ACTIVE VIBRATION CONTROL OF THE SUSPENDED HANDLE USING INERTIA-TYPE PIEZOELECTRIC ACTUATOR

By:

TAN SAK JIE

(Matrix No: 128974)

Supervisor:

Dr. Ahmad Zhafran Ahmad Mazlan

May 2019

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfilment of the requirement to graduate with honors degree in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

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 source are duly acknowledgements by giving explicit references.

Signature:

Name of Student: TAN SAK JIE

Matrix number: 128974

Date: 29 May 2019

ACKNOWLEDGEMENT

First of all, I would like to express my gratitude to my supervisor, Dr. Ahmad Zhafran Ahmad Mazlan, for the encouragement, guidance and suggestion throughout this research. It has been a great experience to be under his supervision as he thoroughly guides me, share his expertise and provides me with precious hints.

Besides that, I also want to extend my gratitude to the all the Assistant Engineers from the School of Mechanical Engineering, Universiti Sains Malaysia, especially the assistance of Mr. Wan Mohd Amri Wan Mamat Ali, who guided me through my experimental works.

Apart from that, I would like to thank all my friends whose gave their help and moral support to me to complete my final year report.

Last but not least, I would like to express my deepest gratitude one and all who directly and indirectly have lent their helping hand in this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Symbol	Descriptions
AVC	Active Vibration Control
DAQ	Data Acquisition
EMA	Experimental modal analysis
FRF	Frequency response function
NI	National Instruments
PID	Proportional , Integral, Derivative

ABSTRAK

Kajian ini membentangkan kawalan getaran aktif (AVC) menggunakan penggerak piezoelektrik jenis inersia untuk menggurangkan getaran pada pemegang jenis gantung secara eksperimen. Analisa Modal Eksperimental (EMA) bagi pemegang jenis gantung telah dilakukan dan keputusan eksperimen menunjukkan bahawa pemegang mempunyai empat frekuensi semula jadi dan bentuk mod antara 100 Hz hingga 500 Hz di mana paksi x pada 520 Hz dan 1558 Hz, paksi y pada 90 Hz dan 186 Hz kemudian paksi z pada 454 Hz. Selepas itu, ciri-ciri penggerak inertia piezoelektrik telah dikaji di mana kerja telah dibahagikan kepada daya dan pecutan. Daya maksimum yang dihasilkan oleh penggerak inertia piezo adalah 0.68N pada frekuensi 500 Hz bersama 4V voltan apabila 95g jisim digunakan pada penggerak dan pecutan maksimum penggerak inertia piezo adalah $0.01\ \mathrm{ms}^{-2}$ pada 500Hz dengan 4 V voltan apabila 45g jisim digunakan pada penggerak. Akhirnya, penggerak piezoelektrik inersia digunakan pada sistem AVC untuk mengatasi getaran pemegang yang digantung menggunakan frekuensi pengujaan bebas dan bergantung. Untuk frekuensi bebas, keputusan menunjukkan bahawa pemegang pegangan aktif boleh mengurangkan tahap pecutan sehingga 39.69% pada frekuensi 400Hz untuk 45g jisim inersia. Sementara itu, untuk frekuensi bergantung, pemegang yang digantung aktif boleh mengurangkan tahap pecutan pada frekuensi semula jadi pemegang sehingga 34.98%. Keputusan kajian ini membuktikan bahawa, pemegang yang digantung secara aktif ini berpotensi untuk digunakan pada peralatan yang kuasa tinggi untuk mengurangkan getaran pada pemegang.

ABSTRACT

This study presents the active vibration control (AVC) using inertia-type piezoelectric actuator to attenuate the vibration of the suspended handle experimentally. Firstly, the Experimental Modal Analysis (EMA) of the suspended handle is conducted and the results shows that, the handle has four natural frequencies and mode shapes within 100 Hz to 500 Hz which in x axis at 520 Hz and 1558 Hz, y axis at 90 Hz and 186 Hz and z-axis at 454 Hz. Then, the characteristics of the inertia piezoelectric actuator are investigated where the works are separated into force and acceleration investigation. The maximum force generated by the inertia piezo actuator is 0.68N at frequency of 500 Hz with 4V of voltage when 95g of mass is applied to the actuator and the maximum acceleration of the inertia piezo actuator is $0.01\ \mathrm{ms}^{-2}$ at 500Hz with 4 V of voltage when 45g of mass is applied to the actuator. Finally, the inertia piezoelectric actuator is applied to the AVC system to overcome the vibration of the suspended handle using frequency independent and dependent excitation. For the frequency independent, the result shows that, the active suspended handle can reduce the acceleration level up to 39.69% at 400Hz of frequency for the 45g of inertia mass. Meanwhile, for the frequency dependent, the active suspended handle can reduce the acceleration level at the natural frequency of the handle up to 34.98%. The results of the study proved that, this active suspended handle is possible to be applied to the power tools for the vibration reduction.

CHAPTER 1 : INTRODUCTION

1.1 Background Study

Piezoelectric materials are the smart materials which able to convert the mechanical stress to electric charge and vice versa (Dakhole & Boke, 2017). This feature is utilized for sensors and actuators in many applications, such as for structural vibration control (Fan et al., 2018). A suspended handle is widely used and can be applied to many type of tools. These power tools using the suspended handle are used in the composite manufacturing and fabrication of products. Unfortunately, prolonged exposure to the high vibration of the suspended handle and power tools will contribute to the operator health problems such as Hand-Arm Vibration syndrome (HAVs) (Ahmad Zhafran et al, 2015). In general, machines must be operated at low level of vibration in order to decrease the stresses and noises. To solve this problem, the best solution is to cancel out all of the disturbance forces in the system. Active Vibration Control (AVC) is one of the methods that can be applied to the suspended handle using an inertia-type piezoelectric actuator.

Piezoelectric measuring devices were firstly used in the development of internal combustion engines, specifically for pressure measurement in the combustion chamber (André V. Buenoa et al, 2012). In year 1880, Pierre and Jacques Curie carried out an experimental method to identify the relationship between the mechanical load and electric charge which resulting piezoelectric effect (Uchino, 2010). Nowadays, piezoelectric have been widely used in many engineering fields. Over the last few decades, piezoelectric materials have been used in many research areas and OEM (Original Equipment Manufacturer) components. These materials are mainly used to measure force, pressure, acceleration strain and torque (Kumar Govind et al, 2012). Piezoelectric devices are also effectively use as actuator and sensor. Piezoelectric actuator has been widely used in diverse applications due to fast response in time and resolution.

AVC is an active application of force in an equal but opposite direction to the imposed by the external vibration. AVC using piezoelectric actuator have been widely studied in reducing the vibration of structures such as for flexible beam (Abreu et al, 2014). Many precision industrial processes could be maintained in a platform essentially vibration-fee using AVC (Sidoti, 2014). There is a study using piezoelectric material as sensor and actuator for the AVC system. This study involves a closed-loop system for the vibration control of flexible structures (Yaman et al., 2003). Some of researchers have foreseen the bright future of piezoelectric material in energy harvesting.

