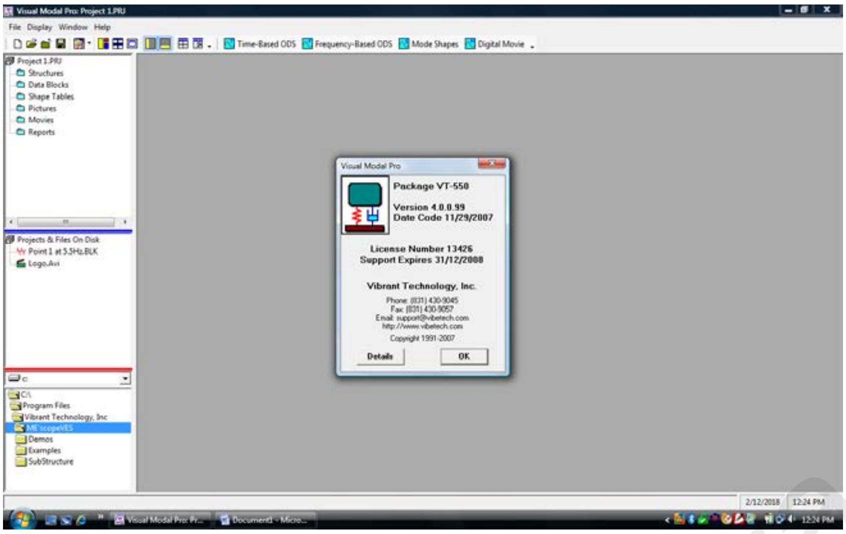


Figure 3.24 : ME'scope VES windows

To begin with, the data in ASCII file will need to be imported to ME'scope VES that is shown in Figure 3.25.

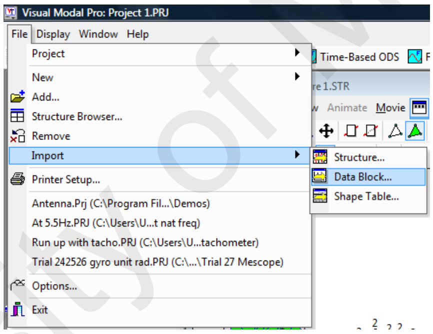


Figure 3.25 : Importing data from ASCII files to form a Data Block file in ME'scope VES

3.5 Performing the mode shapes determination experiment and data processing

There are a few steps involved in determining the mode shapes of each natural frequencies obtained in this study. The settings of the instrumentation and equipment are as explained in section 3.2.1 to 3.2.4. In this method, the frequency that are set at the inverter is at the natural frequency that was determined in run-up test. The VibraScout 6D recording time also to be set at 60 seconds as at natural frequency, the induction motor will be running with resonance so the impact to the induction motor need to be minimized. As an example, the first natural frequency identified is 5.5 Hz. The inverter is set to be at 5.5 Hz and acceleration time is set to be 5 seconds as we only need to acquire the signal from IMU at the specified frequency. First the IMU is placed at disc 1.

Once the impact hammer and the tachometer data acquisition worksheet being set, the IMU being ready to be used and the laser light of tachometer is pointing to the reflector tape at induction motor rotor, the test rig set up are ready to be used. The steps are as follows:-

1) Press play in DASYLab 10 window  as shown in Figure 3.14.
2) Press ‘Start Recording’ in VibraScout 6D window as in Figure 3.13.
3) Knock once using the impact hammer on the surface of IMU as in –Z direction.
4) Put down the impact hammer and start up/run the inverter (induction motor been set to run at natural frequency 5.5 Hz with acceleration time of 60 seconds before).
5) After 60 seconds or till the ‘End of Recording’ button is pressed, the VibraScout 6D will stop recording automatically and press  at DASYLab 10 window to also stop acquiring data from the impact hammer and tachometer.

The 9 parameter data which are acquired from the impact hammer, tachometer and IMU will also being combined in an ASCII file format as in para 3.4.1 and need to go through the delaying process by using DASYLab 10 to make sure that the data from IMU (VibraScout 6D) and the data from impact hammer and tachometer (DASYLab 10) are synchronized.

To perform animation that will represent the real time response of the three disc, the data of all the three disc points need be synchronized as it was taken simultaneously with three unit IMU being used for measurement. The ASCII format file of all the three points data are arranged as shown in Figure 3.26.

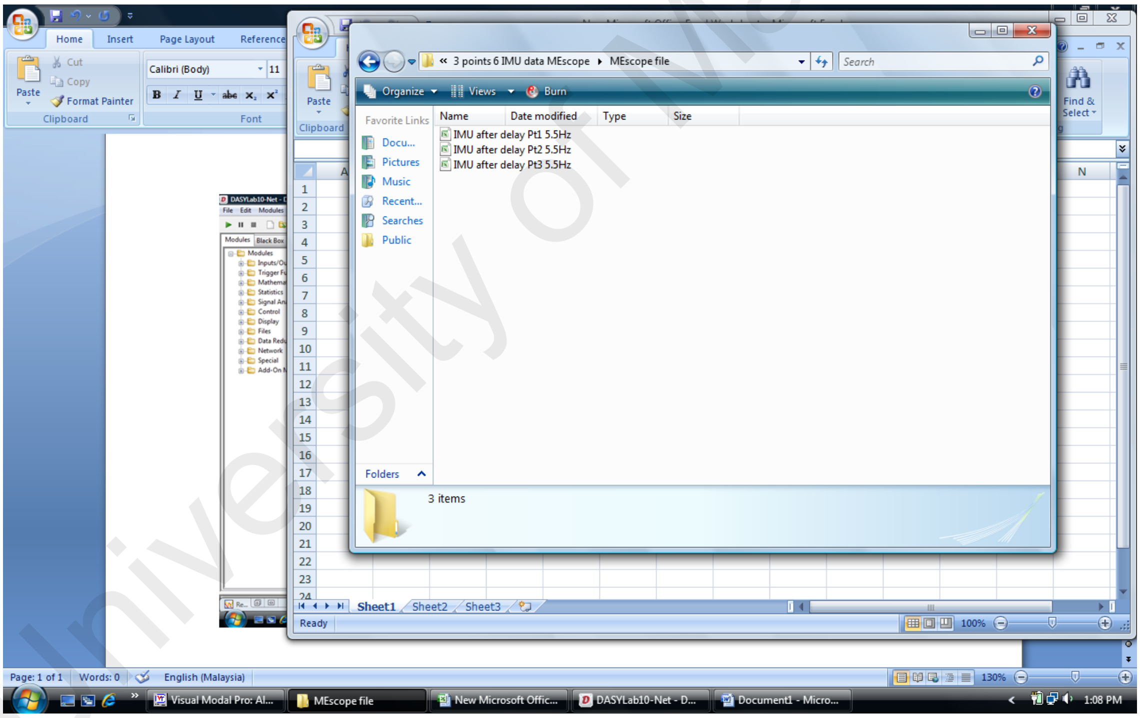


Figure 3.26 : The ASCII format file arranged before imported to ME'scope VES 5

After the data being captured for point 1 (disc 1), locate the IMU at point2 (disc 2) and also at point 3 (disc 3). The data also being captured at other natural frequencies at point 1, point 2 and point 3 respectively.

3.6 Performing modal analysis through impact hammer excitation

The modal analysis with impact hammer excitation is widely used in performing modal analysis in any structures mainly linear motion response structures. In this study, a conventional modal analysis is done using the available equipment in the Vibration Lab which is the Impact Force Test Hammer ICP model: PCB 086C03 with tip. The connection of DASYlab 10 with NI DAQ 9234 together with IMU and VibraScout 6D as IMU acquisition software is done as similar to run-up test. This time, IMU is placed at point 3 only as a fixed response point and the location of excitation input varies from point 1 to point 2 and point 3. During this test, the induction motor is not rotating. The data acquired from the IMU of all the 6 parameter is then transform to frequency domain through FFT and perform Frequency Response Function (FRF) in DASYlab.

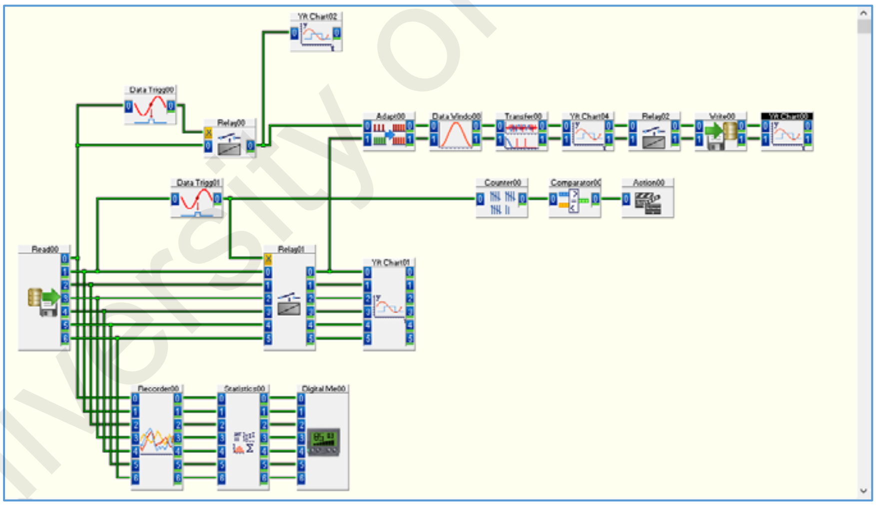


Figure 3.27 : DASYlab worksheet to perform FFT and FRF before using the data in ME'scope

The FRF data is then being used in ME'scope to do curve fitting to obtain the natural frequencies.

CHAPTER 4 : RESULTS AND DISCUSSION

Based on the data acquired from DASYLab is ASCII format file, the raw data then being transferred to ME'scope VES as the results could be visualized and overlay the signals to find natural frequency. Noted that the main challenge of performing this study is the time measurement and data synchronization from different software with different limitation. Those 9 parameters are then displayed in ME'scope VES. The results are visualized in the format of a graph with time in unit seconds in X-axis and amplitude in unit of m/s^2 for acceleration and in units of rad/s for angular velocity.

4.1 Results of transient response test in determining natural frequencies

The results of all the 6 degree of freedom in IMU for all 3 points are presented for points and frequencies as specified in Table 4.1.

Table 4.1 : Types of result acquired from run-up test

No.	Frequency (Hz)	Point
1.	Natural frequency 1	1 2 3
2.	Natural frequency 2	1 2 3
3.	Natural frequency 3	1 2 3
4.	Natural frequency 4	1 2 3

4.1.1 Point 1

The data acquired from the IMU is being processed in ME'scope to visualize at which frequency gives most significant response data to determine the natural frequency of the system. Due to the positioning of the IMU during testing, it was predicted that gyro Y axis data shows a significant amplitude of response that can be seen in the plotted graph of Time vs Amplitude. ME'scope is used to also include the tachometer data which shows the rotation of the induction motor mechanically as there is an elapsed time issue between the NI DAQ 9234 and DASYlab 10. Figure 4.1 shows the peak response area (green area) where the induction motor reach its resonance which might cause vibration in the system in this study.

