CHARACTERIZATION OF THE PIEZOELECTRIC PATCH SENSOR AND ACTUATOR

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DECLARATION

I hereby declare that the work reported in this thesis is the result of my own investigation and that no part of the thesis has been plagiarized from external sources. Materials taken from other sources are duly acknowledgements by giving explicit references.

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LIST OF ABBREVIATIONS

Symbols	Descriptions
AVC	Active Vibration Control
DAQ	Data Acquisition
EM	Electromagnetic
EMA	Experimental modal analysis
FFT	Fast Fourier Transform
FRF	Frequency response function
MAV	Micro Aerial Vehicle
NI	National Instruments
PID	Proportional, Integral, Derivative
PZT	Lead Zirconate Titanate
SHM	Structural Health Monitoring

ABSTRAK

Kajian ini membentangkan pencirian penampal piezoelektrik sebagai pengesan dan penggerak dan juga penggunaan dalam sistem aktif kawalan getaran (AVC). Penampal piezoelektrik adalah komponen serba boleh kerana dwi-fungsinya yang boleh digunakan sebagai pengesan dan penggerak dan ia sepadan dengan penukaran tenaga mekanikal dan elektrik. Kajian ini mengambil kira struktur rasuk dan keputusan EMA menunjukkan bahawa, terdapat empat frekuensi tabii rasuk yang berlaku pada 30.4 Hz, 227.9 Hz, 709.9 Hz dan 923.9 Hz. Untuk pencirian penggerak penampal piezoelektrik, pecutan rasuk tertinggi 315.08 m/s^2 dicapai pada frekuensi operasi 200 Hz dengan 500 V disebabkan oleh kesan frekuensi semula jadi kedua (227.9 Hz) rasuk. Kesan tepu mula berlaku pada kekerapan operasi 300 Hz dengan 300 V voltan input. Penampal piezoelektrik terus menunjukkan kesan tepu dalam frekuensi operasi 300 Hz hingga 500 Hz dengan voltan input 300 V 500 V. Hasil kajian juga menunjukkan bahawa, kesan bukan-kelinearan seperti histerisis, rayapan dan kesan getaran semakin buruk jika frekuensi operasi dan voltan mulai meningkat melebihi 200 Hz dengan 200 V untuk penggerak. Dari segi pengesan penampal piezoelektrik, voltan output tertinggi disebabkan oleh penampal adalah 4.43 V pada frekuensi operasi 200 Hz dengan 500 V yang disebabkan oleh frekuensi resonans rasuk. Walau bagaimanapun, penampal piezoelektrik tidak mengalami apa-apa kesan tepu dalam 100 Hz hingga 500 Hz dengan 100 V hingga 500 V dan ini sepadan dengan FRF rasuk aluminium. Pengesan penampal piezoelektrik berkesan pada frekuensi 100 Hz dan 200 Hz kerana kesan bukan-kelinearan (histerisis, rayapan dan kesan getaran) berkurangan. Semakin tinggi frekuensi, kesan bukan-kelinearan menjadi ketara dan mengakibatkan pembentukan histerisis yang besar. Kajian ini juga termasuk penggunaan penggerak penampal piezoelektrik untuk sistem AVC. Hasilnya menunjukkan patch ini mampu untuk mengurangkan getaran sehingga 42% pada frekuensi 100 Hz dengan 100 V. Walau bagaimanapun, peratusan pengurangan pecutan berkurangan apabila voltan operasi semakin tinggi.

ABSTRACT

The study presents the characterization of the piezoelectric patch as a sensor and actuator and its application for the active vibration control (AVC) system. Piezoelectric patch is a versatile component due to its dual-functionality which can be used as sensor and actuator and it corresponds to the mechanical and electrical energy conversion. This study consider the beam structure and the EMA result shows that, there are four natural frequencies of the beam which occurred at 30.4 Hz, 227.9 Hz, 709.9 Hz and 923.9 Hz. For the characterization of the piezoelectric patch actuator, the highest beam acceleration of 315.08 m/s^2 is achieved at operating frequency of 200 Hz with 500 V due to the effect of second natural frequency (227.9 Hz) of the beam. The saturation effect starts to occur at the operating frequency of 300 Hz with 300 V of input voltage. The piezoelectric patch continues to saturate within operating frequencies of 300 Hz to 500 Hz with the input voltages of 300 V to 500 V. The result also shows that, the non-linearity effects such as hysteresis, creep and vibrational effects are getting worse, as the operating frequencies and voltages increase above 200 Hz with 200 V for the actuator. In term of piezoelectric patch sensor, the highest output voltage induced by the patch is 4.43 V at operating frequency of 200 Hz with 500 V which is caused by the resonance frequency of the beam. However, the piezoelectric patch does not experience any saturation effect within 100 Hz to 500 Hz with 100 V to 500 V and this corresponds to the FRF of the aluminium beam. The piezoelectric patch sensor is effective at frequency of 100 Hz and 200 Hz due to less non-linearity effects (hysteresis, creep and vibrational effects). As the frequency gets higher, the effects becomes significant and resulting large hysteresis formation. This study also includes the application of the piezoelectric patch actuator for AVC system. The result shows the patch is capable to reduce the vibration up to 42 % at frequency of 100 Hz with 100 V. However, the percentage of acceleration reduction decreases as the operating voltage is getting higher.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter includes background study, objectives, problem statement, scope of the project and the thesis outline.

1.2 Background study

Piezoelectricity is one of the greatest discoveries in engineering world especially in mechanical and electrical fields. Initially, the piezoelectric effect was discovered during the studies on the effect of pressure on the generation of electrical charge by Jacques and Pierre Curie back in 1880 (Garimella et al., 2015). Since then, plenty of applications and devices have been created based on the piezoelectric effect and most of them are sensors and actuators. Piezoelectricity is the accretion of electric charge in a certain material corresponding to applied mechanical force or stress. Generally, when mechanical energy is being applied on an area, electrical energy is generated. This phenomenon is called direct piezoelectric effect whereas indirect piezoelectric effect is vice-versa of this occurrence. For direct piezoelectric effect, the mechanical energy is treated as input energy and electrical energy is the output energy. The input energy can be in the form of stress or strain whereas the output energy is in the form of surface charge density, electric field or electric voltage (Vijaya, 2012). In contrast, the indirect piezoelectric effect is opposite from the early effect which the electrical energy serves as the input energy while the mechanical energy is the output energy.

Piezoelectric devices are mostly utilised as either actuator, sensor or combination of both. For example, piezoelectric sensor has been effectively deployed as impact detector, early-age strength monitoring and building health monitoring system due to its reasonable cost, flexibility in shapes, fast response and simplicity for implementation (Chen et al., 2016). Other than that, it also has been used as actuator and applied as a synthetic jet actuator for flow control, generation of micro-thrust for propulsion and attitude control of Micro Aerial Vehicle (MAV) (de Luca et al., 2016). A method has been developed which uses piezoelectric material as sensor and actuator simultaneously and is known as Active Vibration Control (AVC). This method involves closed loop system and widely used in vibration control of flexible structures (Yavuz et al., 2016). Other than that, many researchers and manufacturers have foreseen the bright future of piezoelectric materials in energy harvesting. For example, motion energy harvesting devices are commercially developed by several companies to store small amount energy and just enough to power small electronic gadgets (Patel and Dewangan, 2015). However, typical piezoelectric materials exhibit hysteresis, creep, saturation and temperature dependence behaviour (Stefanski et al., 2016) and these factors should be included in careful considerations in order to avoid undesirable results.

Previously, a research has been done to study the AVC system which included the characterization of piezoelectric stack actuator and its application for an active suspended handle (Mazlan, 2016). For this project, piezoelectric patch is the main component that is used to be characterized as an actuator and sensor by considering the effect of hysteresis, saturation creep and vibration. An aluminium beam is used as a structure with piezoelectric patch attached on it and the application of the piezoelectric patch as an actuator for the AVC system is investigated.

1.3 Problem statement

Piezoelectric patch is one type of piezoelectric materials. Several studies have been made based on this material to determine its capabilities especially in vibration suppressing via sensing and actuating. Many micro positioning units nowadays utilise piezoelectric patches in precision-based operations due to its high positioning accuracy and displacement (Milecki and Pelic, 2016). However, piezoelectric materials exhibit non-linearity such as hysteresis and the occurrence can be detected when the same value of measurand is measured and the output readings are differently produced when the measurand is measured increasingly and decreasingly (Wheeler and Ganji, 2010). This non-linear effect degrades accuracy in open loop system and complicates the tuning for closed loop system (Stefanski et al., 2016).

In this study, the piezoelectric patch will be analysed in two different ways which is sensor and actuator. Voltage and frequency will be the main parameters to determine the characteristics of the piezoelectric patch actuator. The large range of voltage along with high level of frequency will lead to the non–linear hysteresis, creep, vibration and saturation effects. The results will be tabulated and compared between the input and output parameters to observe the characteristics of the piezoelectric patch along with the non-linearity effects such as hysteresis, creep, vibration and saturation. In addition, an AVC system will be developed using the piezoelectric patch actuator to attenuate the vibration of the flexible structure.