This study will investigate the effectiveness of using piezoelectric actuator to reduce the vibration of the suspended handle. This project deals with the design of a suspended handle together with the inertia type piezoelectric actuator. Three different masses of 45, 63 and 95 g are fabricated and mounted on the top of the piezoelectric actuator in order to investigate the influence of the cap (inertia) mass to the performance of the piezoelectric actuator.

1.2 Problem Statement

The operators whose involve the use of high level vibration power tool such as hand-held power tools and powered machines are exposed to the HAVs, which is a disease caused by the prolonged exposure to the high level of vibration that transmitted to the operator hand (Miljković, 2009) .

Nowadays, there is a lot of solutions that have been discovered to attenuate the vibration transmitted to the operator hand such as the use of anti-vibration glove. However, this passive vibration control is not very effective.(M.Eissa ,& M.Sayed, 2006) One of the techniques that can be used to reduce the exposure of hand to the transmitted vibration from the power tools is by using AVC method. AVC has been widely used in different field of engineering but rarely been studied for the vibration attenuation of power tools. In this study, the suspended handle using an inertia-type piezoelectric actuator will be investigated which aiming for a better solution to reduce the vibration of the suspended handle.

1.3 Objective

In this project, there are three objectives to be achieved, which are:

- To fabricate a suspended handle using three different masses of an inertia-type piezoelectric actuator
- To characterize the performance of the inertia-type piezoelectric actuators

- To reduce the vibration of the suspended handle using AVC method with inertia-type piezoelectric actuator.

1.4 Scope of Project

In this project, the scope is on the fabrication and experimental work which require the fundamental knowledge in vibration and control system. First of all, the inertia masses of 45 g, 63 g, and 95 g will be designed using SolidWorks software. After that, these designs will undergo fabrication process using CNC and lathe machines. The different weight of masses will be implemented on the piezoelectric actuator and undergo experiment according to their masses in order to find out the influence of different masses on the performance of actuator and vibration reduction of the suspended handle.

1.5 Thesis Outline

The thesis is divided into five chapters which comprises:

- **Chapter 1 (Introduction),** explain about the background study of the project, the objective that need to achieved, the problem statement of the project and thesis outline
- **Chapter 2 (Literature Review),** focus on material characteristics of the piezoelectric actuator, the vibration from power tool, theory of AVC and application of inertia-type piezoelectric actuator to AVC system.
- **Chapter 3 (Methodology),** shows the design of an inertia piezoelectric actuator with suspended handle, EMA, characterization of the inertia piezoelectric actuator with three different masses and AVC experiment using inertia piezoelectric actuator.
- **Chapter 4 (Results and Discussion),** present the results of EMA, the inertia-type piezoelectric actuator and vibration reduction of the suspended handle using AVC.
- **Chapter 5 (Conclusion),** summarizes the outcomes of the project and the recommendation of the possible future works.

CHAPTER 2 : LITERATURE REVIEW

2.1 Overview

In this chapter, five topics will be presented:

- Material characteristics of the piezoelectric sensor and actuator
- Non-linear effect of piezoelectric materials
- Vibration of power tools
- Active Vibration Control (AVC)
- Application of inertia piezoelectric type actuator to AVC system

2.2 Material characteristics of the piezoelectric sensor and actuator

Piezoelectric materials have been widely used as sensor and actuator in many applications such as in structural vibration reduction (Ducarne et al, 2010) and positioning control (Leang & Devasia, 2002). Besides, it can also be used as a smart actuator due to several useful features in actuating mechanism for advanced technologies (Trindade, 2014). Piezoelectric materials will produce positive and negative electrical charges on their prism surfaces when mechanical force or stress is applied. Pierre and Jacques Curie conducted an experimental method for the relationship between mechanical forces and electric charge and this is called a direct piezoelectric effect. When an external force is applied on the surface as result from the deformation of the crystal lattice, the positive and negative lattice points will push against each other. This action produces an electric dipole moment of the polar crystal axes with respected force applied (Maslanet et al., 2012). Figure 2.1 shows the principle of the longitudinal piezoelectric effect and the method of increasing the charge field.

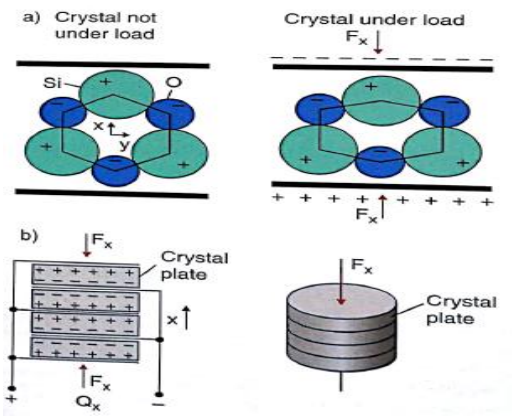


Figure 2.1 (a)Principle of the longitudinal piezoelectric effect and (b) method of increasing the charge yield

From Figure 2.1, the charge can be tapped off with the longitudinal effect due to the force applied on the surface. Therefore, the plate should be connecting mechanically in series and electrically in parallel (Dineva et.al, 2014). This effect is found in tourmaline, quartz and Rochelle salt. Quartz is an ideal material as it can be manufactured easily and can be used at temperature up to 400 Celsius. Furthermore, both pressure sensitive and shear sensitive elements can be cut from quartz (Feust & Geol, 2014) .

A piezoelectric effect can be detected by change which pressure , acceleration and force can be measured from this measurement. Piezoeletric crystal are considered smart materials for the purpose of producing piezoelectric effect and the built of piezoelectric sensor technology. Figure 2.2 shows the function principle of mechanical sensors to measure piezoelectric effect :

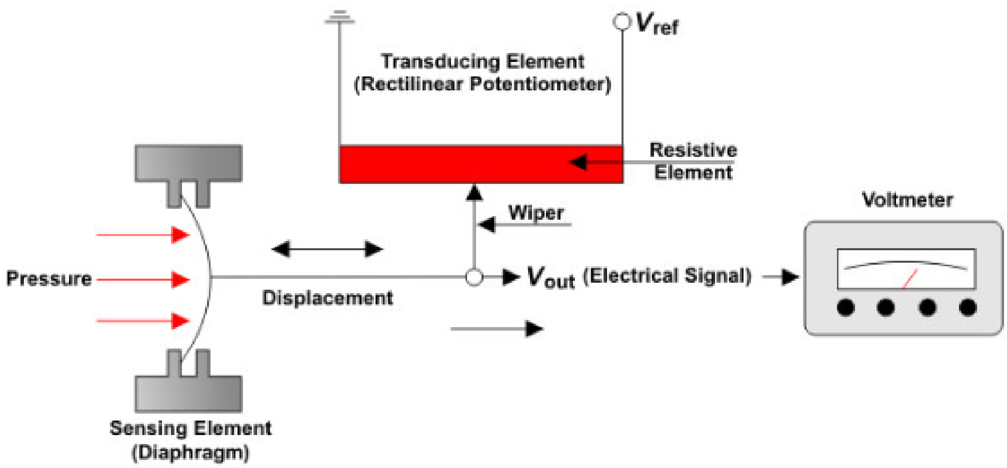


Figure 2.2 Function principle of mechanical sensor illustrate piezoelectric effect

Mechanical sensors are made of diaphragm, three therminal resistor that act as a voltage divider and direct current voltage source.When pressure is applied to the diaphragm ,the displacement change between the connecting rod and it will activate the potentiometer component in sanity of output voltage (Kal Kaur, 2012).