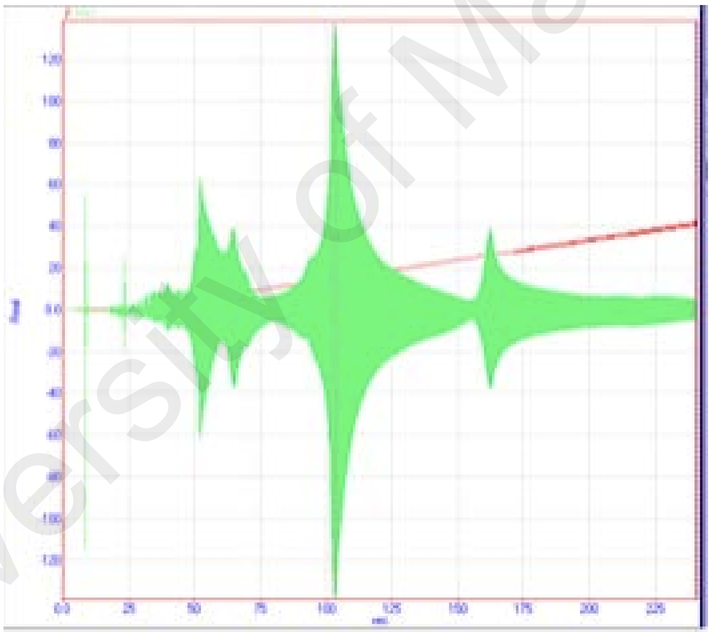


Figure 4.1 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity at Y-axis.

It is observed that the highest amplitude reach by the system at point 1 is around 100th second from the beginning of the rotation at approximately 15Hz (from the red incline line). The second highest amplitude is on the 50th second at about 5.5Hz. The next high amplitude observed at 8 and 25 Hz. Angular velocity Y-axis (1RY) shows a very significant signal of natural frequencies at 4 frequencies namely at 5.5Hz, 8Hz, 15Hz and

26Hz as shown in Figure 4.1. Note that the vertical line is placed at the peak of the amplitude and the intersection of this line to red incline line is the frequency reading from tachometer. This point is the natural frequency obtained for point 1. Results of angular velocity Z axis shows quite obvious response. This is due to the position of the IMU at point 1 has made the Z axis is at tangential direction of the disc. Refer to Figure 4.6. The angular velocity of Z axis is disturbed which noise in the signal due to the whirling effect of the disc which give a sign of whirling effect of the induction motor too. However the graph shown in acceleration data for X, Y and Z axis as well as angular velocity results of X axis are not show significant signal to make a good conclusion. This is consistent with the prediction of the signal acquired as orientation of the IMU being position at point 1. Since the gyroscopic movement and force from the rotating induction motor transmitted to the three static disc, the gyroscopic effect can be obtained from the IMU angular velocity readings at points of test conducted. Below are the results of accelerometer X, Y and Z axis and gyroscope X and Z axis.

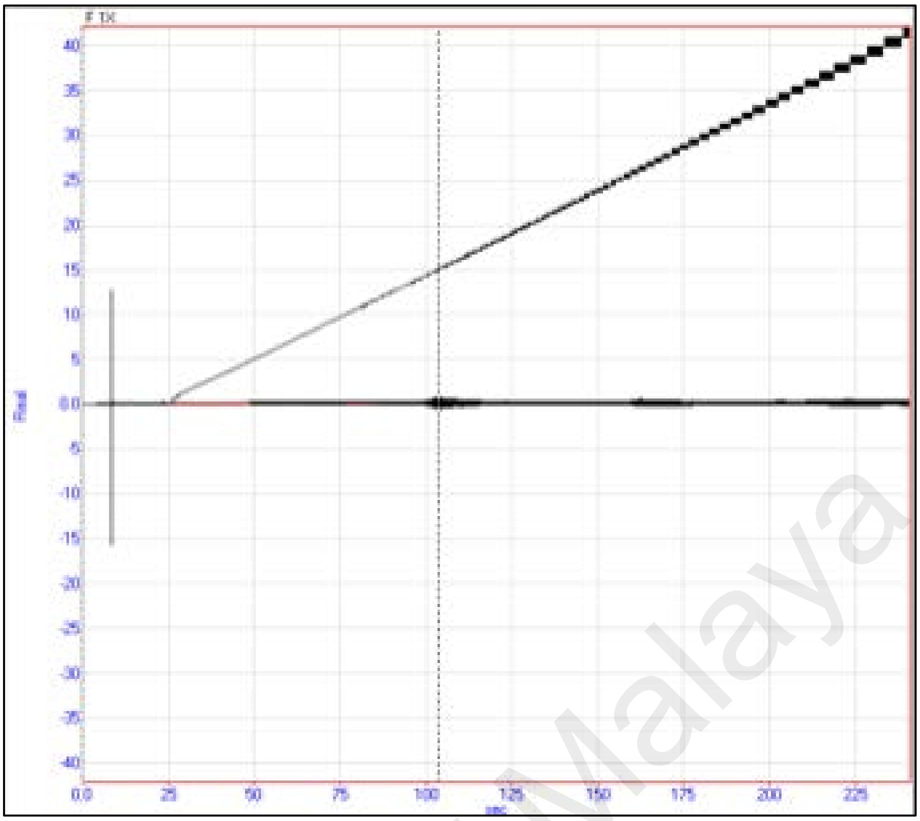


Figure 4.2 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration X-axis.

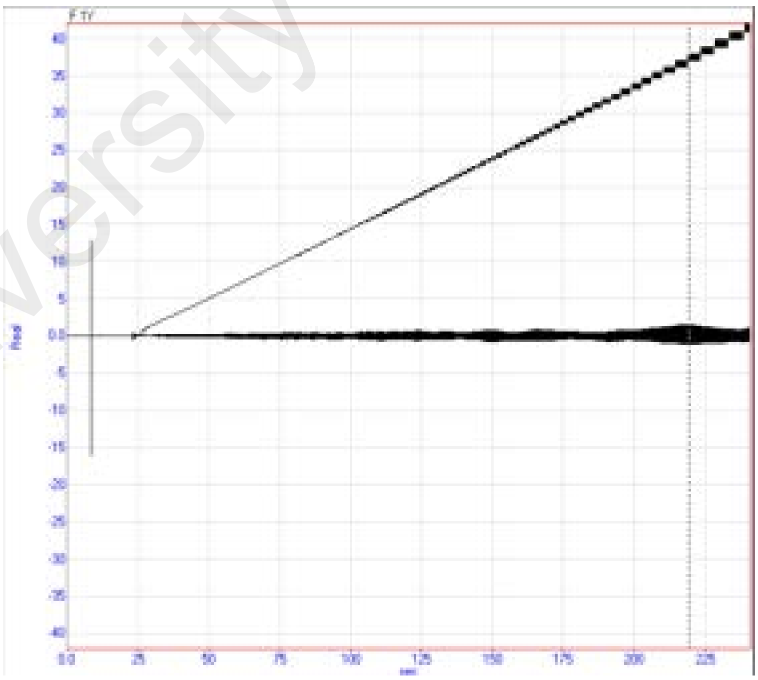


Figure 4.3 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration Y-axis.

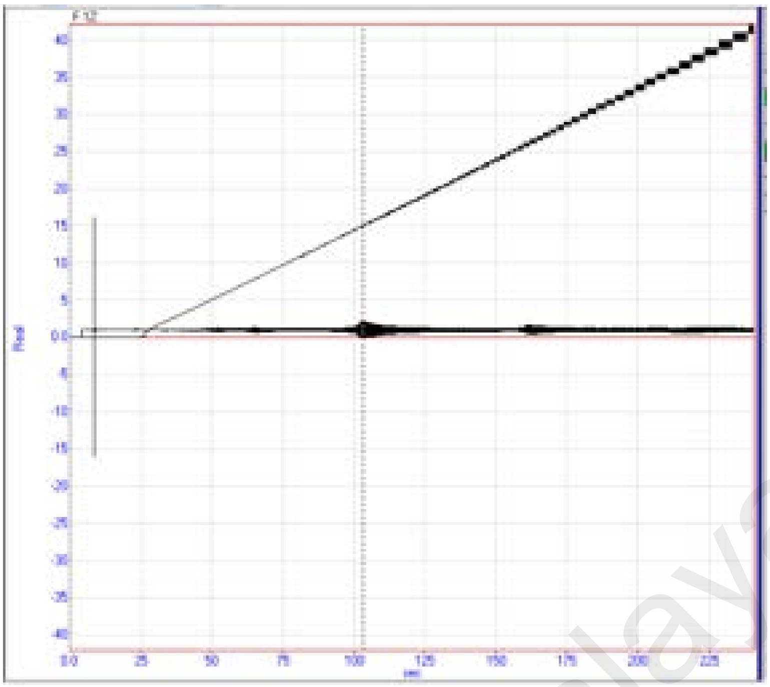


Figure 4.4 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration Z-axis.

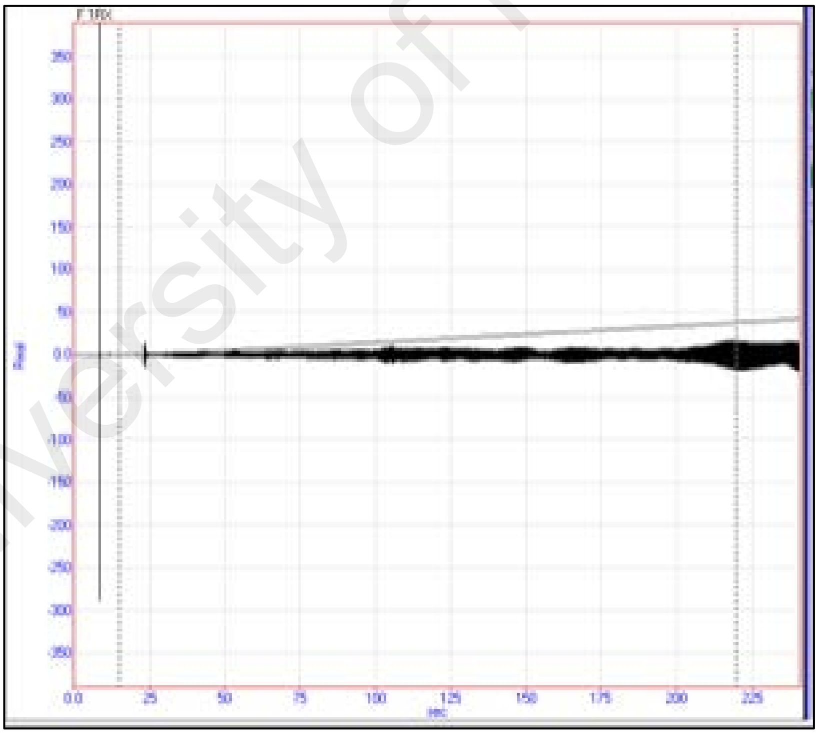


Figure 4.5 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity X-axis.