1.4 Objectives

In this research, three objectives are set to be achieved:

1. To characterize the dynamic behaviour of the beam structure using an experimental modal analysis (EMA).
2. To characterize the piezoelectric patch in two separate manners which is sensor and actuator.
3. To apply the piezoelectric patch actuator for the AVC system.

1.5 Scope of the project

Focal point of this project is the characterization of the beam structure using EMA, characterization of piezoelectric patch as sensor and actuator and application of the piezoelectric actuator for the AVC system. EMA of the beam is an essential step to determine the mode shapes and natural frequencies of the beam. For simplicity, a data-acquisition system will be used for this measurement.

The hypothesis of the project is that, the piezoelectric patch sensor characteristics will not be identical with the characteristics of the piezoelectric patch actuator in term of voltage and frequency response. For piezoelectric patch actuator, voltage and frequency will be the main input parameters to create sine wave signal. These parameters are crucial to control and the goal is to determine the range of voltage and frequency that cause the non-linearity effects such as hysteresis, creep, vibration and saturation by measuring the acceleration of the beam.

For the piezoelectric patch sensor, it is attached on the beam and excited by shaker. Voltage and frequency are used as input parameters. These parameters will be applied to the shaker and the voltage produced by the piezoelectric patch will be measured along with the acceleration of the beam. The behaviour of non-linearity effects will be observed in order to compare the behaviour of piezoelectric patch as sensor and actuator.

1.6 Thesis outline

The thesis of this project is divided into five chapters which comprises:

- **Chapter 1 (Introduction)**, explains about the background study of the project, the objectives that need to be achieved, the problem statement of the project and thesis outline.
- **Chapter 2 (Literature Review)**, presents the literatures regarding the piezoelectric material, the behaviour of piezoelectric material with consideration to the hysteresis, creep, vibration and saturation effects and the application of piezoelectric material in the AVC.
- **Chapter 3 (Methodology)**, focuses on the EMA of the beam, the piezoelectric patch characterization and application of the piezoelectric patch sensor for the AVC system.
- **Chapter 4 (Results and discussion)**, presents the results of the piezoelectric patch characteristics and the modal analysis of the beam includes the mode shape and the natural frequencies. A thorough discussion is made relating the behaviour of the piezoelectric patch with the hysteresis, creep, saturation and vibration effects and how it effects the overall performance of the material in engineering applications.
- **Chapter 5 (Conclusion)**, summarizes the outcomes of the project and the recommendation of the possible future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter presents the piezoelectric materials, non-linear effects of piezoelectric materials and the AVC application using the piezoelectric patch material.

2.2 Piezoelectric material

Most of the devices that based on the piezoelectric effect are originated from the ferroelectric materials. Ferro-electricity is a property of certain materials that have a spontaneous controllable electric polarization (Kirova and Brazovskii, 2016). Good piezoelectric effect can be obtained from these materials which able to deliver high efficiency of electromechanical transformation of energy (Wersing et al., 2008). The electromechanical transformation of the piezoelectric material can be shown as following equations (Takács and Rohal'-Ilkiv, 2012):

$$\theta = C_E S - e_p E_e \tag{2.1}$$

$$D_e = e_p^T S + E_S E_e \tag{2.2}$$

where,

θ = stress

C_E = stiffness coeffiecient under constant electric field

S = strain

e_p = piezoelectric coupling coefficient

E_e = electric field strength

D_e = electric displacement

E_s = electric permitivity matrix under constant strain

T = matrix transformation

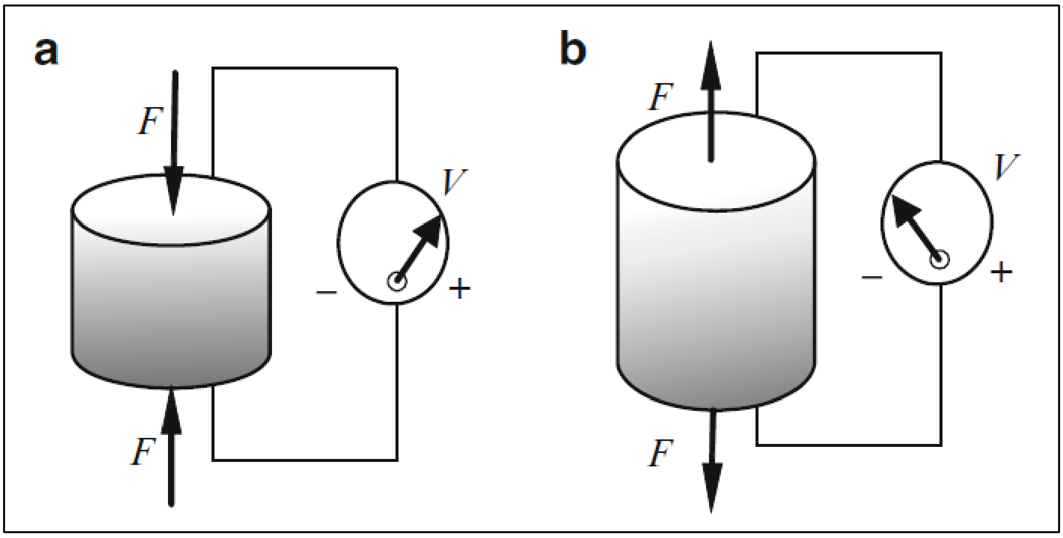


Figure 2.1: Piezoelectric effect in axial configuration (Jalili, 2009).

Figure 2.1 shows the concept of electromechanical energy transformation of the piezoelectric material. From this figure, the compressive force will produce positive voltage magnitude while tensile load causes negative voltage magnitude. For the actuating of piezoelectric material (patch-type), the displacement of the material depends on the polarity, as shown in Figure 2.2. The piezoelectric material which in the form of film is sandwiched between two electrodes. The coupling between the electrical and mechanical fiels causes the patch to bend upward if positive voltage is supplied and vice versa.

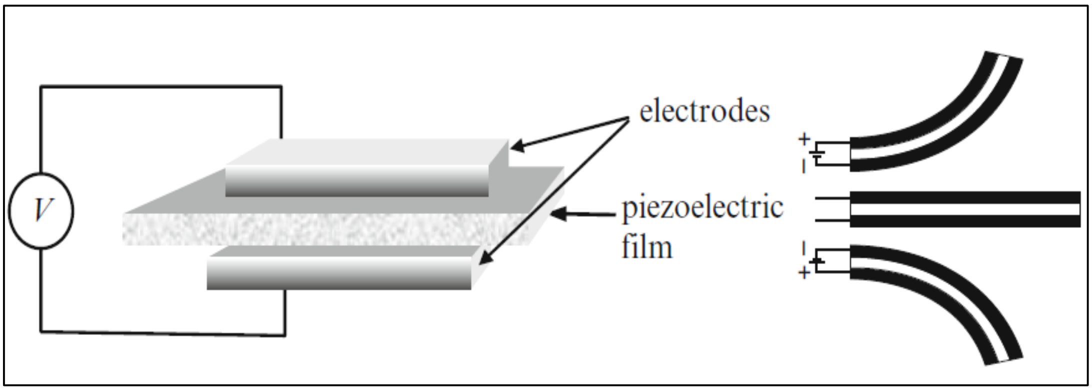


Figure 2.2: Piezoelectric effect for patch-type piezoelectric material (Jalili, 2009)

Lead Zirconate Titanate (PZT) is a smart material that has piezoelectric effect. PZT transducer is widely utilised mostly as damage indicator in structural health monitoring (SHM) system which can produce electric charges when subjected to strain energy and conversely generates strain energy when electric field is supplied (Chalioris et al., 2016). Other than that, piezoelectric sensor is known as pressure sensing device compared to capacitive and piezo-resistive sensors due to its advantages of self-powering and fast response of highly dynamic load (Liang and Wang, 2015). In most teleoperation where the master and slave robots interact to each other via specific channels, piezoelectric materials are widely used as manipulators in micro-macro manipulation applications (Amini et al., 2016).

2.3 Non-linear effects (hysteresis, creep, saturation and vibration) of piezoelectric materials

Although piezoelectric material is extensively used as actuator and sensor for many applications, hysteresis, creep, vibration and saturation are the non-linear inherent characteristics which give the disadvantages for the material. Hysteresis is described as a dynamic lag between the input and output and it is typically assumed to be rate-independent. Previous studies showed that hysteresis contributes as much as 15% of tracking error to total displacement range (Leang and Devasia, 2006). Figure 2.3 shows an example of a typical ferroelectric hysteresis loop. From the figure, the output values yield different patterns from the input, when it was measured increasingly and decreasingly for the same range.

Besides hysteresis, creep behaviour is also one of the challenges when using the piezoelectric material. Basically, creep will cause the location of piezoelectric material to slowly drift over long period and this is probably due to dipoles in the material that are not currently aligned with the electric field (Orszulik and Shan, 2017). There is a study that proposed an alternative method to cope with the hysteresis and creep problems in a piezoelectric stack actuator. The method comprises a set of mathematical models that describing the hysteresis and creep phenomenon and the inverse control loop is developed to reduce these effects. The result shows a reduction in tracking error caused by hysteresis and creep from 17% to less than 2% (Changhai and Lining, 2005).