Actuator is a device that convert an input power such as electric energy , thermal energy and others into mechanical energy (Uchino, 2003). A piezoelectric actuator is an electrically controlled positioning element that working based on the reversed piezoelectric effect. Based on the reverse piezoelectric effect , an electrical field is parallel to the direction of polarization and elongation of crystalline material is determined in the same direction. A longitudinal actuator is a good example to explain the working principle of an actuator to convert an electric energy into mechanical energy. It is created by placing multiple layer of piezo elements on top of each other .When an voltage is applied to longitudinal actuator , it will combine the piezoelectric effect of each element expansion to produce a large mechanical motion.

2.3 Non-linear effect of piezoelectric materials

Although the piezoelectric material is widely used as actuators and sensors for high precision positioning and tracking applications, there are some non-linearity effects when operating the piezoelectric material such as hysteresis, creep saturation and vibration.

2.3.1 Hysteresis

Hysteresis is a non-linearity effect where the output displacement depends on the combination of current and past values of applied voltages (An et al, 2018) . It is undesired in high precision sensors and actuators application. It is more clearly shown when the operating frequency ranges are wider and the effect can be reduced by operating the piezo actuator in a linear range by minimizing the amplitude of the applied voltage signal. Hysteresis loop is illustrated as in Figure 2.3:

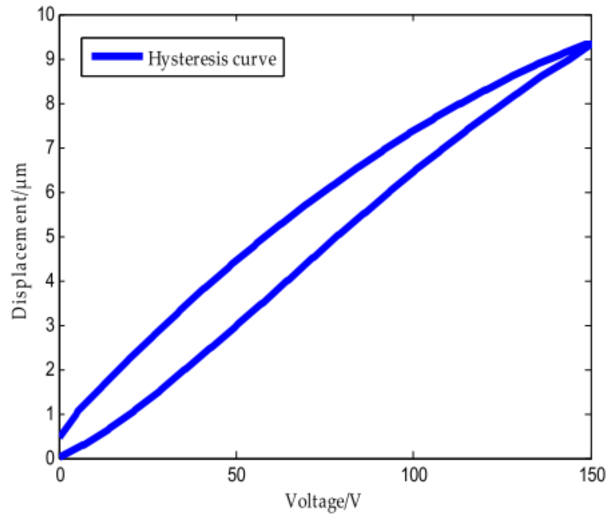


Figure 2.3 Hysteresis loop

Nowadays, there are various kind of dynamic models that have been developed to estimate the hysteresis behaviour of the piezoelectric actuator, such as Prandtl-Ishlinskii (Al Janaideh et al, 2009) , quadratic polynomial (Gan & Zhang, 2019) and many more.

2.3.2 Creep

Creep is a significant factor in many applications of the piezoelectric actuators. Piezoelectric materials exhibit creep effect which it will expands continuously for certain period upon application of voltage and does not return to original strain level immediately after set to zero voltage (Jung & Gweon, 2000). Figure 2.4 shows the graph of creep response region:

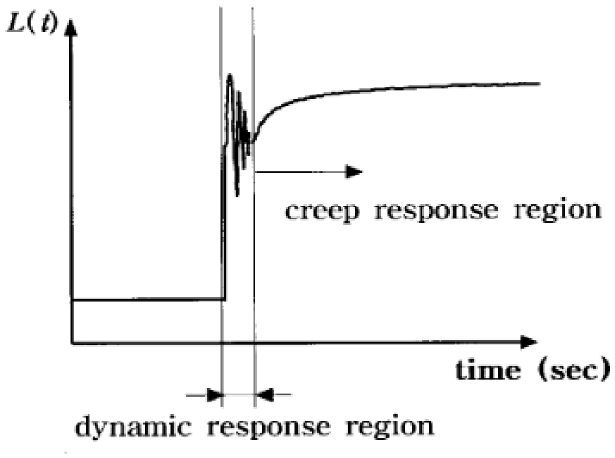


Figure 2.4 Graph of creep response region

2.3.3 Saturation

Saturation is one of the non-linear behaviours of the piezoelectric actuator. Saturation is defined as the state of output is unchanged when it reached a certain range of input value (Douce et al, 2006). Many of the existing controllers ignore the saturation nonlinearity or constraining the control input so that it will not reach the saturation limit. However, there is a study that proved the saturation effect must be considered in the saturation control of piezoelectric actuators for a fast settling time response in positioning application with an improvement of 12% to 31% for step length of 50 to 10000 nm as shown in Figure 2.5 and Table 2.1. The result shows that the saturation effect is significant and cannot be ignored (Zheng & Fu, 2013).

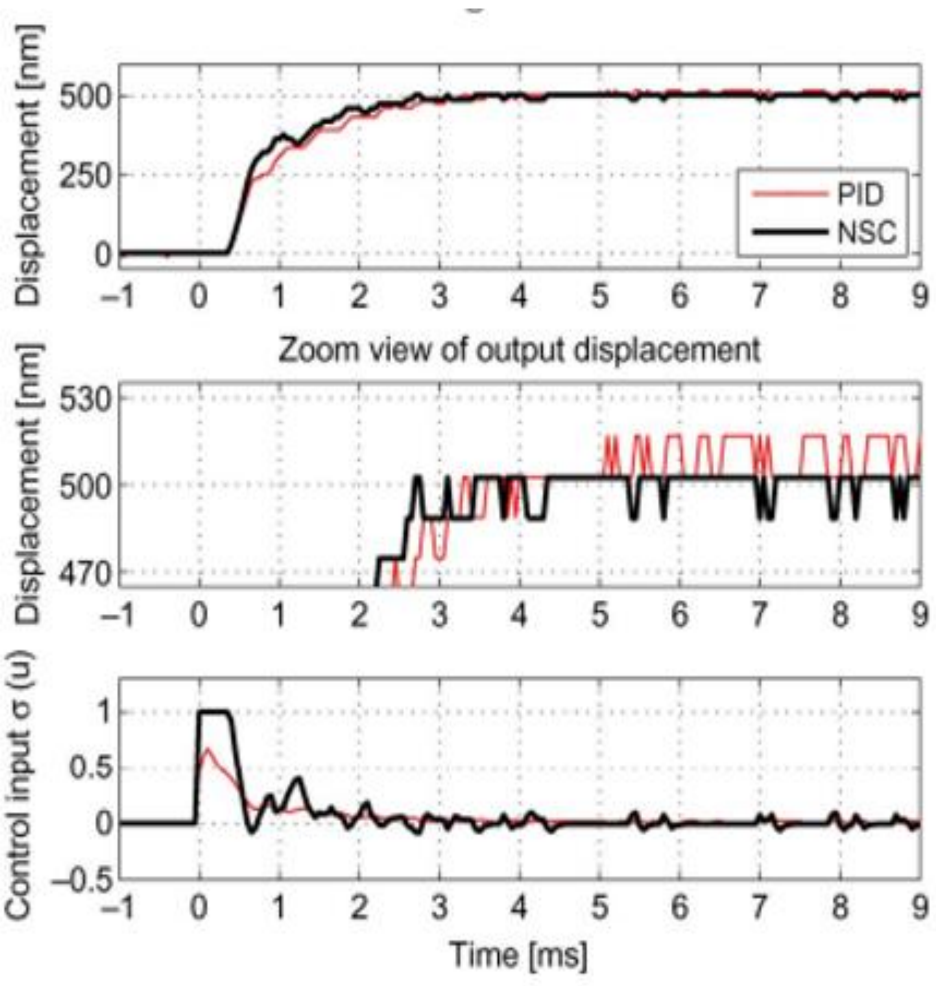


Figure 2.5 Comparison of step responses between NSC and PID. The NSC achieves faster setting time by properly control the saturation input