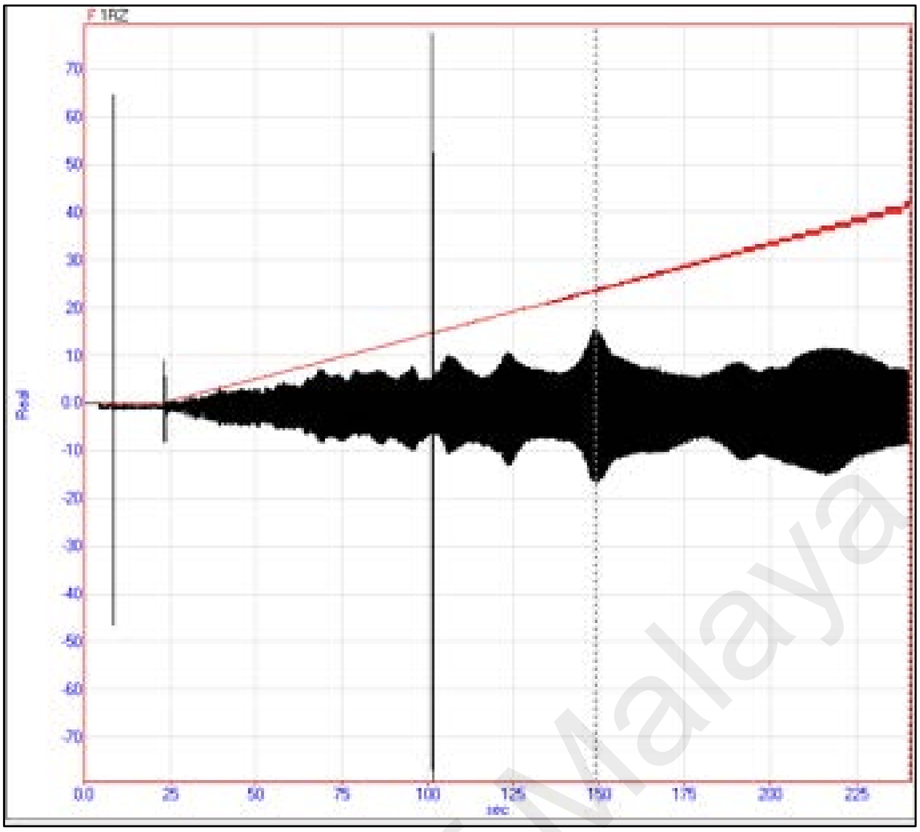


Figure 4.6 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity at Z-axis.

4.1.2 Point 2

Here , the data from IMU is being processed in ME'scope in time domain and to visualize at which frequency gives most significant response data to determine the natural frequency of the system at point 2. Due to the positioning of the IMU during testing, again it was predicted that gyro Y axis data shows a significant amplitude of response that can be seen in the plotted graph of Time vs Amplitude. ME'scope is used to also include the tachometer data which shows the rotation of the induction motor mechanically as there is an elapsed time issue between the NI DAQ 9234 and DASYlab 10. Figure 4.7 shows the peak response area (black area) where the induction motor reach its resonance which might cause vibration in the system in this study.

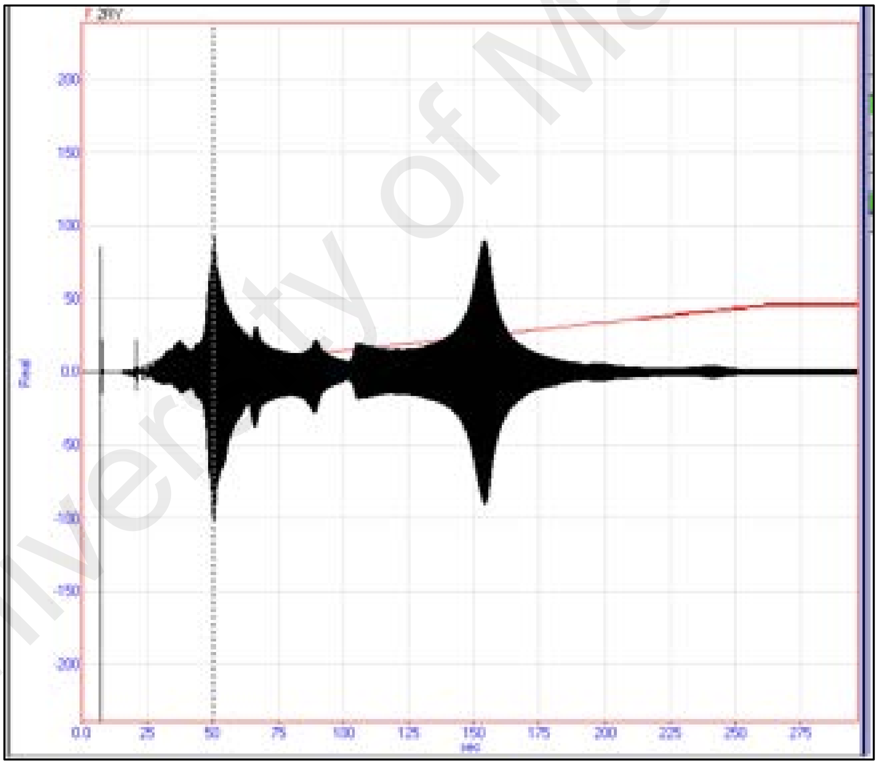


Figure 4.7 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity at Y-axis (the first high amplitude).

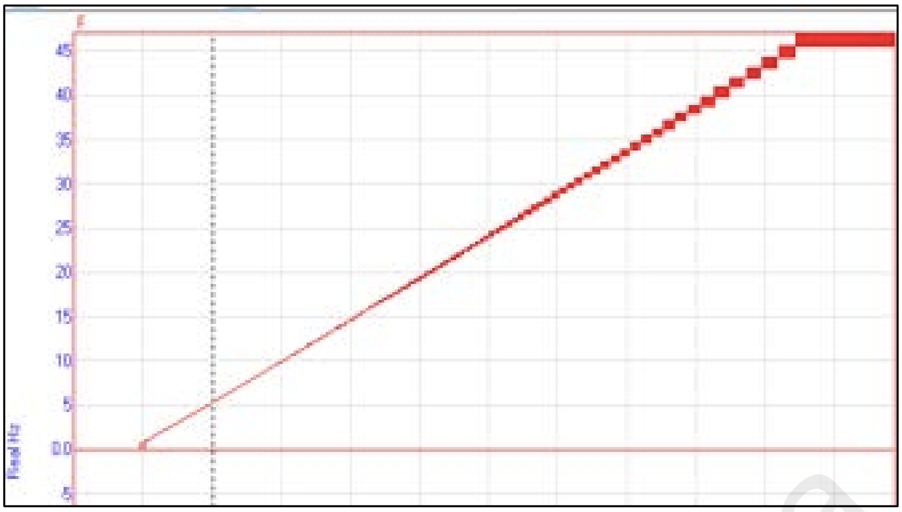


Figure 4.8 : Graph of Amplitude vs Time which shows an increasing frequency (red inclining line) where vertical cursor positioned at the highest peak of amplitude of angular velocity Y-axis .

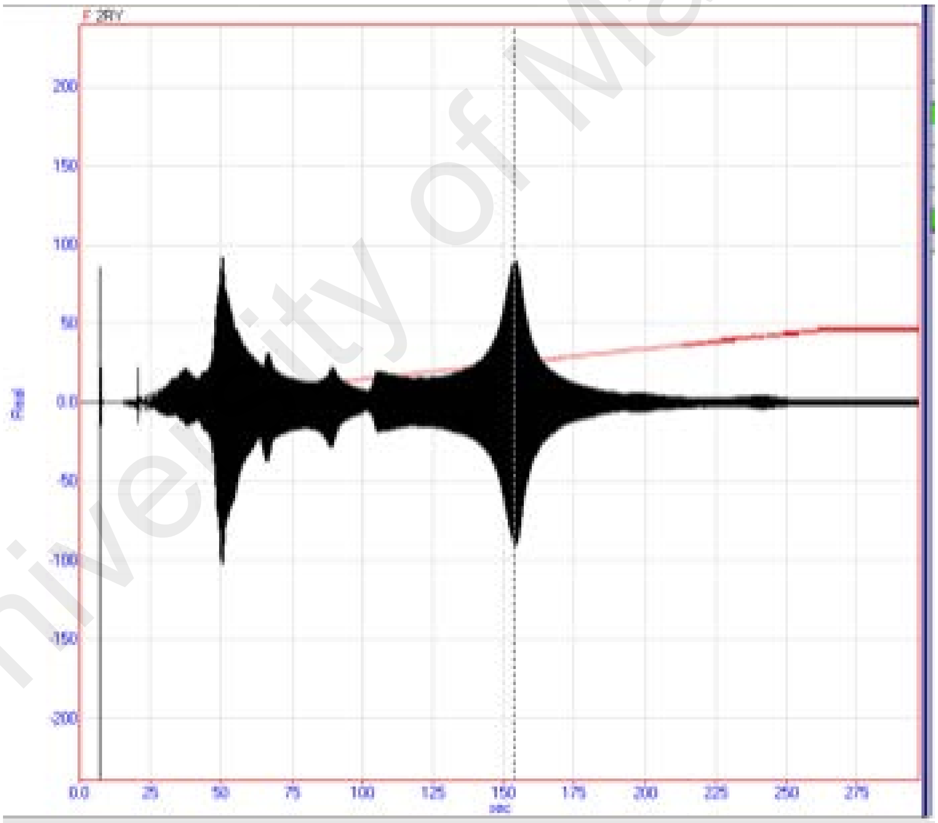


Figure 4.9 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity at Y-axis (the second high amplitude)

Figure 4.10 : Graph of Amplitude vs Time which shows an increasing rotational frequency where vertical cursor positioned at the highest peak of amplitude of angular velocity Y-axis (second high)

It is observed that the highest amplitude reach by the system at point 2 is around 50th second from the beginning of the rotation at approximately 5.5Hz (from the red incline line as shown in Figure 4.8). The second highest amplitude is on the 155th second at about 25 Hz. The next high amplitude observed at 8 and 12.55 Hz. Angular velocity Y-axis (2RY) shows a very significant signal of natural frequencies at 4 frequencies namely at 5.5Hz, 8Hz, 12.5Hz and 25Hz as shown in Figure 4.7 and Figure 4.9. Note that the vertical line is placed at the peak of the amplitude and the intersection of this line to red incline line is the frequency reading from tachometer. This point is the natural frequency obtained for point 2. Results of angular velocity Z axis shows quite obvious response as the same condition as point1 . This is due to the position of the IMU at point 2 has made the Z axis is at tangential direction of the disc. Refer to Figure 4.15. The angular velocity of Z axis is disturbed which noise in the signal due to the whirling effect of the disc which give a sign of whirling effect of the induction motor too. However the graph shown in acceleration data for X, Y and Z axis as well as angular velocity results of X axis are not likely to show significant signal to make a good conclusion. This is consistent with the prediction of the signal acquired as orientation of the IMU being position at point 2. Since the gyroscopic movement and force from the rotating induction motor transmitted to the three static disc, the gyroscopic effect can be obtained from the IMU angular velocity readings at points of test conducted. Below are the results of accelerometer X, Y and Z axis and gyroscope X and Z axis. Refer to Figure 4.11 to Figure 4.15.