Saturation is one of the non-linear characteristics of the piezoelectric material which defined as an unchanged output state when reached certain range of input value (Mazlan, 2016). The parameters that can achieve saturation in piezoelectric material are voltage, force and displacement (Mazlan and Ripin, 2015). Dynamic vibration is also affecting the accuracy of positioning precision in the piezoelectric materials

(Leang and Devasia, 2007). This effect degrades the accuracy in which the frequency of the piezoelectric materials is almost similar to the system first resonance frequency (Clayton et al., 2006). The vibration can be compensated either by changing the shape of input signal (Rakotondrabe et al., 2008) or using an inversion based feedback approach (Leang and Devasia, 2002).

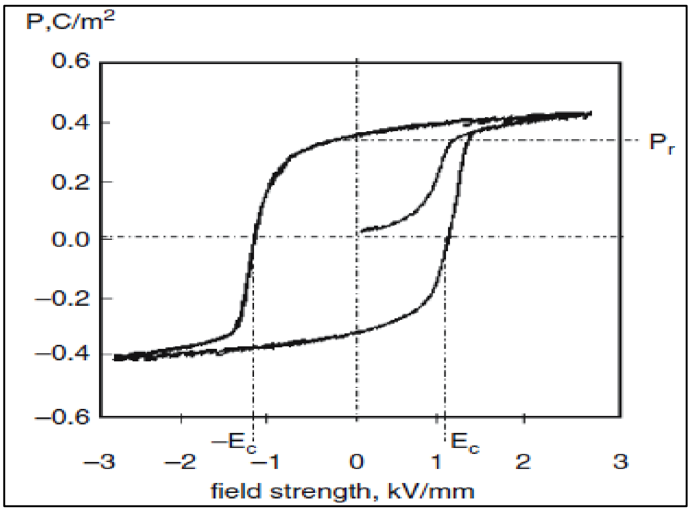


Figure 2.3: The ferroelectric hysteresis loop (Helke and Lubitz, 2008)

2.4 AVC applications using piezoelectric patch

AVC is a system that reduces vibration of structures using the theory of superposition whereby the system generates a counter-signal to cancel out the signal from the sources (Rahman and Darus, 2011). An experiment has been done to demonstrate AVC for smart structure by using PZT patch whereby three patches are attached on a beam as shown in Figure 2.4. From this figure, the patch sensor is placed near the vibrator to measure the structure’s vibration, middle patch sensor is used to detect overall vibration along the beam and patch actuator is attached at the end of the beam to attenuate the vibration (Heganna and Joglekar, 2016).

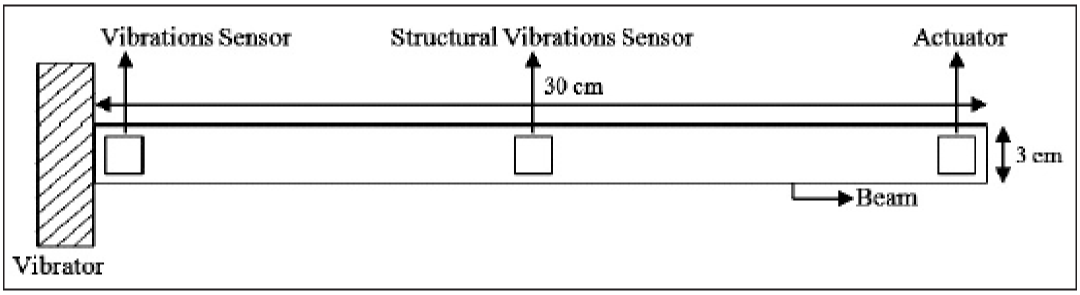


Figure 2.4: The configuration of the smart structure with AVC (Heganna and Joglekar, 2016)

2.5 Summary

Based on the literatures that related to the piezoelectric materials, several factors and characteristics are crucial and needed to put into careful consideration. This research will determine:

1. The hysteresis effect on the piezoelectric patch. This effect will be determined by experimental data with different input frequencies and voltages.
2. The saturation in the piezoelectric materials which could limit the overall performance when it reaches certain range of input value. This effect on the piezoelectric patch will be shown in the experimental data and the saturation point are going to be determined for each individual frequencies and voltages.
3. Creep behaviour in the piezoelectric patch. The minor drift which defines the effect will be closely determined in this project.
4. The vibration effect of the piezoelectric material for certain excitation frequency and amplitudes.
5. The AVC application using the piezoelectric patch. The application involves the use of piezoelectric patch actuator which to counter the vibration from an external source on a beam structure.

CHAPTER 3

METHODOLOGY

3.1 Overview

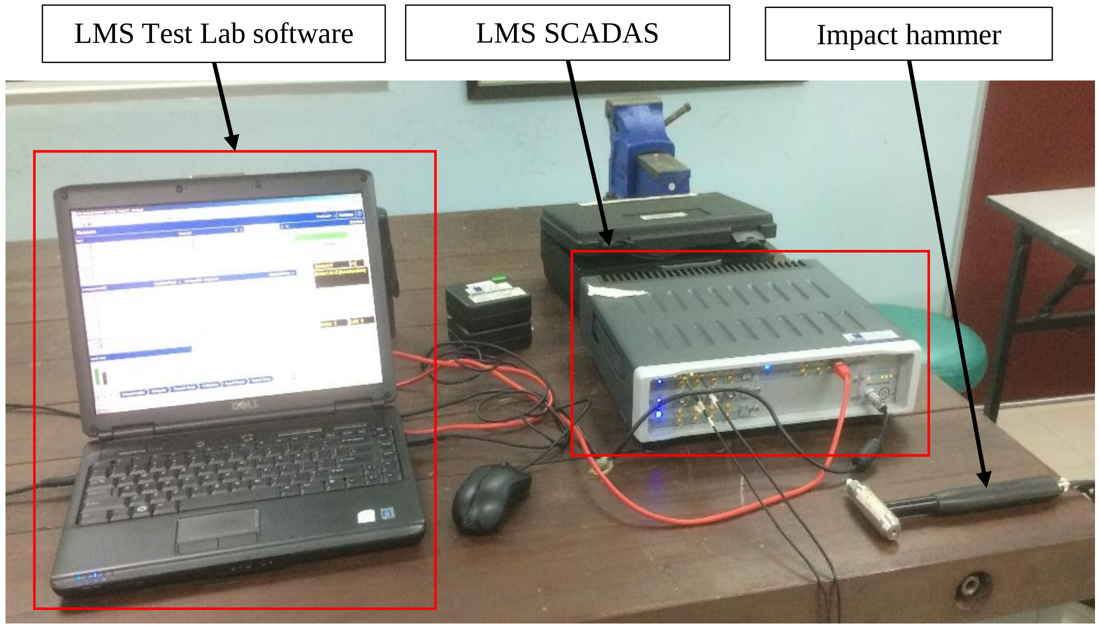
This chapter describes the experimental modal analysis of the beam, piezoelectric patch actuator and sensor characterization and the application of the piezoelectric patch actuator in AVC system. This chapter also comprises the overall experimental setup and LabVIEW diagram development.

3.2 Experimental modal analysis (EMA)

In order to study the dynamic characteristics between piezoelectric patch material and the aluminium beam, an EMA was carried out to determine the natural frequencies and the mode shapes of the beam. The instrumentation used included LMS Test Lab software, LMS SCADAS, impact hammer (Kistler model 9724A5000) and accelerometer (Dytran model 3224A2).

Figure 3.1(a) shows the instrumentation used for the EMA. The LMS Test Lab software was used to construct the geometry of the aluminium beam which has 40 mm width and 180 mm length. The construction of the beam used coordinate-based method in which eight points are assigned and numbered accordingly on the beam, as shown in Figure 3.1(b). Four points were allocated for both right and left sides of the beam and the distance between each point was 45 mm. The rest of the beam length used to attach on the table. In Figure 3.1(b), an accelerometer was used to measure the acceleration of the beam and attached at point 7 which also set as a reference point.

For the EMA of the beam, LMS SCADAS was used along with the impact hammer to measure the natural frequencies and the mode shapes. The experiment is carried out by hitting the impact hammer (input force) on the beam and the hitting process was continued by following the sequence of the point numbers on the beam. Then, the software will automatically calculated and generated the natural frequencies, mode shapes and frequency response function (FRF) graph of the aluminium beam.