Table 2.1 Comparison of the settling time improvement

Step Length (nm)	Settling Time (ms)		Improvement (%)
	PID	NSC	
50	0.572	0.505	12
500	2.683	2.233	17
3000	3.7	3.1	16
10000	5.065	3.49	31

2.3.4 Dynamic vibration

Dynamic vibration is one of the effects that influence the exactness of positioning precision in the piezoelectric materials (Leang & Devasia, 2007). This effect diminishes the accuracy in which the frequency of the piezoelectric materials is same as the resonance frequency in the system (Clayton et al., 2006). However, this vibration can be eliminated either change the shape of input signal (Rakotondrabe et al., 2008) or using an inversion based feedback approach (Leang & Devasia, 2002). The decoupling of hysteresis and creep controls from the vibration control simplifies the inversion-based approach and the use of feedback will provides the robustness of the system.

2.4 Vibration of power tools

Vibration is concern due to the adverse effects of HAVs that shown by exposure guidelines and standards for segmental vibration (Edwards & Holt, 2006) . Work-related exposure from tools that vibrate may cause the finger to feel numb and tingly. This is a phenomenon which affected blood vessels, nerves, muscles, joints of the hand, wrist, and arm. Vibration exposure has been estimated for operators who requires the use of high vibration tools during working (Chiad, 2018). There are several types of power tools which may cause health problem from vibration such as chainsaws, concrete breakers, hammer drills, impact wrenches and jigsaws.

Raynaud's phenomenon is a medical condition in which the spasm of arteries due to the reduction of blood flow (Edwards, 2016). It is generally happening to the fingers when holding the tool. Vibration limits the blood supply to the hands and fingers which depending on the vibration level and duration of exposure which may contribute to damage (Ahmad Zhafran et al, 2015). The high vibration level of the power tools is beyond the limit of vibration exposure action value (EAV) and exposure limit value (ELV) (Heaver et al, 2011). The graph of vibration level and duration exposure is shown at Figure 2.6:

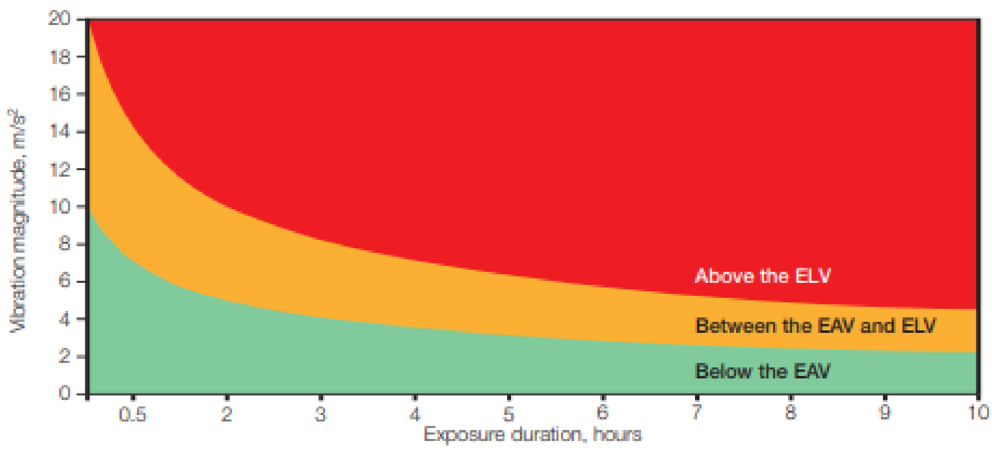


Figure 2.6 vibration level and duration affect exposure

EAV is the amount of vibration can exposure to employers daily and need to take care to control the exposure. When exposure level is increase, more action employers should take to minimize the risk. On the other hand, ELV is the maximum amount of vibration which an employee can exposed daily. The higher the exposure level, the higher the risk and precaution should be taken. A survey has been done to investigate some vibration level of hand-held power tools (Ahmad Zhafran et.al, 2017). Typical vibration levels for power tools are shown at Table 2.2:

Table 2.2 Typical vibration levels for power tool

Tool Type	Lowest (ms^{-2})	Typical (ms^{-2})	Highest (ms^{-2})
Road breakers	5	12	20
Demolition hammers	8	15	25
Hammer drills	6	9	25
Needle scalers	5	-	18
Angle grinders	4	-	8
Chainsaws	-	6	-
Sanders	-	7-10	-

2.5 Active Vibration Control (AVC)

The purpose of vibration control is to reduce the level of vibration of the mechanical structure. Most of the machines and structures are needed to operate at low level of vibration and run as smooth as possible in order to reduce the negative effect. There are two alternative ways to minimize the level of vibration which is passive and active vibration control. Passive vibration control can be divided into two segments which are vibration isolation (Jain & Soni, 2007) and vibration absorption method (Huang & Lin, 2014). For the vibration isolation, an isolator has to be inserted between the hand and the handle. The isolator can be in the form of anti-vibration glove or straightforward inclusion of elastomeric cushion. However, this kind of isolator will affect the efficiency of worker due to limitation of finger movement. For vibration absorption method, dynamic vibration absorbers (DVA) is usually used to eliminate the transmitted vibration from the power tools. DVA is acted as secondary mass to absorb the motion at the natural or operating frequencies of the system (Wagner & Helfrich, 2017). However, the effectiveness of DVA is limited due to narrow bandwidth and this can be solved by introducing the AVC method.

AVC is an active application of force in equal and opposite direction to the forces applied by an external vibration. A precision industrial process can be maintained on a platform essentially vibration free with AVC application. The main components of AVC system are sensors, actuators and controller (Miljković, 2009).There are two methods can be used for the AVC system which are open loop and closed loop control (Maslanet et al., 2012). General idea of AVC system is illustrated in Figure 2.7:

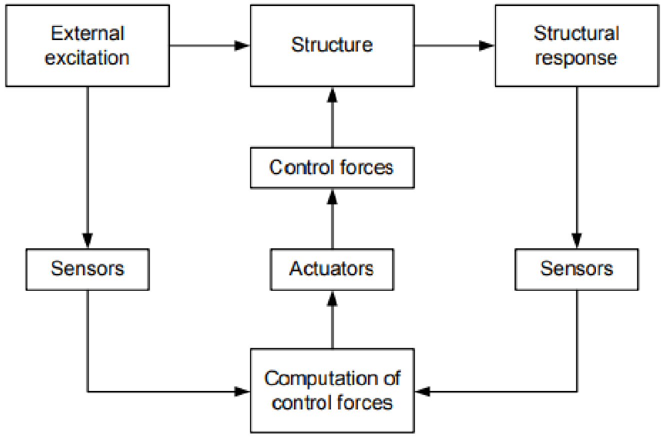


Figure 2.7 General idea of AVC system

From Figure 2.7, the sensor measures the feedback signal and sent it to controller for analysis. The difference between the measured signal and expected output was taken as a counter signal for the actuator to attenuate the disturbances of the plant (Zeqiri & Luma, 2008).