Figure 4.11 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration at X-axis.

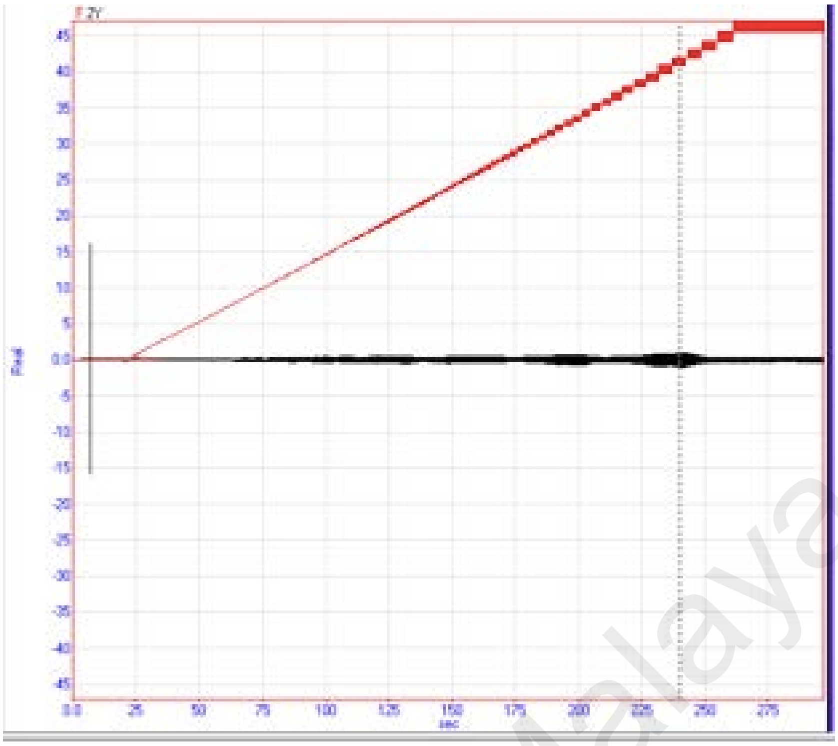


Figure 4.12 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration at Y-axis.

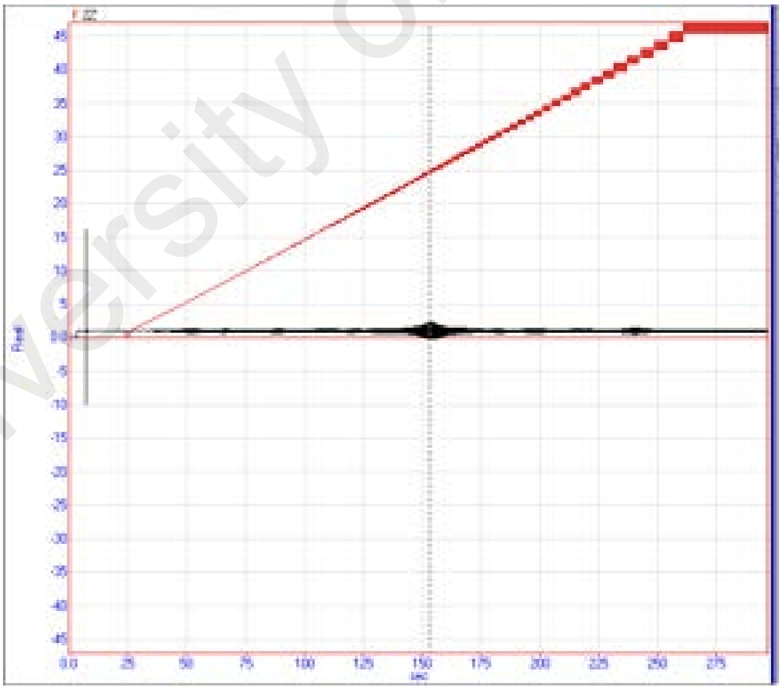


Figure 4.13 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration at Z-axis.

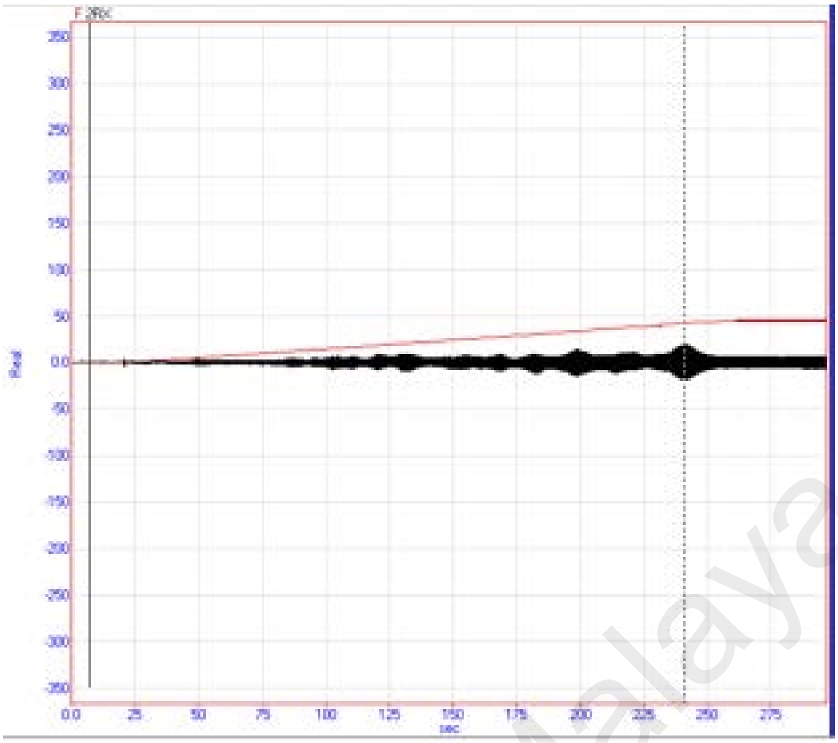


Figure 4.14 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity at X-axis.

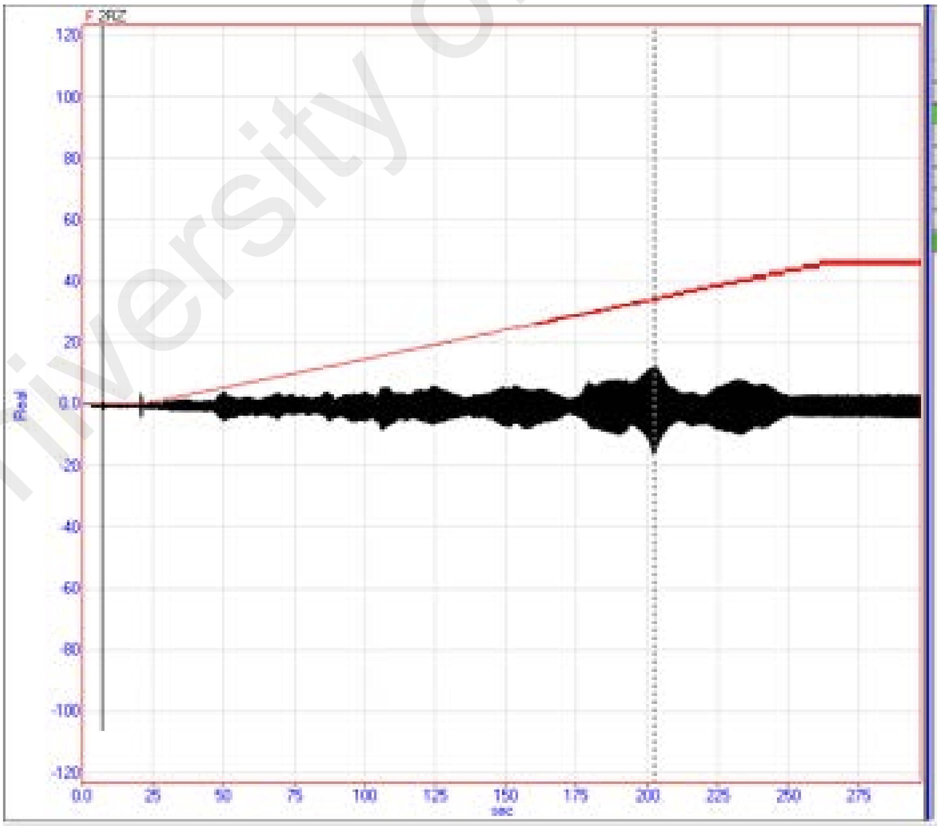


Figure 4.15 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity at Z-axis.

4.1.3 Point 3

Similar to point 1 and point 2, at this point the response signal for angular velocity Y axis gives a significant measurement results of high amplitude resonance at a few frequencies as shown in Figure 4.18. There are two peak response observed at 70th second and at 125th second at approximately at 4.5 Hz and 15 Hz. Another two slightly lower amplitude and quite significant response observed are at 7.5 Hz and 26 Hz. Due to the positioning of the IMU during testing, again it was predicted that gyro Y axis data shows a significant amplitude of response that can be seen in the plotted graph of Time vs Amplitude. ME'scope is used to also include the tachometer data which shows the rotation of the induction motor mechanically as there is an elapsed time issue between the NI DAQ 9234 and DASYlab 10. Figure 4.18 shows the peak response area (black area) where the induction motor reaches its resonance which might cause vibration in the system in this study.