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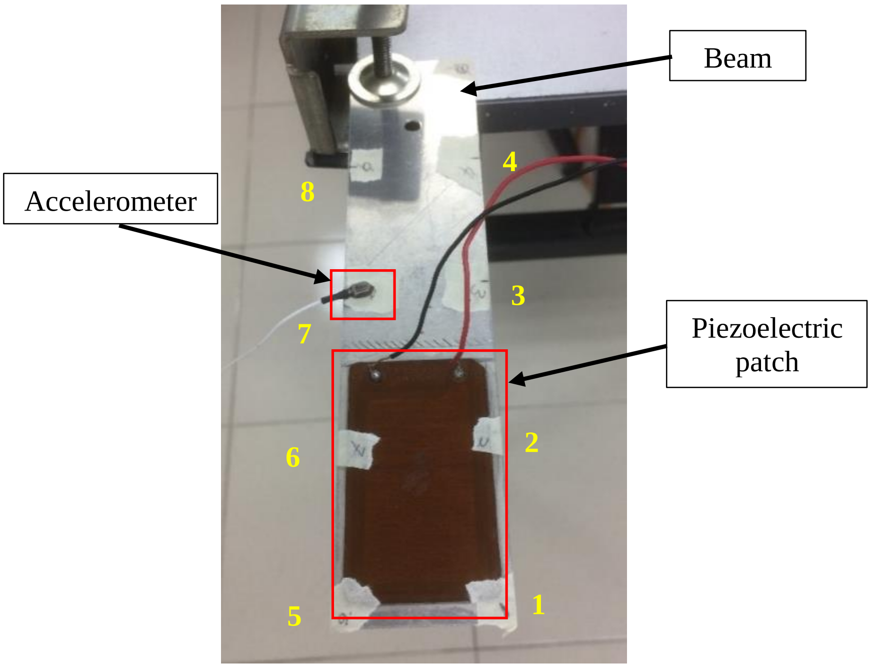


(b)

Figure 3.1: (a) EMA setup and (b) The aluminium beam setup

3.3 Piezoelectric patch actuator characterization

In this section, the piezoelectric patch will be characterized as an actuator. The piezoelectric patch was mounted on the aluminium beam and input voltage was supplied to generate the piezoelectric patch

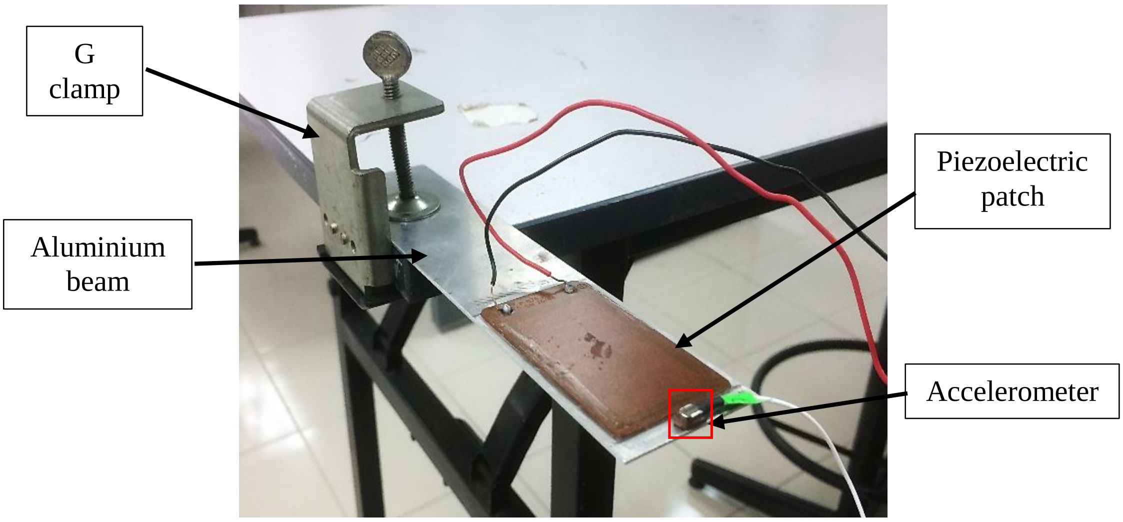
3.3.1 Experimental setup

In this experiment, the piezoelectric patch type Physik Instrumente DurAct Patch Transducer (P-876.A15) was used and the specifications of the piezoelectric patch are tabulated in Table 3.1. The experiment involves the use of the aluminium beam, piezoelectric patch (PI P-876.A15), accelerometer (Dytran model 3224A2), data acquisition system (NI cDAQ 9263 and NI cDAQ 9234), piezo voltage amplifier (PI E-508.00) and LabVIEW software. Figure 3.2(a) shows the beam with the piezoelectric patch attached on it and mounted at the edge of a table along with an accelerometer to measure the acceleration of the beam.

Table 3.1: The specifications of the piezoelectric patch

Model	P-876.A15
Operating voltage (V)	-250 to 1000
Min. lateral contraction (µm/m)	800
Relative lateral contraction (µm/m/V)	0.64
Blocking force (N)	775
Max. bending radius (mm)	70
Electrical capacitance (nF)	45
Dimension	61mm x 35mm x 0.8mm

Figure 3.2(b) shows the schematic diagram of the experiment. From the figure, the LabVIEW software was used to create the block diagram to manipulate the sinusoidal input signal in term of amplitude and frequency. Then, the sine wave input was sent to the piezo amplifier through the NI module 9263 to amplify the input signal. The piezo amplifier supplied the amplified signal to the piezoelectric patch for the excitation. The accelerometer will measure the acceleration of the beam and sent the output signal to NI module 9234 and the LabVIEW software for data analysis.



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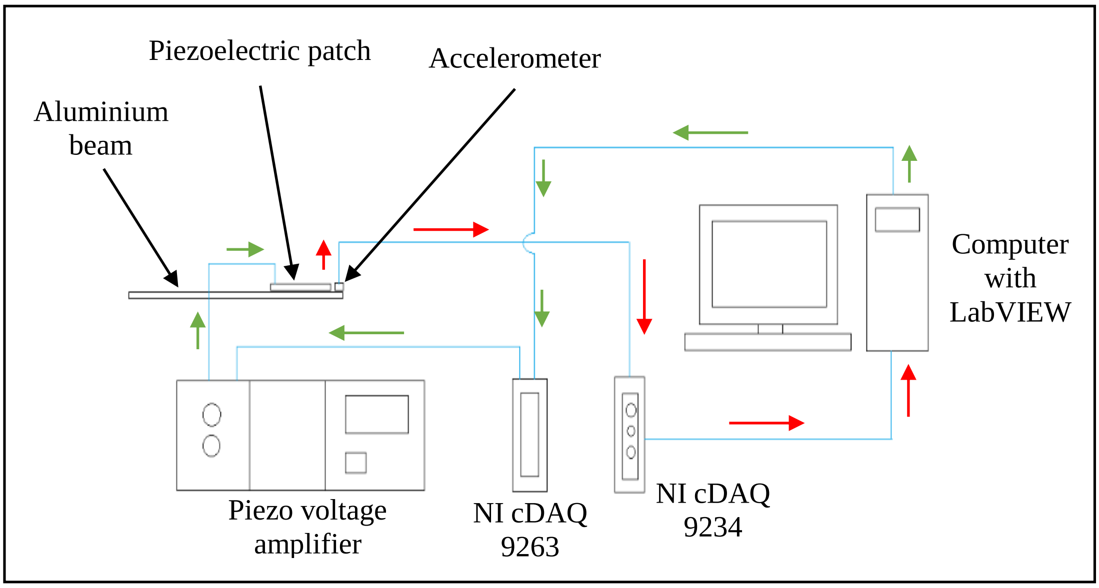
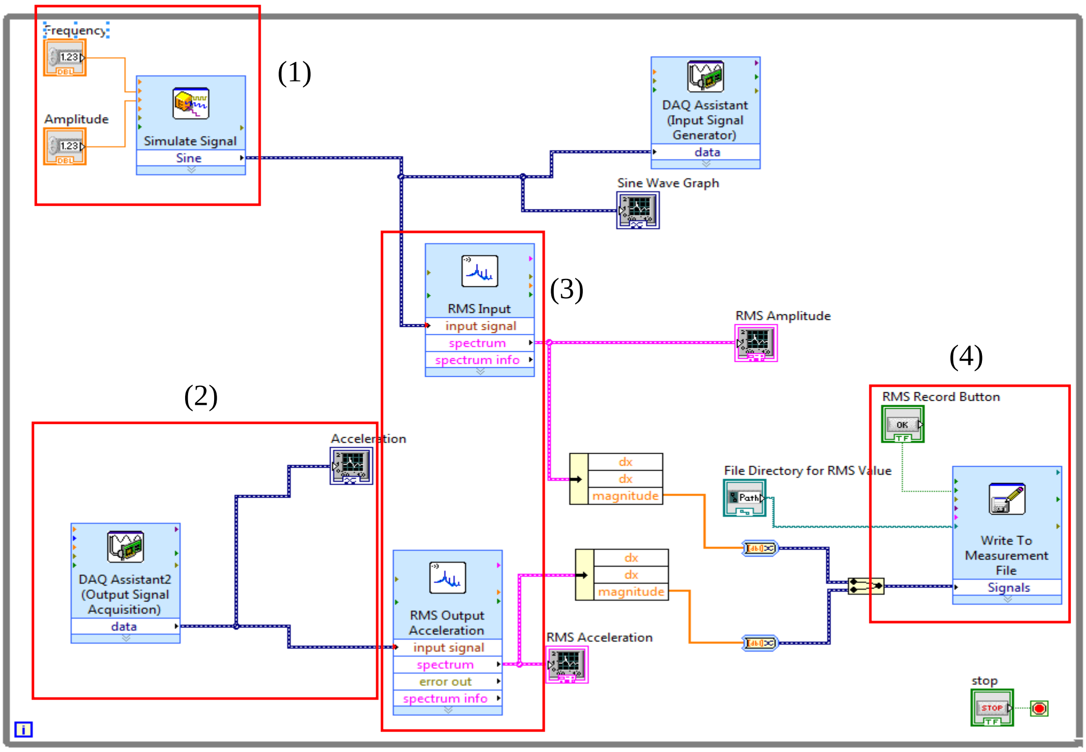


(b)

Figure 3.2: (a) The setup of the aluminium beam, piezoelectric patch and accelerometer and (b) The schematic diagram of the actuator experiment

3.3.2 LabVIEW block diagram development

In this study, the LabVIEW software was used as a data processing and analysis platform for the experiment. Using this software, a desired input signal such as saw-tooth, linear, square and so forth can be created. In this experiment, a sine wave voltage input signal was supplied to the piezoelectric patch through the NI module 9263 and amplified using the piezo voltage amplifier (E-508.00). Figure 3.3 shows that, two input controls (frequency and amplitude) were used to manipulate the signals, as shown in (**1**). The piezoelectric patch was operated based on frequency range of 100 Hz to 500 Hz along with the voltage range of 100 V to 500 V. This range was selected based on the linearity of the amplifier response which is up to 500 Hz (Mazlan, 2016).