The working principal of AVC system can be explained further in Figure 2.8. In this figure, the sensor is senses the vibration from passive engine mount and send the vibration signal to controller. The controller produces a cancelling signal and fed to the power amplifier to amplify the low voltage signal to the greater voltage signal. The amplified voltage is sent to actuator and it generates a force to cancel the primary disturbance signal which resulting a zero chassis vibration.

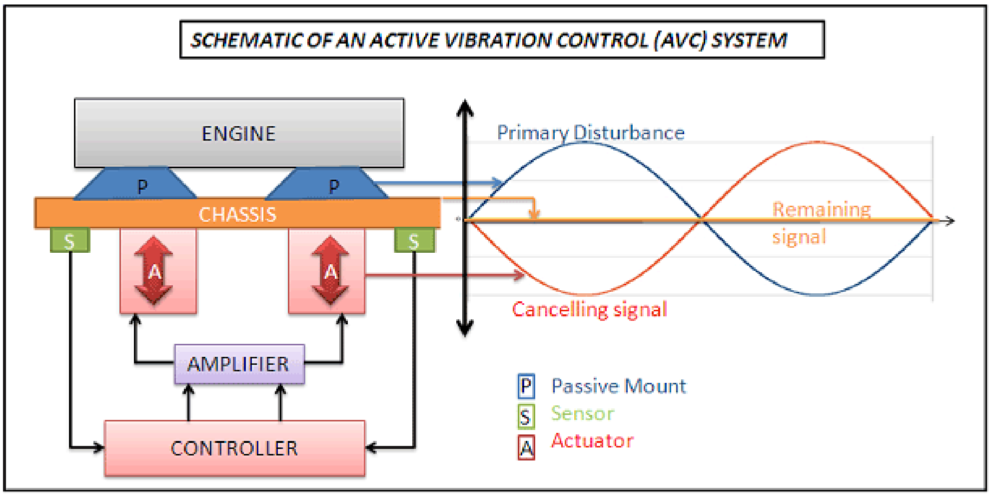


Figure 2.8 Schematic of an AVC system

AVC is based on the concept of superposition and destructive interference as shown in Figure 2.9. It can be achieved by identical force with same application distinction in stage to the vibration.(Miljković, 2009).

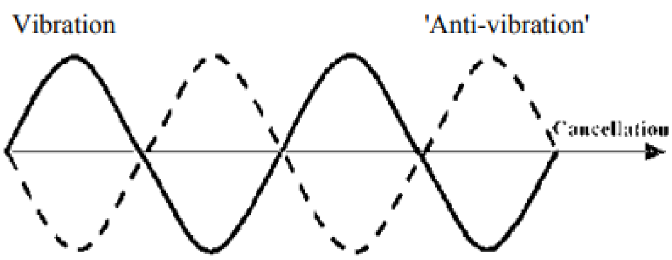


Figure 2.9 Active vibration control is based on destructive interference between vibrations

Consider the case when source of vibration is sinusoidal as:

$$F_1 = A \sin\omega t \tag{2.1}$$

So, the actuator force will be:

$$F_2 = -(A + a) \sin (\omega t + \theta) \tag{2.2}$$

Where F_1 is the vibration force from the source, F_2 is the actuator force, ω is the excitation frequency, A is the amplitude of vibration source, a is the amplitude between two force, θ is the phase error between two force and t is the time required to complete one cycle of vibration.

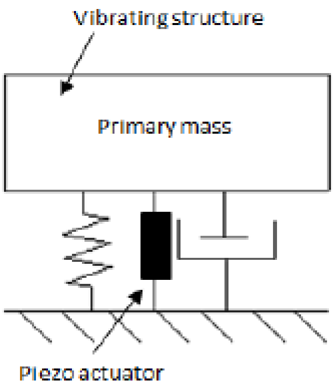
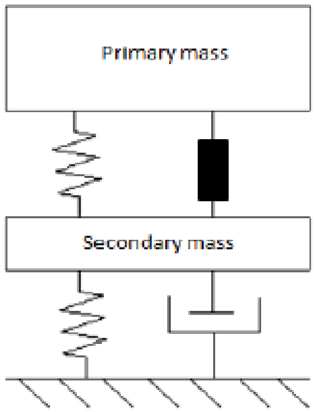
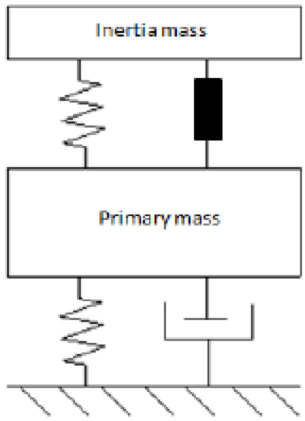
AVC is needed for the improvement of semiconductor wafers and the machines used for the photolithography steps be utilized in a basically vibration-free environment. AVC has been commercially used for diminishing the level of vibration in helicopters which provide a much better light weight mass than traditional passive technologies (Leroy & January, 2013).

2.6 Application of inertia piezoelectric type actuator in AVC system

AVC system could diminish the level of vibration using an extra energy source. This system could create forces that related to variable assignment of system point source for signal control (Wang & Mak, 2016). Piezoelectric actuator is commonly considered as elastic element. In common approach, piezoelectric actuator is considered as a mechanical spring driving a mass with some damping. The piezoelectric effect is modelled as an external force acting on the system (Raimundas Lucinskis, 2016). When driving force (i.e. voltage amplitude) is applied, the amplitude of the displacement will increase up to the mechanical resonance and the phase will change from 0 to 180°. However, the amplification factor can be substantial, leading to increased stress on the piezo element. Therefore, excitation signal will need to be reduced around resonance. (Raimundas Lucinskis, 2016)(Raimundas Lucinskis, 2016)(Raimundas Lucinskis, 2016)

As shown in Table 2.3,there are three methods of coupling the piezo actuators to the structure which are parallel (Oikawa, 2002), series (Liu et al, 2014) and inertia type (Lu et al., 2018).

Table 2.3 Method of coupling the piezo actuator to the structure

Parallel Type	Series Type	Inertia Type
		
Required external preload	Require external preload	No external preload
No added mass	Require secondary mass (below primary mass)	Require inertia mass (above primary mass)
Limited by displacement	Limited by displacement	Limited by force of inertia mass

Based on these arrangements, the parallel and series types are limited by actuator displacement and required external preload. For the inertia type arrangement, the piezoelectric actuator is placed on the top of primary mass and generate the active force by accelerating the inertia mass. This method has been used for an active mount application and reference.