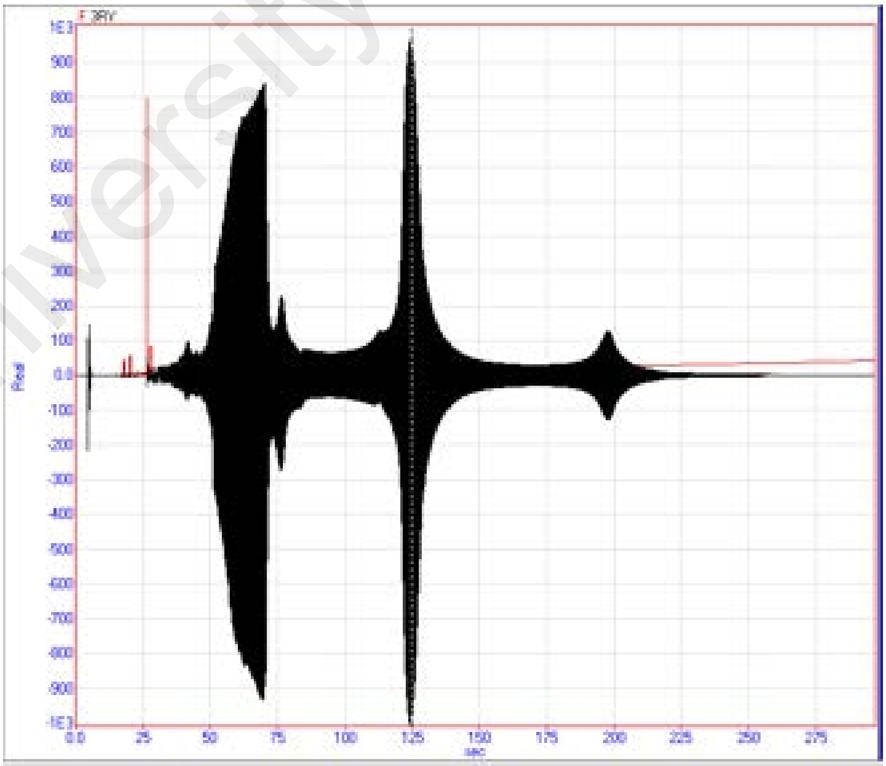


Figure 4.16 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity at Y-axis.

Note that there are disturbance reading of tachometer before the starting of the rotation of the induction motor. The tachometer reading before 30th second is the movement due hammer applied at point 3 during testing. However this disturbed data are not deleted or tampered as the important measurement data for observation is after the induction motor starts running from 0 Hz onwards. Results of angular velocity X and Z axis shows quite obvious response unlike point 1 and point 2 . This is due to the position of the IMU at point 3 at which this point is the end of the test rig set-up as shown in Figure 4.17.

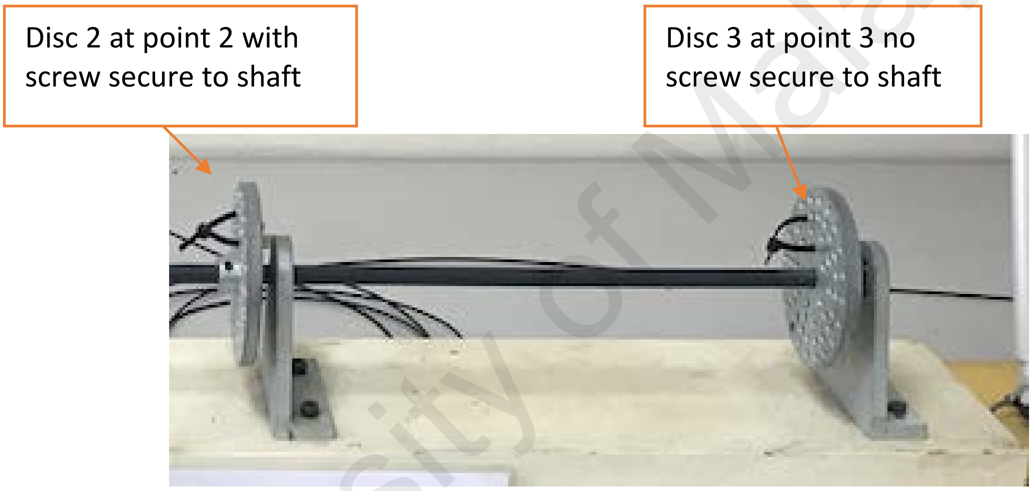


Figure 4.17 : Picture showing the disc 3 at point 3 mounting as compared to disc 2 at point 2.

There are no screw attached to the shaft as it makes this point may suffer more whirling effect than the other two points. This condition of the test rig has made the angular velocity of X and Z axis shows more significant signal than the other points. However the graph shown in acceleration data for X, Y and Z axis are not likely to show significant signal to make a good conclusion. This is consistent with the prediction of the signal acquired as orientation of the IMU being position at point 3 and the physical set-up of the test rig itself. Since the gyroscopic movement and force from the rotating induction motor transmitted to the three static disc, the gyroscopic effect can be obtained from the IMU angular velocity readings at points of test conducted. Below are the results of accelerometer X, Y and Z axis and gyroscope X and Z axis. Refer to Figure 4.18 to Figure 4.22.

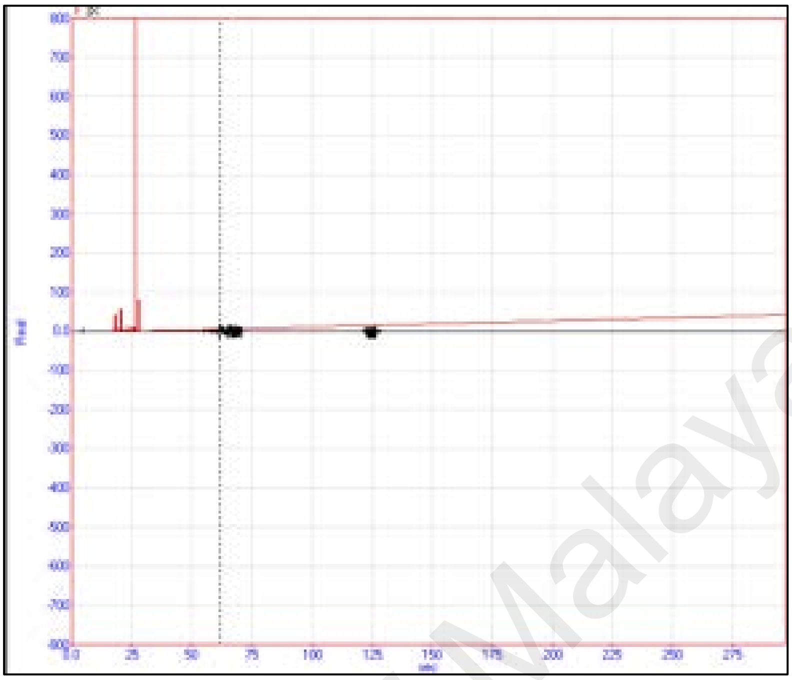


Figure 4.18 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration at X-axis.

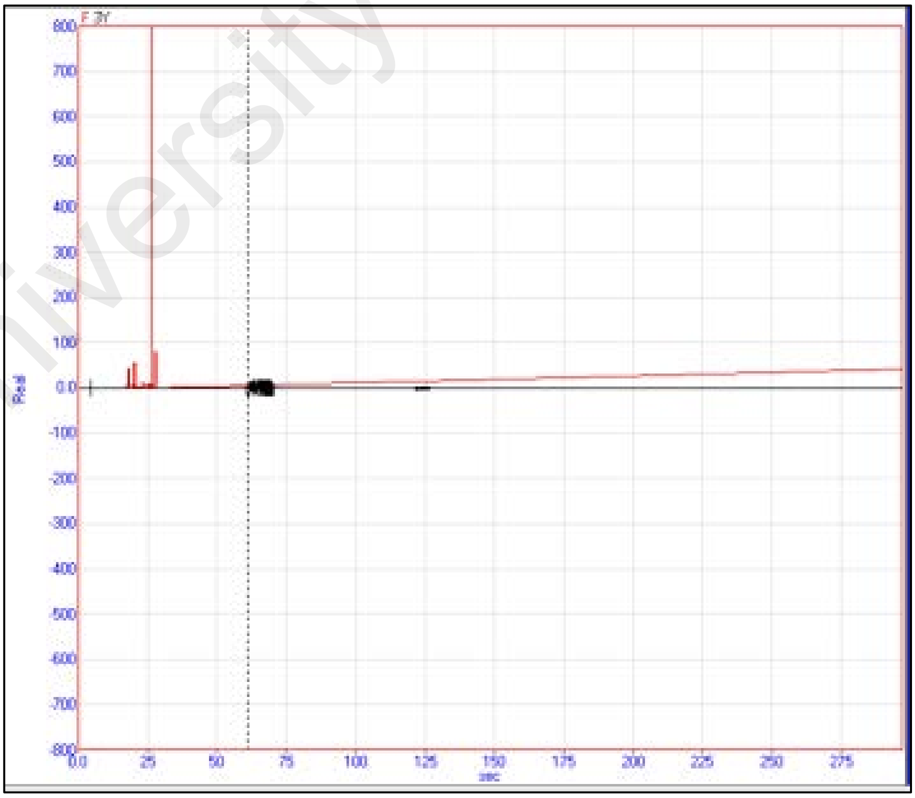


Figure 4.19 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration at Y-axis.

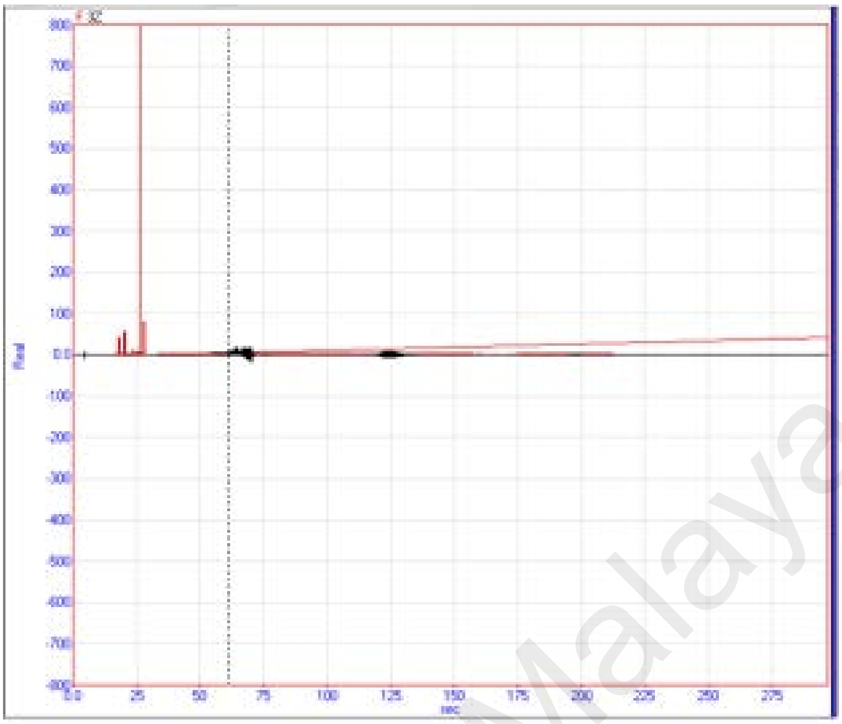


Figure 4.20 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding acceleration at Z-axis.