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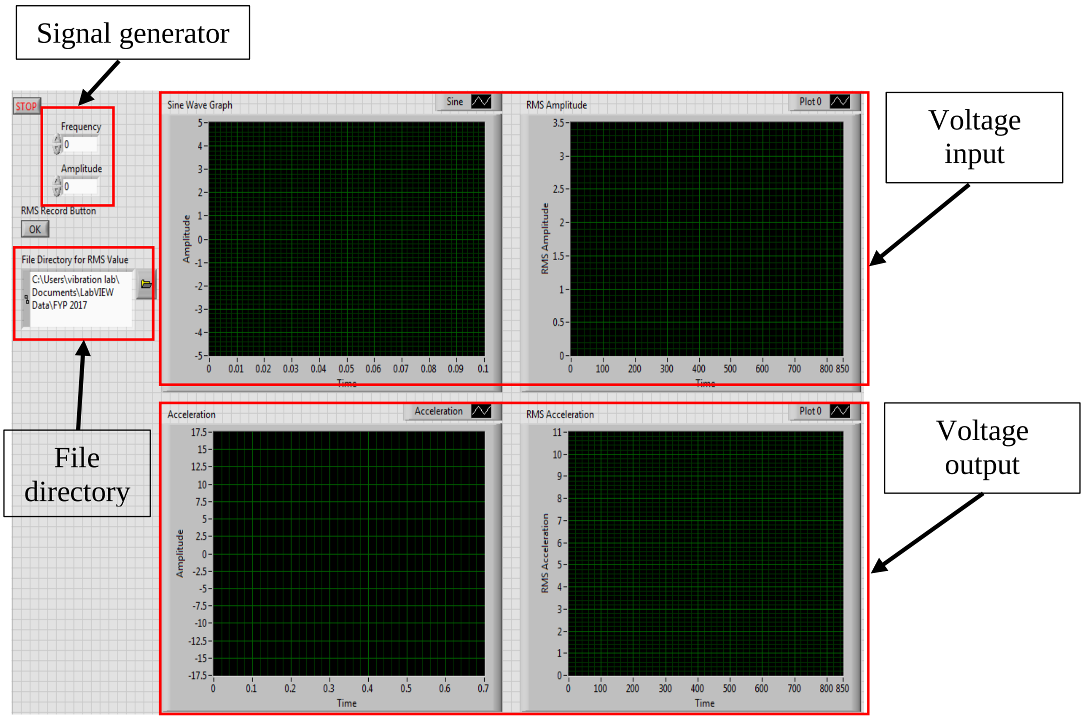


(b)

Figure 3.3: (a) The block diagram and (b) the front panel for the piezoelectric patch actuator experiment

To obtain and analyse the results, a NI module 9234 was used to capture the output of the accelerometer. From Figure 3.3 (**2**), the DAQ Assistant block was used to receive the acceleration signal from the accelerometer and a graph block was connected to display the output in a real time. Two power spectrum blocks shown in Figure 3.3 (**3**) were used to convert the time domain to the frequency domain (FFT) for both input and output accelerations. Since the time domain output signal is very disturbed due to the presence of noise, the FFT is necessary to analyse the signal. Two graph blocks were used to display time domain and frequency domain input and output signal. The data of time domain and frequency domain were recorded using data saving block as shown in Figure 3.3 (**4**).

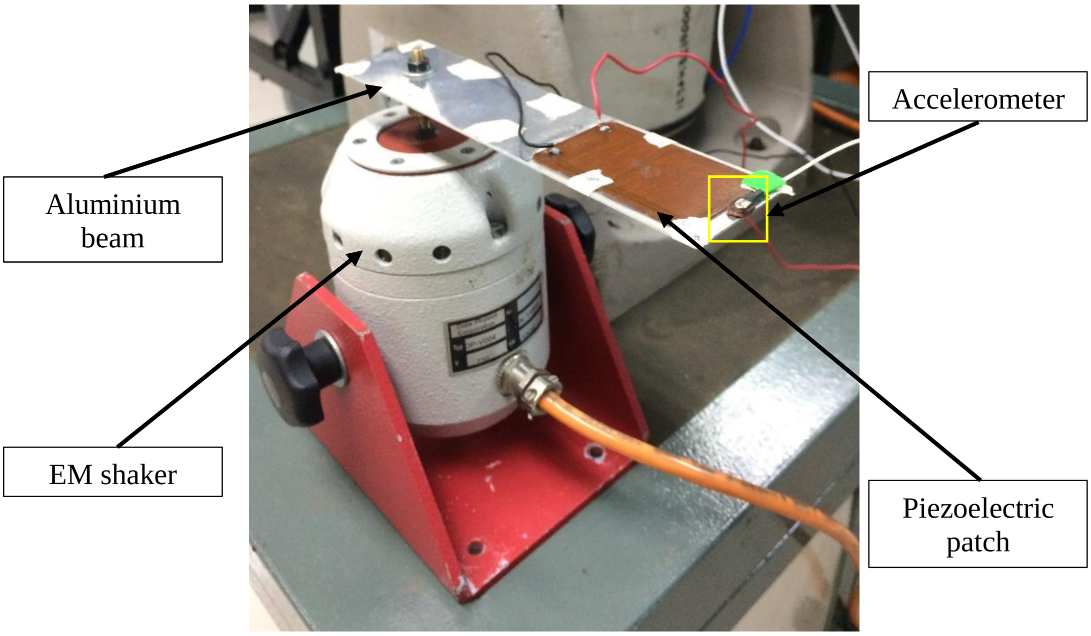
The experiment was initiated with the input signal of 100 Hz and 1 V. From Figure 3.3 (b), the signal generator was used to insert the input value of amplitude and frequency. The experiment continued with the multiple combinations of amplitude and frequency varying from 100 Hz to 500 Hz and 1 V to 5 V. File directory column in the figure was used to save the data in a specific location using the Excel file format. The figure also shows four graph blocks which represented the voltage and FFT input signals and the acceleration and FFT output signals. For each experiment, sampling rate of 26 500 sample/s was set to determine an accurate data.

3.4 Piezoelectric patch sensor characterization

In this section, piezoelectric patch will be characterized as a sensor. An electromagnetic (EM) shaker was used as an external source of vibration to the aluminium beam and piezoelectric patch. A sinusoidal input voltage was supplied to the shaker with amplitude of 1 V to 5 V and frequency of 100 Hz to 500 Hz which is similar as previous actuator experiment. From this experiment, the output voltage produced by the piezoelectric patch can be determined and used as a sensor of a piezoelectric patch.

3.4.1 Experimental setup

In this experiment, the instrumentation required are the aluminium beam, piezoelectric patch, data acquisition system, EM shaker (Data Physics type DP-V004), shaker voltage amplifier (Data Physics type A-060) and LabVIEW software. From Figure 3.4(a), the aluminium beam along with the piezoelectric patch were mounted on the EM shaker. The acceleration of the beam was measured in this experiment using an accelerometer which was mounted at the end of the beam.