2.7 Summary

From the literature, it can be summarized that:

- The characteristics of the piezoelectric materials are important in order to understand the concept of application for sensors and actuators.
- Several non-linearity effects of piezoelectric material such as hysteresis, creep, saturation and dynamic vibration could affect the overall performance of the piezoelectric actuator.
- Most of the power tools contribute to the high level of vibration and exceed the EAV and ELV values. The daily amount of vibration exposure to the workers should to be controlled.
- Concept of AVC is studied and it can be applied to the power tools to diminish the level of vibration.
- Application of inertia piezoelectric type actuator to AVC system is possible to counter the vibration of the structure.

CHAPTER 3 : METHODOLOGY

3.1 Overview

In this chapter, the design of an inertia piezoelectric actuator with the suspended handle, experimental modal analysis of the handle, characterization of inertia piezoelectric actuator with three different masses and AVC experiment using inertia piezoelectric actuator are presented. Figure 3.1 shows the overall flowchart of this study.

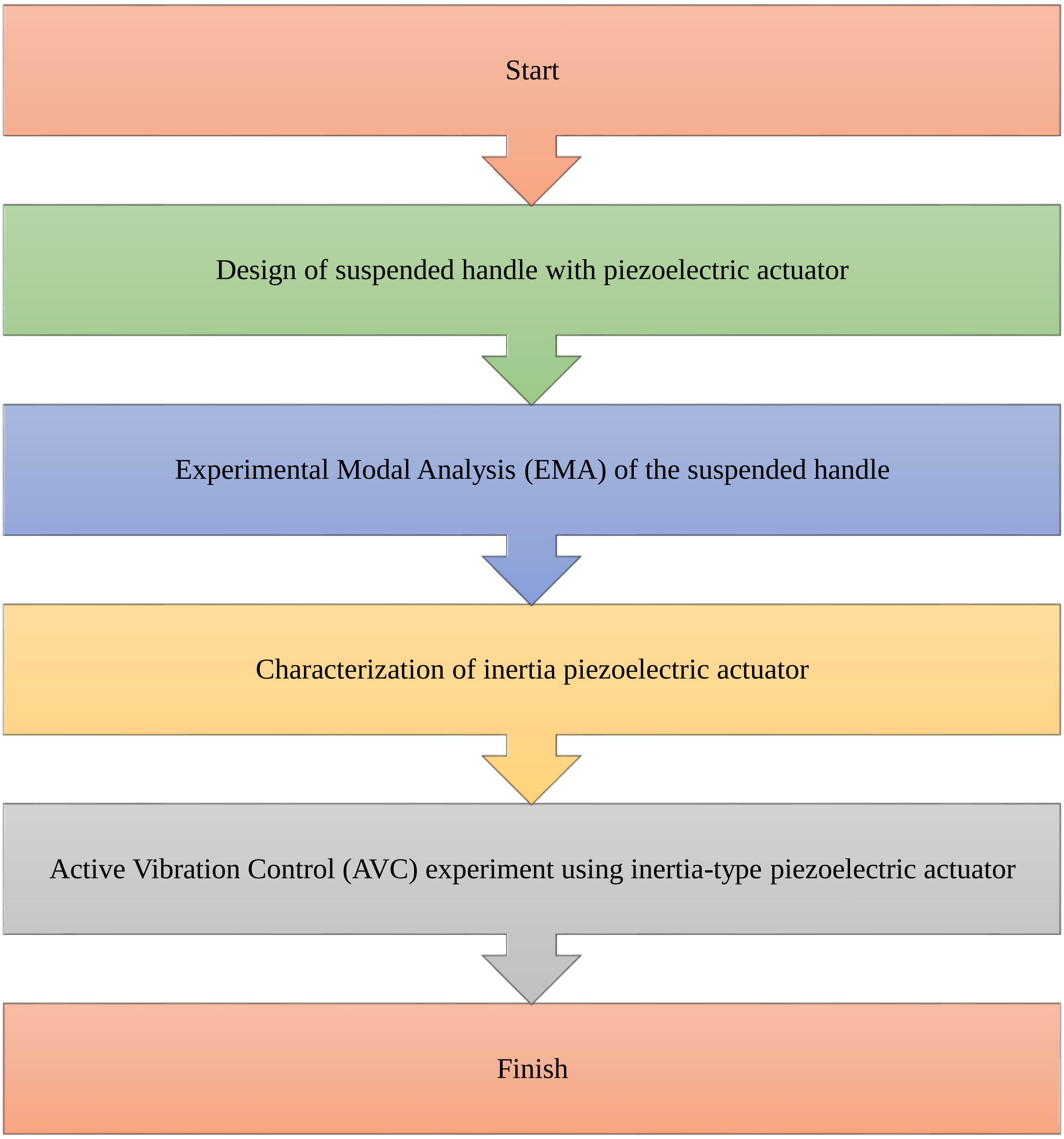


Figure 3.1 Flow chart of the overall project.

3.2 Design of an inertia piezoelectric actuator with suspended handle

The design of inertia type piezoelectric actuator is the main topic of this study This study uses the piezoelectric stack type actuator (P-010.00) as a base actuator to design the inertia type actuator. Three type of inertia masses with same diameter but different in heights (45g, 63g and 95g) are designed in SolidWorks software and fabricated using CNC machine. Figure 3.2 shows the SolidWorks model and the fabricated inertia masses and Figure 3.2 shows SolidWorks model and the fabricated suspended handle.

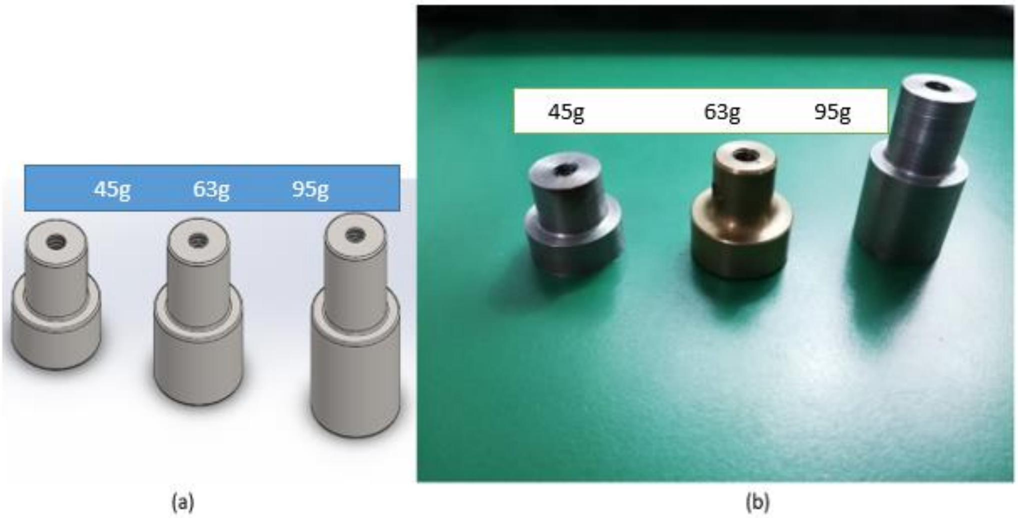


Figure 3.2 Design of the three different inertia masses (a) SolidWorks design (b) fabricated design

From Figure 3.3, the inertia piezoelectric actuator is mounted on the lower beam of the suspended handle. The mass is locked on the top of P-010.00 piezoelectric stack actuator which act as an inertia mass to provide the counter force from the actuator to the handle. The stiff rubber is placed in between the piezo actuator and the inertia mass as a preload.