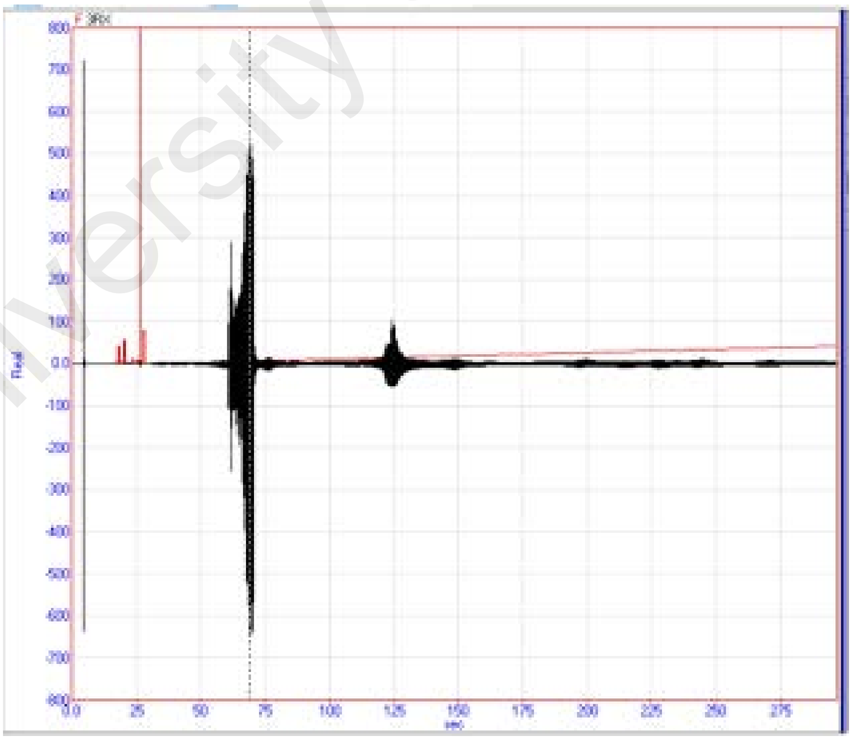


Figure 4.21 : Graph of Amplitude vs Time which shows an increasing rotational frequency and corresponding angular velocity at X-axis.

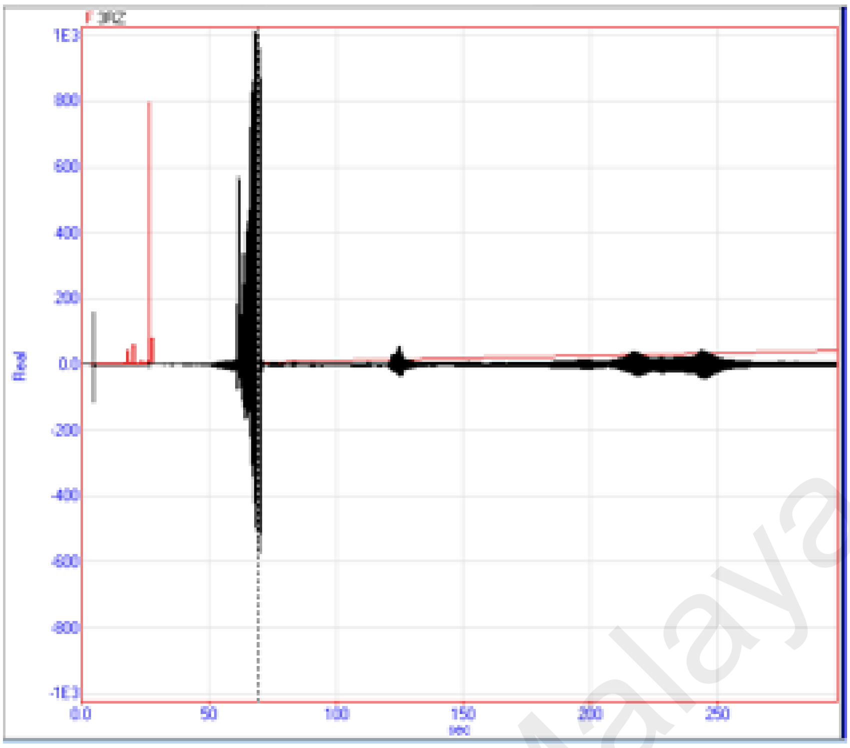


Figure 4.22 : Graph of Amplitude vs Time which shows a high amplitude resonance for angular velocity of Z axis.

4.1.4 Summary of the results of transient response test

Note that the position of the IMU at the disc is representing the type of data acquired from the IMU as been discussed previously. Since the disc in this experimental set up is a static rigid disc, the gyroscopic motion of rotational vibration is observed to be significantly high as the Gyro Y-axis of the IMU gives data on angular velocity of Y axis of all the three points. Angular velocity Z axis reading from the IMU shows some significant signal of resonance at or near the obtained natural frequency.

The results of the determination of natural frequencies of the systems are summarized in Table 4.2.

Table 4.2 : Summary of the results of run-up test in determining natural frequencies for Point 1, Point 2 and Point 3.

Point	Natural Frequency (Hz) (Mode shape 1)	Natural Frequency 2 (Hz) (Mode shape 2)	Natural Frequency 3 (Hz) (Mode shape 3)	Natural Frequency 4 (Hz) (Mode shape 4)
1.	5.5	8	15	26
2.	5.5	8	12.5	25
3.	4.5	7.5	15	26

From this summarized results of determining natural frequencies of the test rig system at, it can be concluded that all the three points have shown four patterns or modes at few frequencies. The results show that this particular system have at least four mode shapes. At 5.5 Hz rotation of induction motor, the system vibrates more at disc 1 and disc 2 but slightly less at disc 3. During transient response test, the difference in the movement of the three disc at 5.5 Hz rotation of induction motor could not be seen and not obvious as the natural frequency at mode shape 1 is quite close from one to another.

Similar problem observed for mode shape 2 and 4. In mode shape 3, point 2 at disc 2 seems to be the nodal point where at 15Hz running of induction motor disc 2 will not vibrate. During the simulation of the mode, at mode shape 3 animation is expected to give a significant difference between the movement of all the disc.

4.2 Results of the determination of mode shapes

In this study, the determination of mode shapes is only using the acquired data from IMU, perform delaying of data using DASYLab 10 and perform the animation in ME'scope VES through Time Domain Functions and Time-Based ODS Animation. (V. T. Inc, 2018).

In ME'scope VES a structure must be drawn first. In this study, three disc connected by a shaft is been drawn as shown in Figure 4.23.

Another important features that need to be performed in order to formulate the animation movement is the Measurement Equation that need to be assigned to each points of structure designed. An example shown in Figure 4.24. The measurement axes are from the ASCII data files that are imported as data block file as shown in Figure 4.25 in the upper right side of the window.

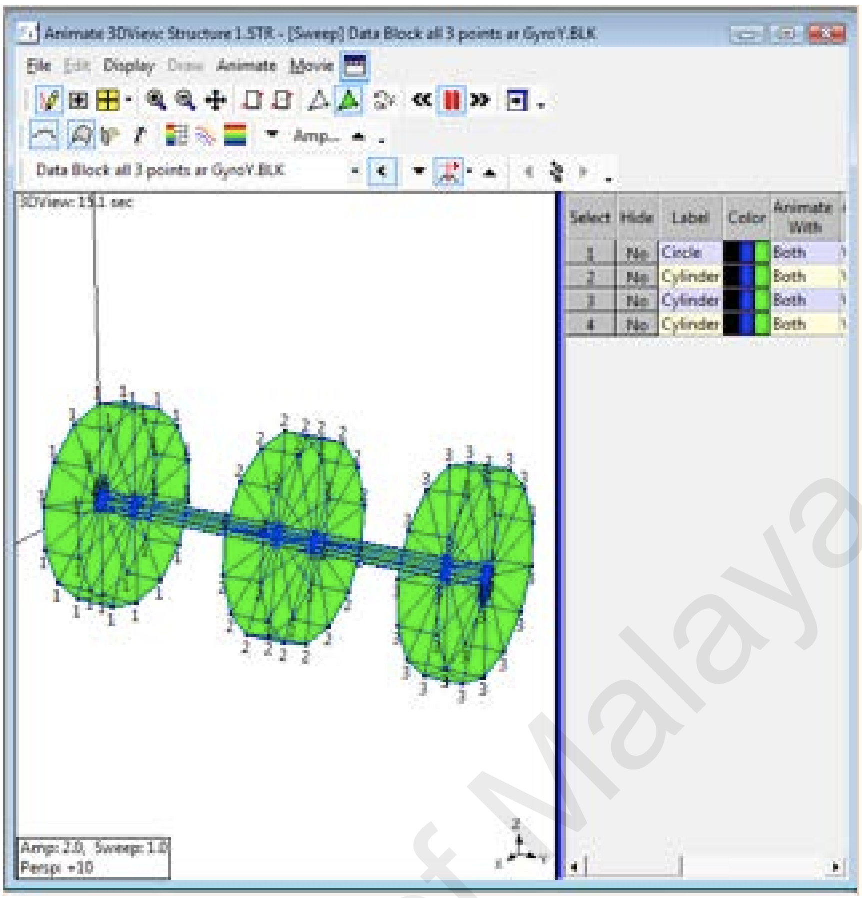


Figure 4.23 : Structure drawn to resembles the test rig.