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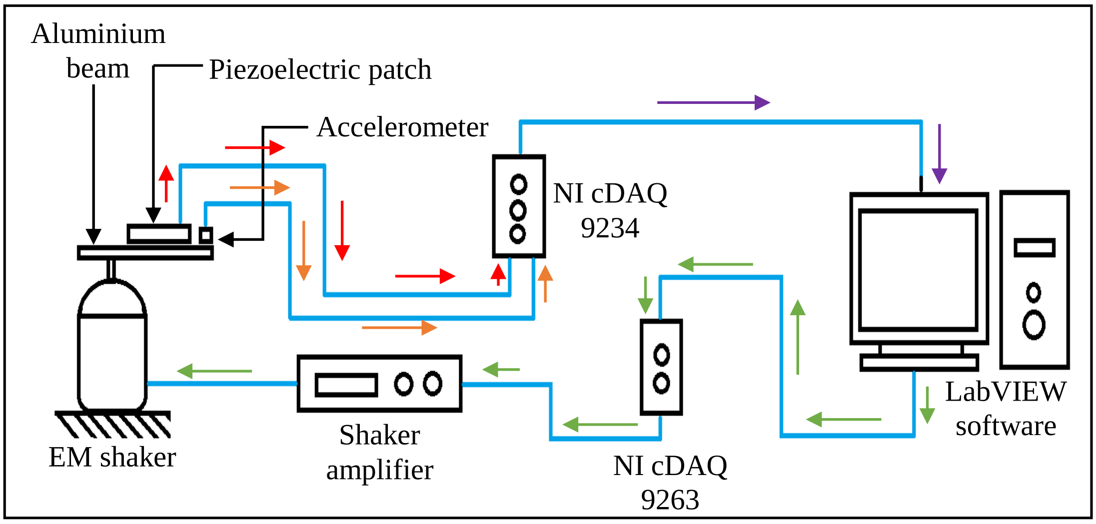
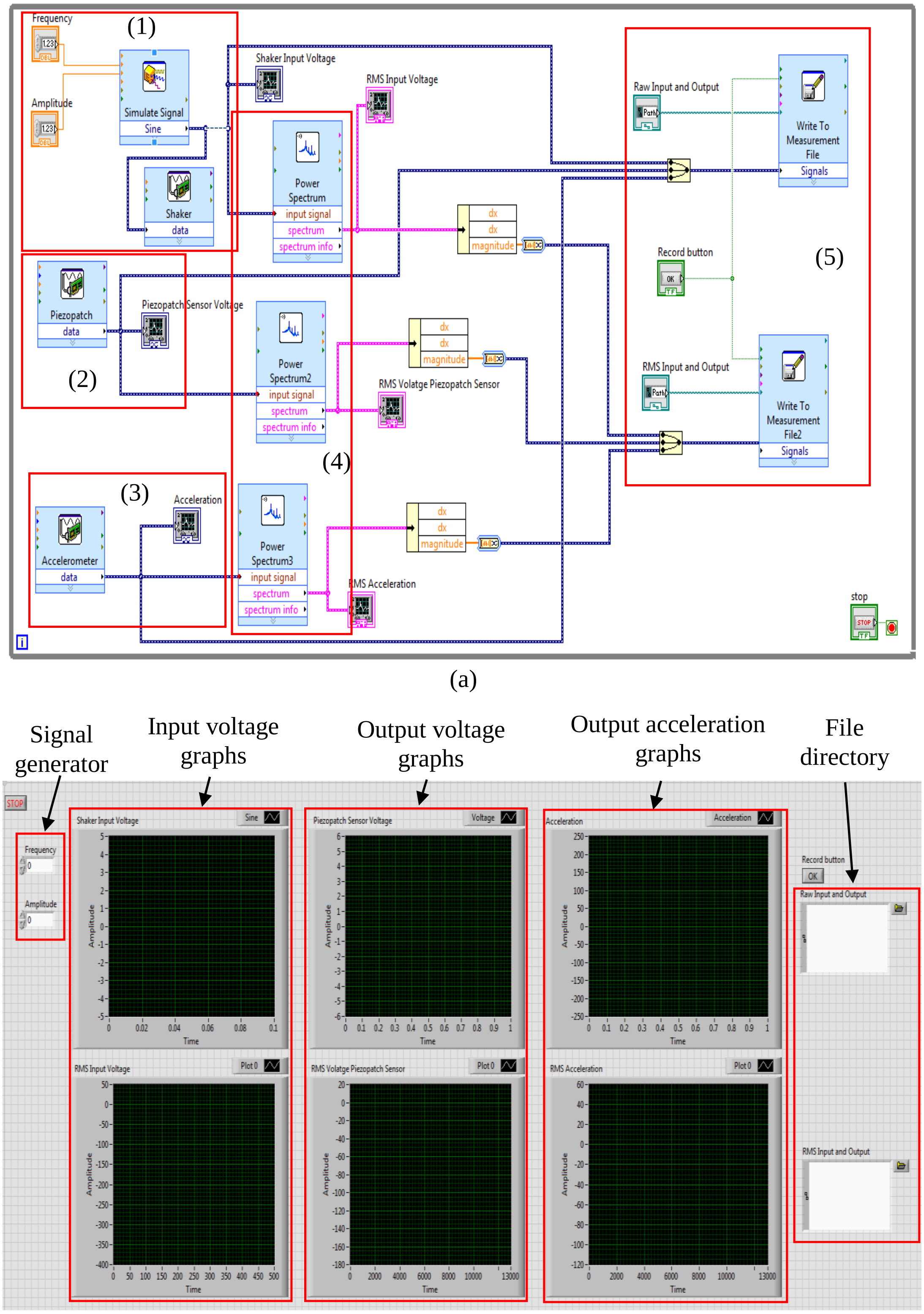


(b)

Figure 3.4:(a) The configuration of the beam, piezoelectric patch, accelerometer and EM shaker and (b) the schematic diagram of the piezoelectric patch sensor experiment

3.4.2 LabVIEW block diagram developement

In this study, the LabVIEW software was used to construct the block diagram of the sensor experiment. From Figure 3.5(a), there are five regions whereby each of them carried specific tasks. To generate the sine wave input, a Simulate Signal and DAQ Assistant blocks were used as shown in region **(1)**. Sine wave input with 25600 sample/s of sampling rate was set in the block with change of amplitudes and frequencies during the experiment.



(a)

(b)

Figure 3.5: (a) The block diagram and (b) the front panel of the sensor experiment

In region **(2)**, DAQ Assistant block was added to the diagram for the receiver of the output voltage signal from the piezoelectric patch. A graph block was included to display the output signal on the front panel as shown in Figure 3.5(b). Similar blocks were used in the region **(3)** for the output acceleration signal measurement. Both of the regions were set to record 25600 sample/s data of output voltage and acceleration.

In Figure 3.5(a), three Power Spectrum blocks were added into the diagram to obtain the FFT data in region **(4)**. The block graphs were used to display the FFT input and output data on the front panel. The diagram also comprised two Record blocks for data recording as portrayed in region **(5)**. The upper Record block was used to record the time domain input and output data whereas the lower block was used to record FFT input and output data. One Switch button was included to manually record the data.

3.5 Application of the piezoelectric patch actuator in AVC system

In this experiment, the piezoelectric patch actuator was applied for the AVC system. PID controller was used to tune and alter the acceleration signal from the accelerometer and produce an appropriate counter voltage signal for the piezoelectric patch to reduce the vibration of the beam structure. The counter voltage that generated from the PID controller can be shown as following equation:

$$u(t) = K_p e(t) + K_i \int e(t)d(t) + K_d \frac{de(t)}{dt} \tag{3.1}$$

where, e(t) = error signal

K_p = proportional gain

K_i = integral gain

K_d = derivative gain

3.5.1 Experimental setup

The equipment used in this AVC experiment were similar to the experiment of the piezoelectric patch sensor in Figure 3.4(a). Figure 3.6 shows that, the EM shaker was supplied with a frequency of 100 Hz and amplitudes of 1 V to 5 V to generate the vibration for the aluminium beam and it was connected to NI module 9263. To measure the acceleration of the beam, an accelerometer was used as a vibration sensor which connected to NI module 9234. The piezoelectric patch was used as an actuator for the aluminium beam and it received the counter voltage signal from the LabVIEW software through NI module 9263 and the piezo amplifier.