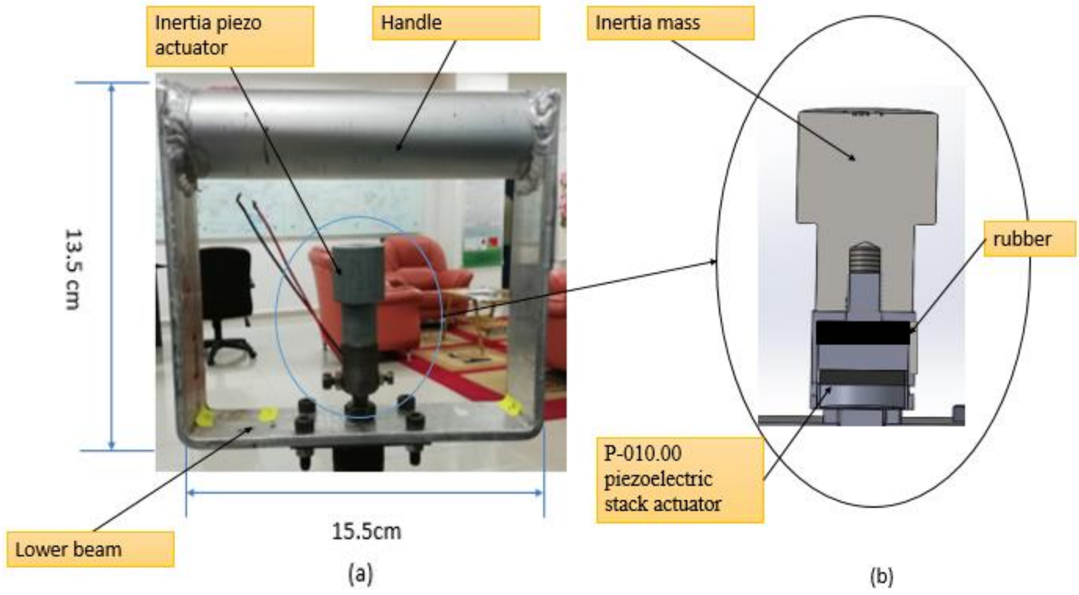


Figure 3.3 Design of the suspended handle with inertia piezo actuator (a) Fabricated design (b) Cross sectional view of inertia piezo actuator

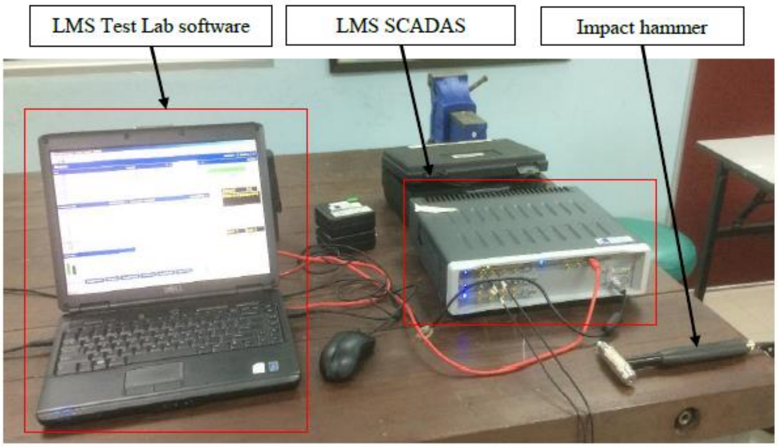
3.3 Experimental Modal Analysis (EMA) of the suspended handle

EMA is an investigation of the dynamic properties of the structures. The dynamic behaviour of the structure in a given frequency range can be modelled as a set of individual mode of vibration. This experiment is executed using LMS Test Lab Impact Testing software to investigate the dynamic properties such as natural frequency, mode shapes and frequency response function (FRF) of the suspended handle.

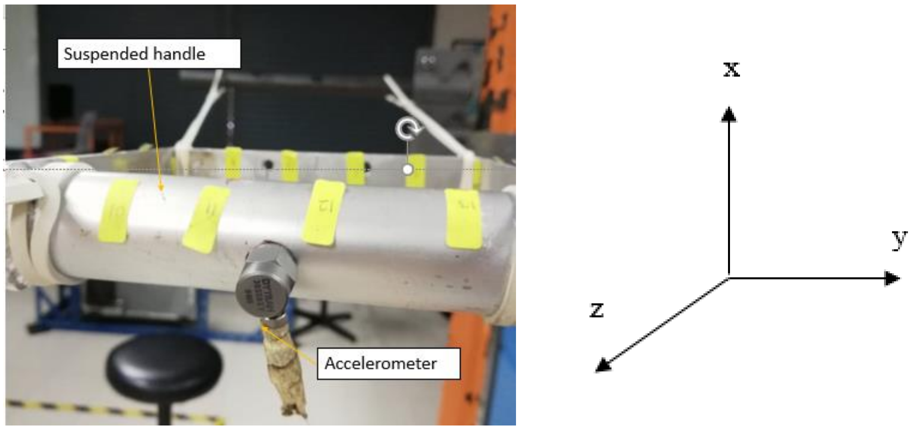
3.3.1 Experimental Setup

The apparatus used in this experiment involving the LMS SCADAS, impact hammer, accelerometer and LMS Test Lab software as shown in Figure 3.4 (a). LMS Test Lab software is used to create the geometry of suspended handle which has 145mm width and 135mm height. Eighteen nodes are assigned and numbered accordingly on the real handle as illustrated in Figure 3.4 (b). Six points are located on top and bottom of the handle, respectively and other three points are located at the left and right side of the handle. An accelerometer is used to measure the acceleration of the handle which allocated at point 11 as a reference point. Impact hammer is used to create an input force to the handle and the natural frequencies, mode shaped and frequency response function (FRF) graph of suspended handle is generated and calculated by LMS Test Lab software.

The measurement is taken in x-axis, y-axis and z-axis direction of suspended handle, respectively.



(a)



(b)

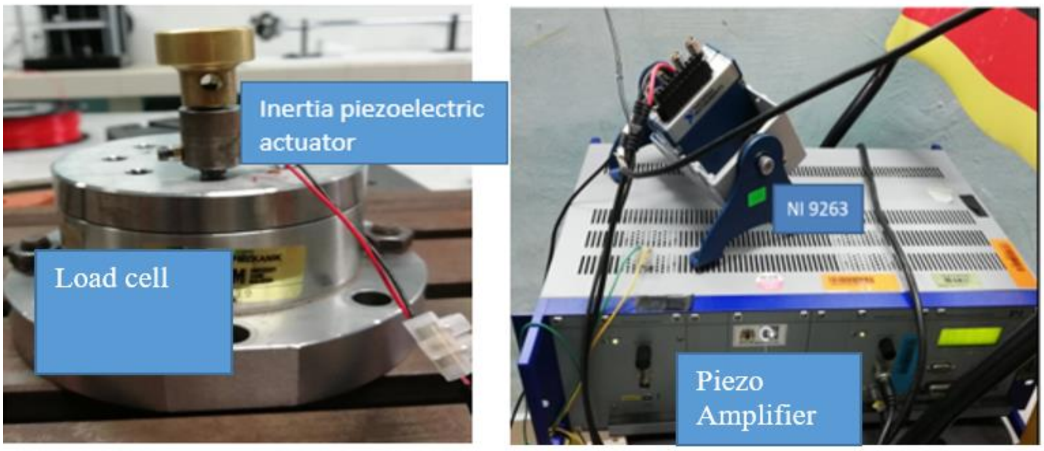
Figure 3.4 (a) Experiment setup of EMA and (b) suspended handle mounting setup

3.4 Characterization of the inertia piezoelectric actuator

In this study, the characteristics of the inertia piezoelectric actuator was performed and the specification of the piezoelectric actuator is shown in Table A1. The inertia piezoelectric actuator is mounted on the top of the load cell as shown in Figure 3.5 (a) to measure the dynamic force base on the following equation:

$$F_a\,(t) = m_i \ddot{x}(t) \qquad (3.1)$$

where m_i is the inertia mass and $\ddot{x}(t)$ is the acceleration of the piezoelectric actuator, respectively.