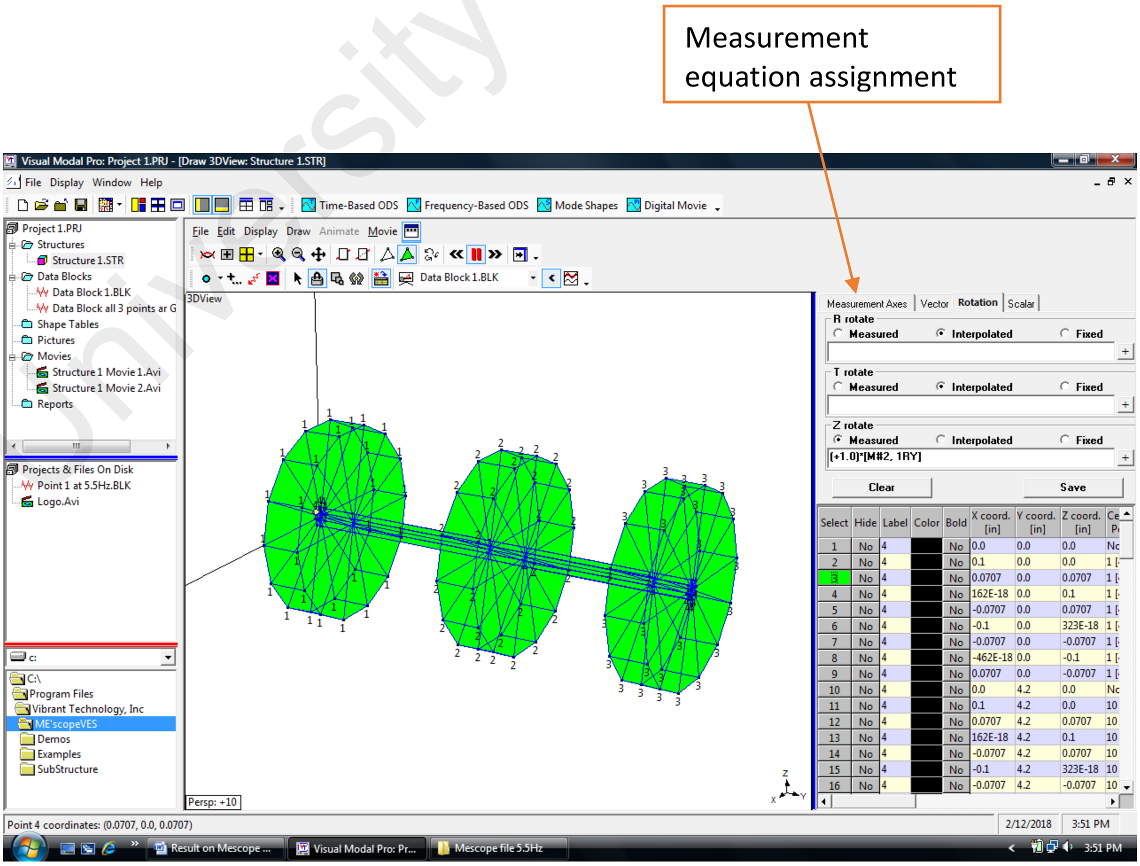


Figure 4.24 : Example of measurement axes and points of the structure assigned

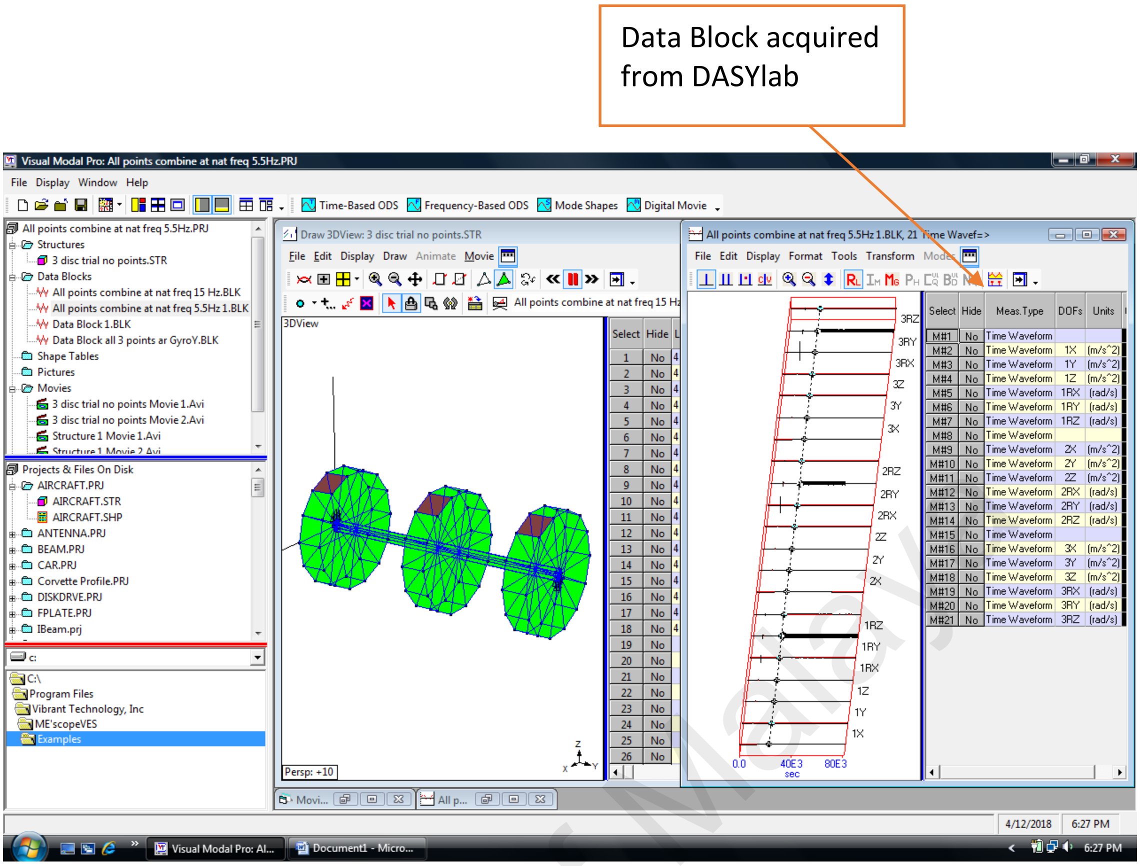


Figure 4.25 : Data block is the information of the movement of the animation.

In this study, the mode shapes are animated and simulated in ME'scope. The 3 disc structure are colored on the surface so that animated movement will be seen clearly. Attached are the screen shot of video capturing the movement of the three disc structure at natural frequency 5.5Hz as shown in Figure 4.26. It is observed that during the first 5 seconds (Figure 4.26 the upper right frame) disc 1 and disc 2 is moving to the same direction and disc 3 is moving to the opposite direction. This initial pattern of movement is consistent with the result of the run-up test where at 5.5 Hz , disc 3 is the nodal point.

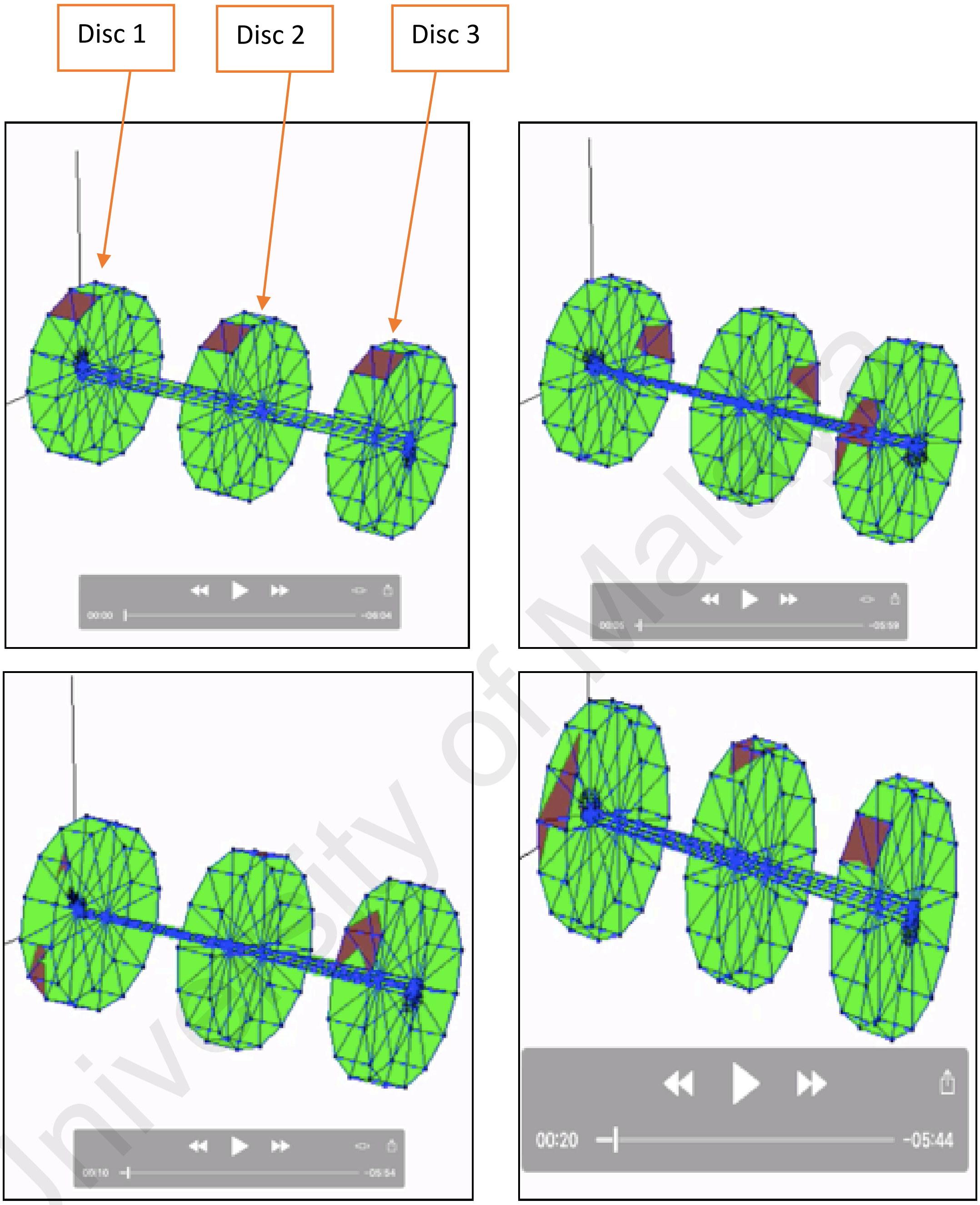


Figure 4.26 : Sequence of movement of the three disc animation at 0 sec (upper left), 5 sec (upper right), 10 sec (lower left) and 20 sec (lower right) at natural frequency 5.5Hz.

The second highest natural frequency are identified to be at 15Hz with different mode shapes as compared to the mode at 5.5Hz. It is observed that the movement of the disc 2 is slightly lesser that the other disc. Attached are the snap shot of the animation video capturing the movement of three disc structure at frequency 15Hz. Refer to Figure 4.27.