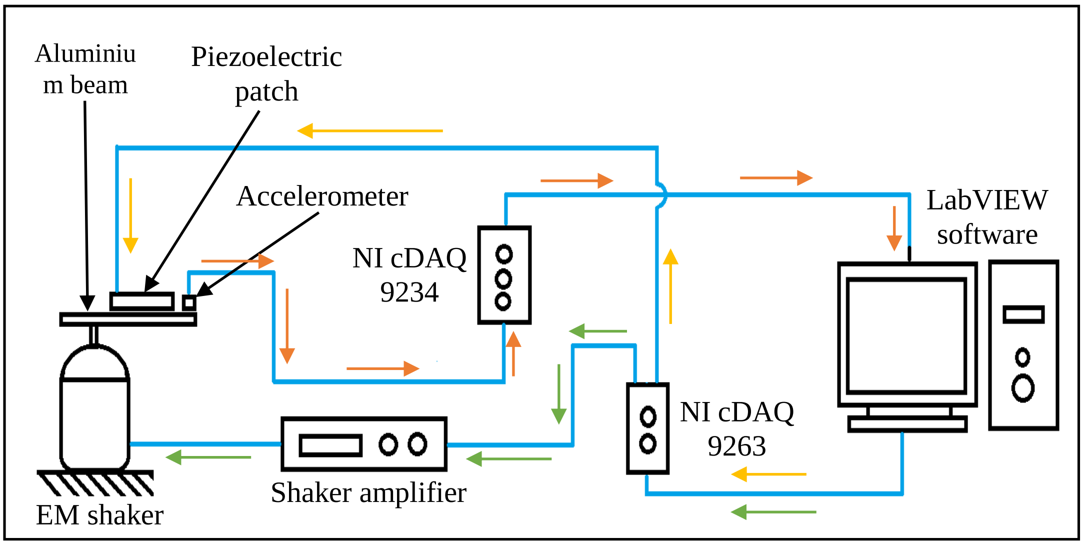
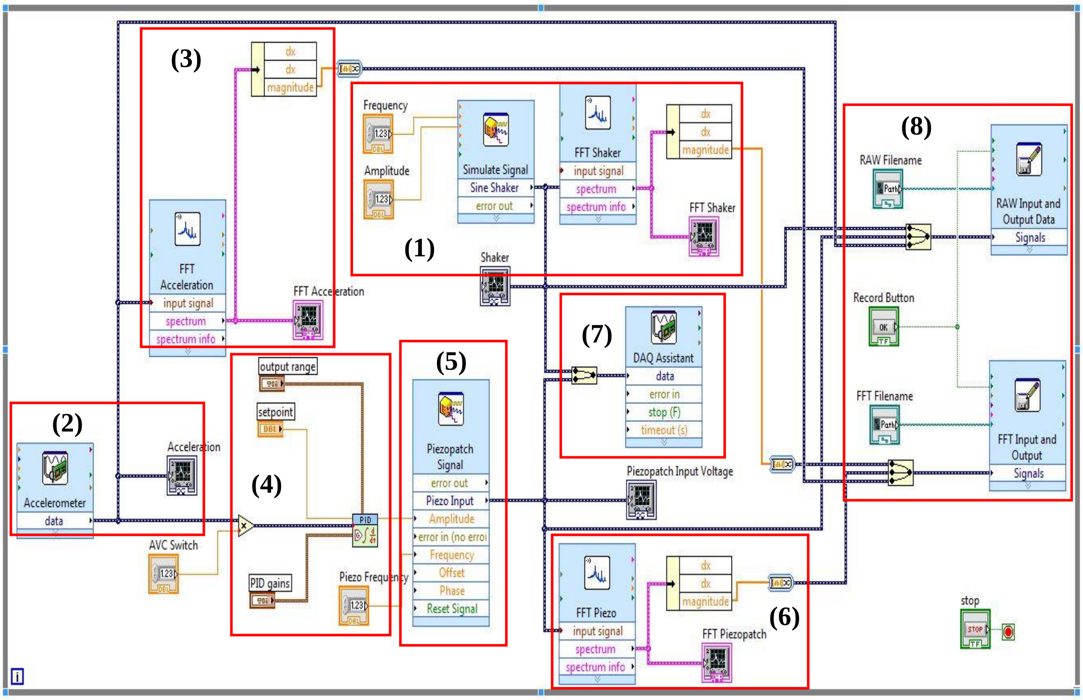


Figure 3.6: The schematic diagram of the AVC experiment

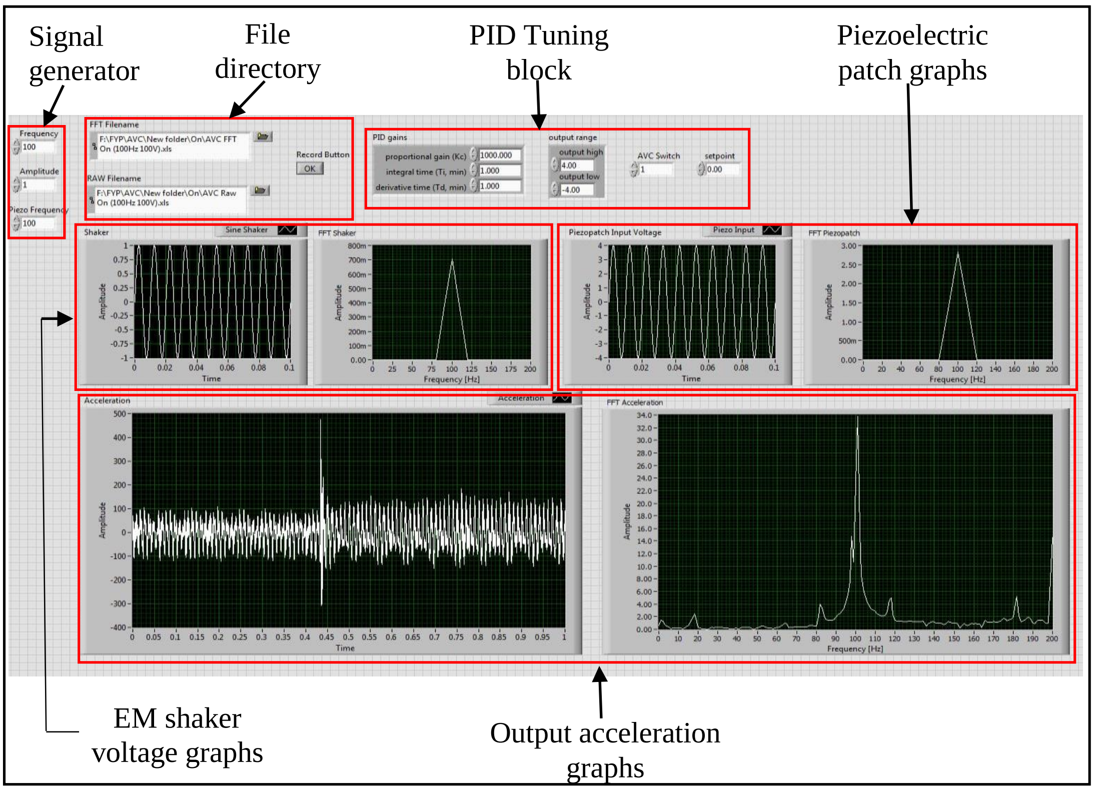
3.5.2 LabVIEW block diagram development

In this experiment, the LabVIEW software was used to create the block diagram for the AVC system of the piezoelectric patch actuator and aluminium beam. Figure 3.7(a) shows the block diagram of the experiment with 7 different regions and each of them carries different tasks. In region **(1)**, a Simulate Signal block was used to create sine wave input signal for the EM shaker. Two control blocks were used and connected to the Simulate Signal block to change the frequency and amplitude of the EM shaker. The FFT signal was created from the sine wave input signal using the Power Spectrum block. For acceleration measurement, DAQ Assistant block was used to receive the acceleration signal from the aluminium beam as shown in region **(2)**. In region **(3)**, Power Spectrum block was also used to obtain FFT of the output acceleration signal.

Region **(4)** shows that, the AVC system in this experiment required a PID controller tuning block and it was placed after the acceleration measurement region. There are several control blocks used to fully utilise the PID tuning which are Output Range, Setpoint and PID Gains blocks. Output Range determines the range of output voltage to the piezoelectric patch and it was set to ±4 V. Setpoint block was set to 0 to eliminate the beam vibration. For PID Gains block, K_p, K_i and K_d values were set to 1000, 1 and 1 respectively. These values were obtained from the previous study by Mazlan and Ripin (2015) and it able to produce the most significant vibration reduction compared to other PID combinations.



(a)



(b)

Figure 3.7: (a) The block diagram and (b) front panel of the AVC system experiment

Region **(5)** shows another Simulate Signal block was used for the piezoelectric patch and a control block was connected to it to set the frequency. The amplitude of the piezoelectric patch was set based on the value produced from the PID controller tuning block. FFT signal of the piezoelectric input voltage signal was created using the Power Spectrum block as shown in region **(6).** DAQ Assistant block was used to generate the input sine wave signal for both EM shaker and piezoelectric patch with different amplitudes as shown in region **(7)**. Finally, the data was recorded using two Record blocks which stored raw and FFT signals separately in region **(8)**.

3.6 Summary

All topics of methodology regarding the EMA of the beam, the piezoelectric patch characterization as actuator and sensor and the application of piezoelectric patch actuator in AVC system have been clearly explained in this section and flow chart of overall research is shown in Figure 3.8.