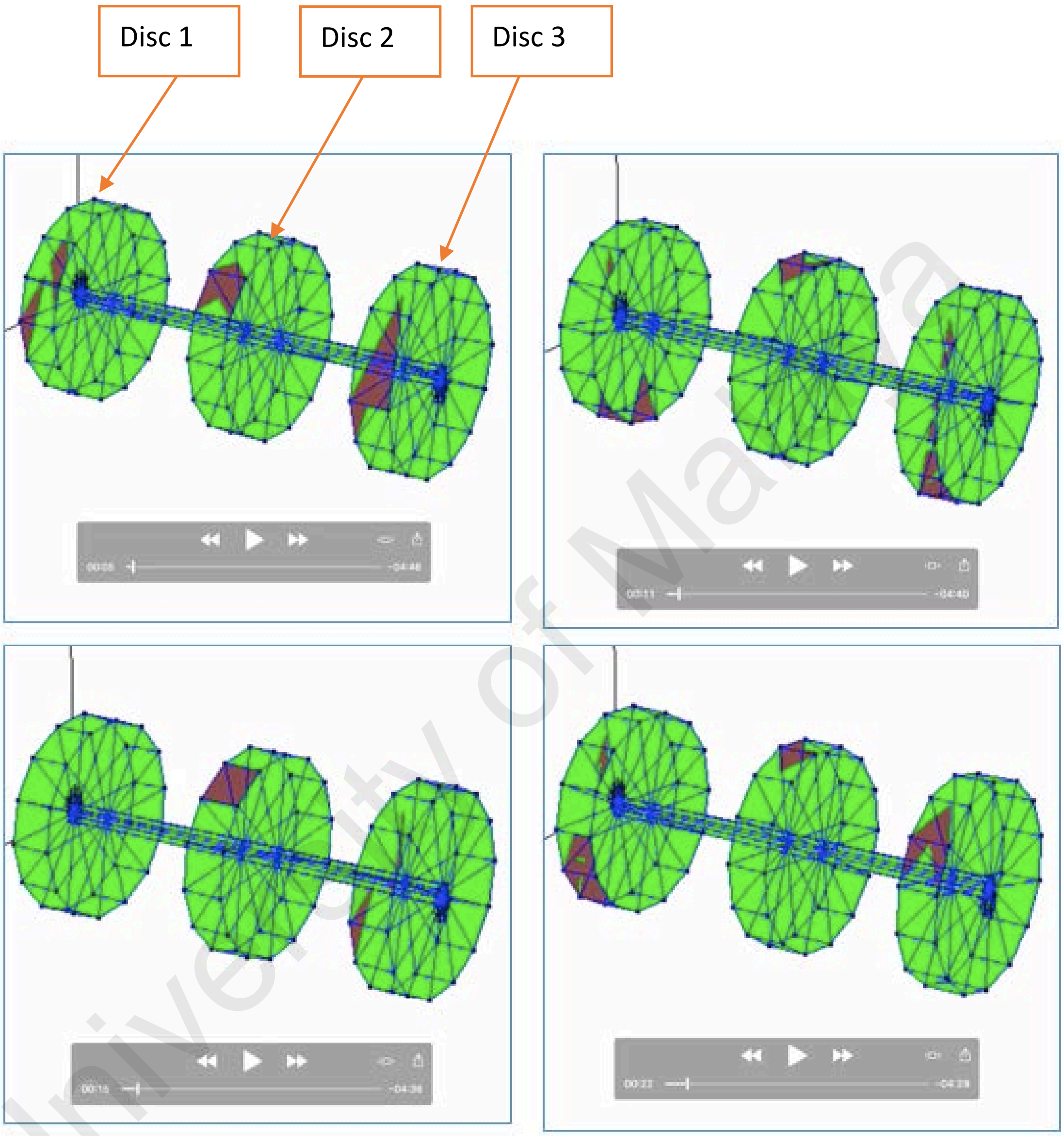


Figure 4.27 : Sequence of movement of the three disc animation at 5th sec (upper left), 11th sec (upper right), 15th sec (lower left) and 22nd sec (lower right) at natural frequency 15 Hz.

At any seconds, disc 2 undergo minimum movement as disk 2 is the nodal point at natural frequency 15Hz of the system.

In this research report, only two mode shapes are being shown and screen shot animated here for the purpose to prove either the data captured is correct and as in the real movement and situation of the experimental test rig.

4.3 Results of conventional modal analysis through impact hammer excitation

The raw data acquired from IMU in DASYlab is in the time domain. The measurement data is then transformed to frequency domain through FFT and later undergo FRF measurement. The FRF measurement data then being transfer to ME'scope for further analysis. Figure 4.28 shows 18 measurement data for all the three points of 6 DOF from IMU. The 18 measurement data are overlayed to perform curve fitting.

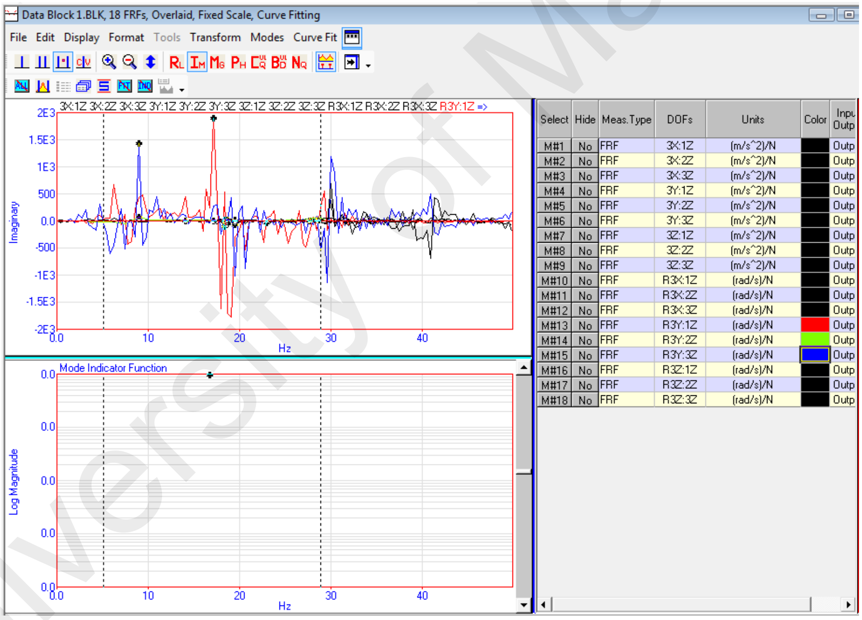


Figure 4.28 : 18 FRF data of the three points of IMU overlayed in ME'scope.

Simple curve fitting done in ME'scope to identify frequencies response that are at peaks during impact testing. Refer to Figure 4.29.

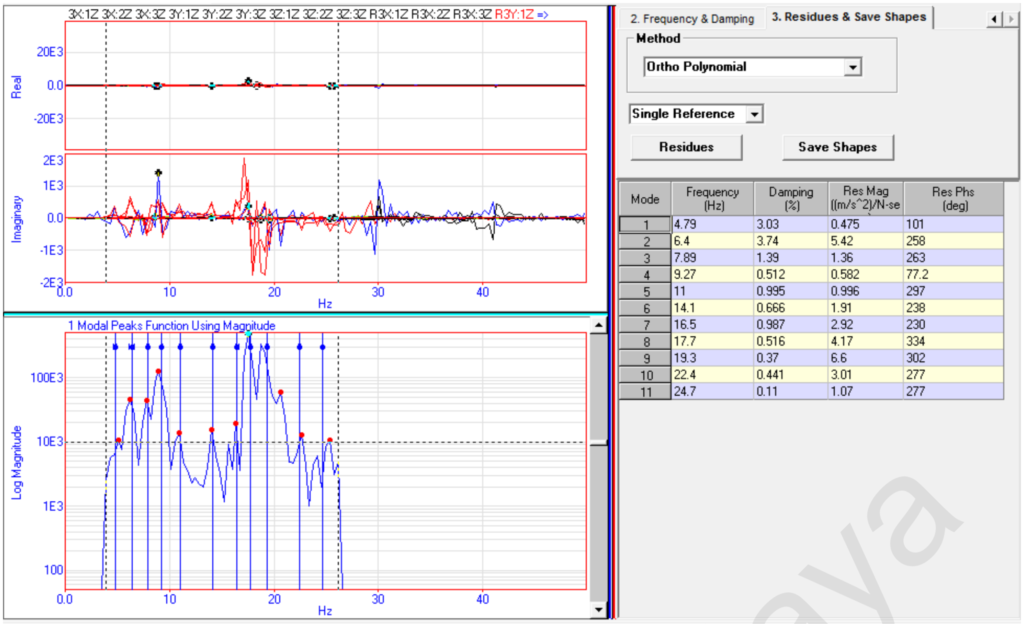


Figure 4.29 : Curve fitting and frequencies at peak identified.

The results shows as many as 11 modes as the 18 FRF data being overlayed together. The limitation of this method is, it is not possible to maintain such uniform excitation at every excitation input applied to the system and the enough energy of the force pulse by means of a hammer. However the hammer excitation method is fast and simple method. Unfortunately, since the energy of the force pulse is limited, the method has poor signal to noise characteristics (Prof. Bhirud Pankaj, 2016).

4.4 Conclusion of the results of determination of natural frequencies of the system

Natural frequencies determination from the run-up transient response analysis and impact excitation method are as in Table 4.3. From Figure 4.31 , there are more than 4 modes identified. As mentioned earlier, the poor signal to noise characteristics give the effect of the results of the curve fitting obtained. However, the lower damping percentage gives an indicator of resonance or near resonance at specified frequency. An average difference about ± 1 Hz difference at each natural frequency identified

Table 4.3 : Summary of results of natural frequency

Modes	Natural frequency (Hz)		Average difference (Hz)
	Run-up transient response analysis	Impact excitation method	
	5.5	4.8 6.4	±1
2	8.0	7.9 9.3	+1
3	15	14.1 16.5	±1
4	26	24.7	-1

CHAPTER 5 : CONCLUSION

The run-up test on the test rig has been performed and the signal data acquired has been processed. The results have shown a significant clear signal showing the natural frequencies of the test rig system depending on the orientation of the IMU being placed at the disc. In this study it is obviously shown that Gyro Y-axis gives the most significant signals and data showing the frequencies that gives the highest amplitude of resonance. The IMU are presented to be able to be used to determine the natural frequencies of any system provided that there are a reliable and compatible software to acquire and process the data. It is also depending on what type of data needs to be obtained from the study.

The determination of mode shapes at the natural frequencies are shown through animation in ME'scope VES 5. The animation has shown the movement of the three disc as happened in the real situation except for the intense of the magnitude could not be verified and beyond this study. However, in this paper the snap shot of a few movement of the disc at 5th, 10th and 15^{th} second shows the mode shapes of the system at frequency 5.5Hz and 15Hz.

The results obtained from impact excitation method has not given a good signal due to poor signal as the three disc situated for a distance from each other and the energy of the force applied might not be enough to excite the natural frequency properly.

There are several limitations and constraint to the instrumentation and software involved in this study. It is observed that the time synchronization and the accuracy of the frequency set at the inverter of the induction motor is the main issue and need to verified if any similar study is to be conducted. The ability to understand and get used to the software involves are depending on the student performing this study and will subsequently effect the results obtained.

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