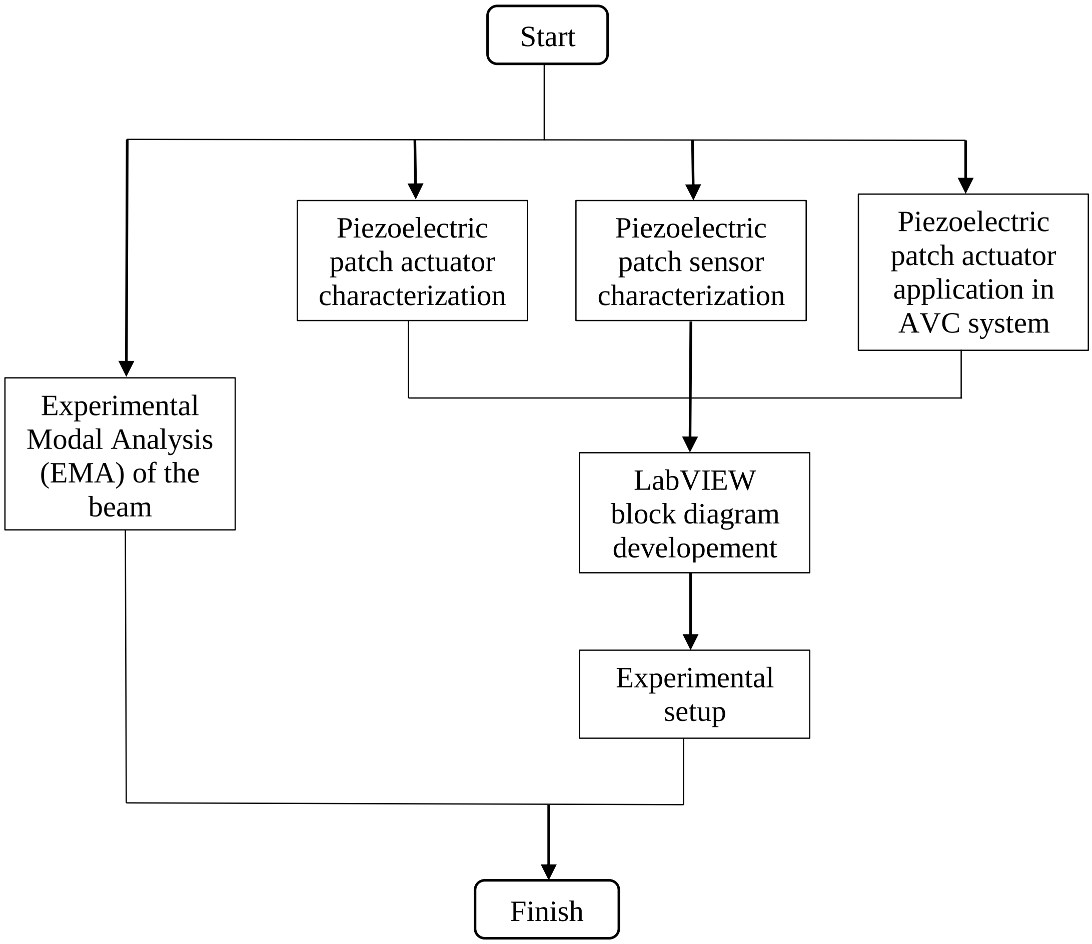


Figure 3.8: Flow chart of the overall project

CHAPTER 4

RESULTS AND DISCUSSION

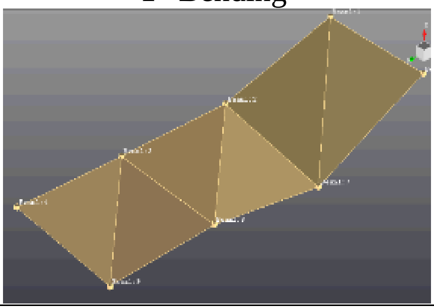
4.1 Overview

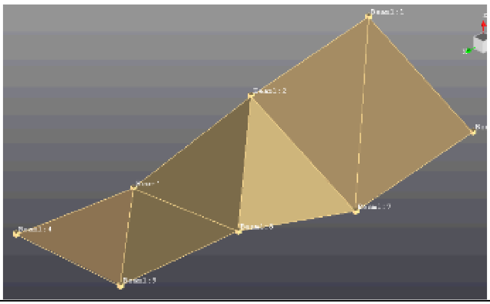
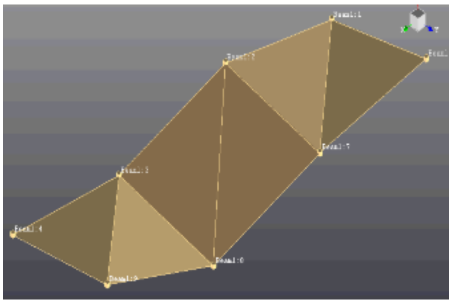
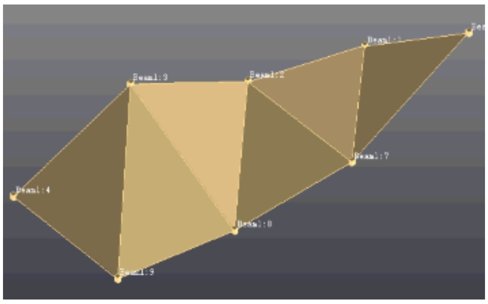
In this chapter, the experimental results and discussion are presented which include the modal analysis of the beam, piezoelectric actuator and sensor characteristics and the application of the piezoelectric patch in the AVC system.

4.2 EMA of the beam with piezoelectric patch

The results of the EMA is presented in Figure 4.1 which is the FRF of the beam. From the figure, four natural frequencies with the mode shapes are shown for the frequency range of 0 Hz to 1000 Hz. The first mode shape was shown at the natural frequency of 30.4 Hz with the first bending motion. At the second natural frequency of 227.9 Hz, the mode shape of the beam shows the first torsional motion with the amplitude of 764.4 (m/s^2)/N. The third natural frequency of the aluminium beam occurred at 709.9 Hz with a second torsional motion at the upper and lower part of the beam. The fourth mode shape is shown at frequency of 923.9 Hz with amplitude of 1304.6 (m/s^2)/N and the beam was experiencing the third torsional motion at the whole beam part. All of the mode shapes and natural frequencies were summarised and tabulated in Table 4.1.

Table 4.1: The mode shapes and the natural frequencies of the aluminium beam

Mode Shape	**Natural Frequency (Hz)**	**Amplitude (m/s^2)/N**	**Motion Type**
1	30.4	158.2	1st Bending 

2	227.9	764.4	1^{st} Torsion 
3	709.9	786.1	2^{nd} Torsion 
4	923.9	1304.6	3^{rd} Torsion 

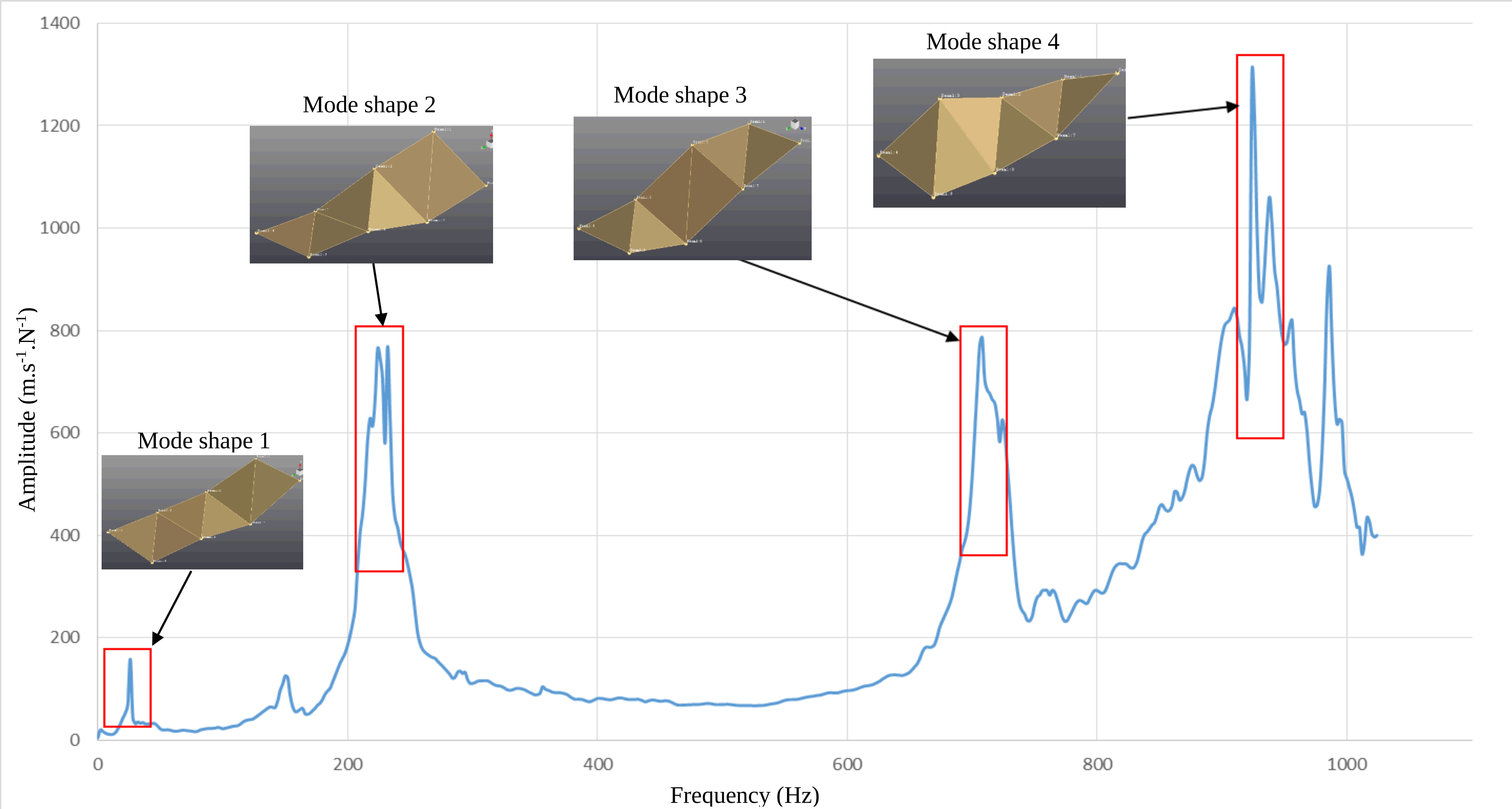


Figure 4.1: The FRF of the aluminium beam