(a) (b)

Figure 3.5 (a) Setup of inertia piezoelectric actuator mounted on the load cell (b) NI 9263 and piezo amplifier used in this experiment

3.4.1 Experimental setup

The schematic diagram of the experimental setup for the inertia piezoelectric actuator characterization is shown at Figure 3.6. The voltage signal is supplied from the LabVIEW software to NI9263 and amplified to required voltage signal to shake the inertia piezoelectric actuator. The force acceleration signals of the piezoelectric actuator are measured using the load cell and acceleration, respectively and the signals are recorded using IMC devices. Finally, these signals are send to the computer with LabVIEW software for data analysis.

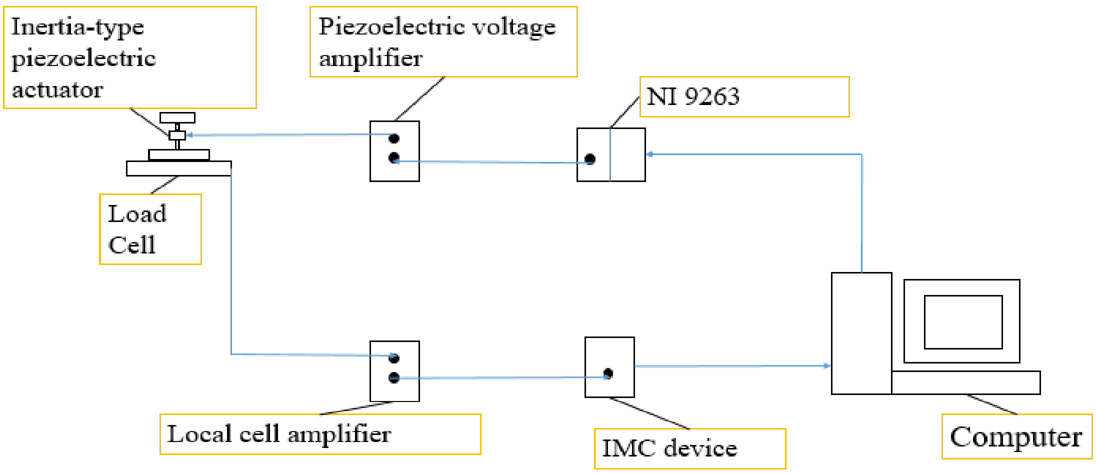
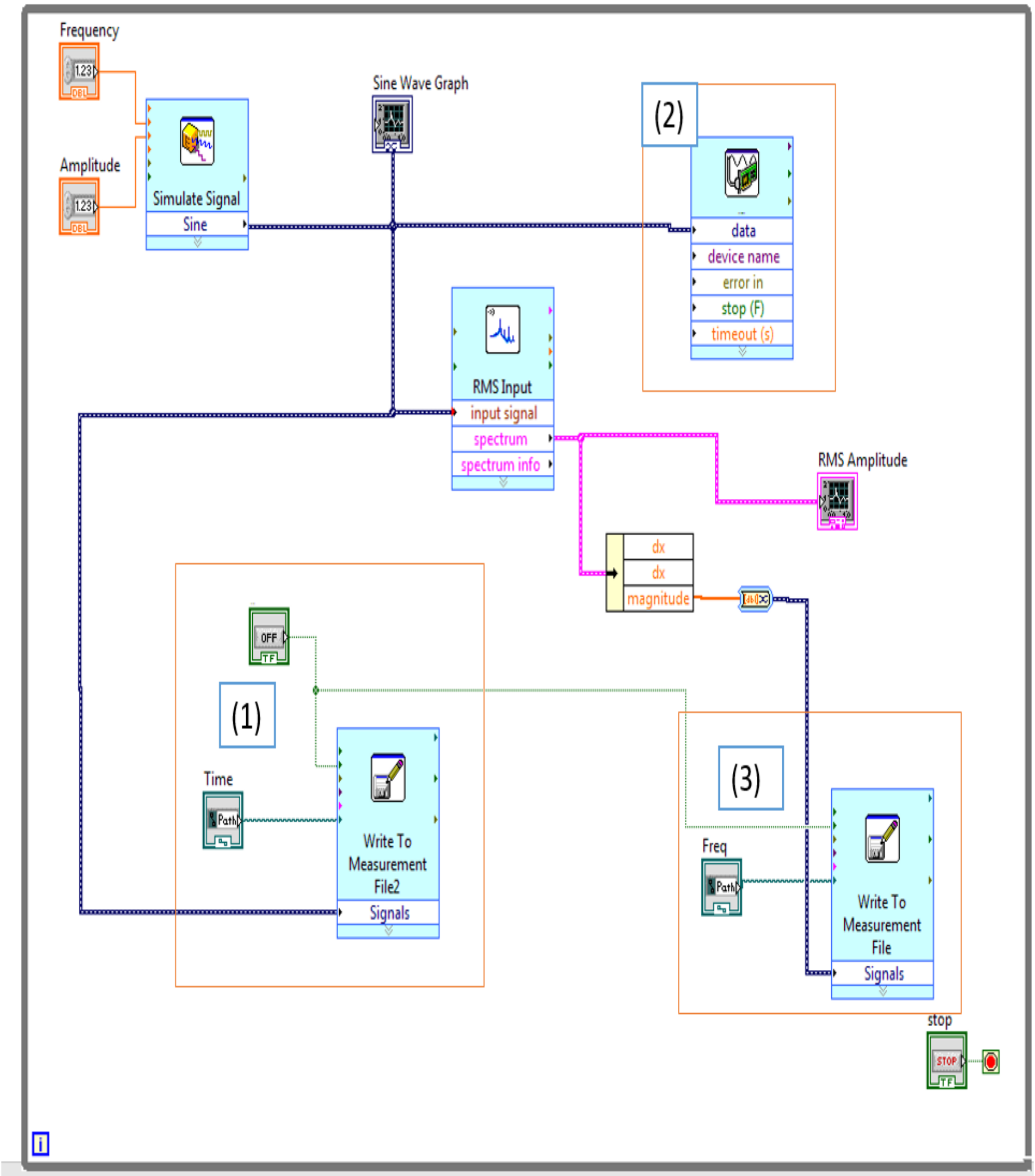
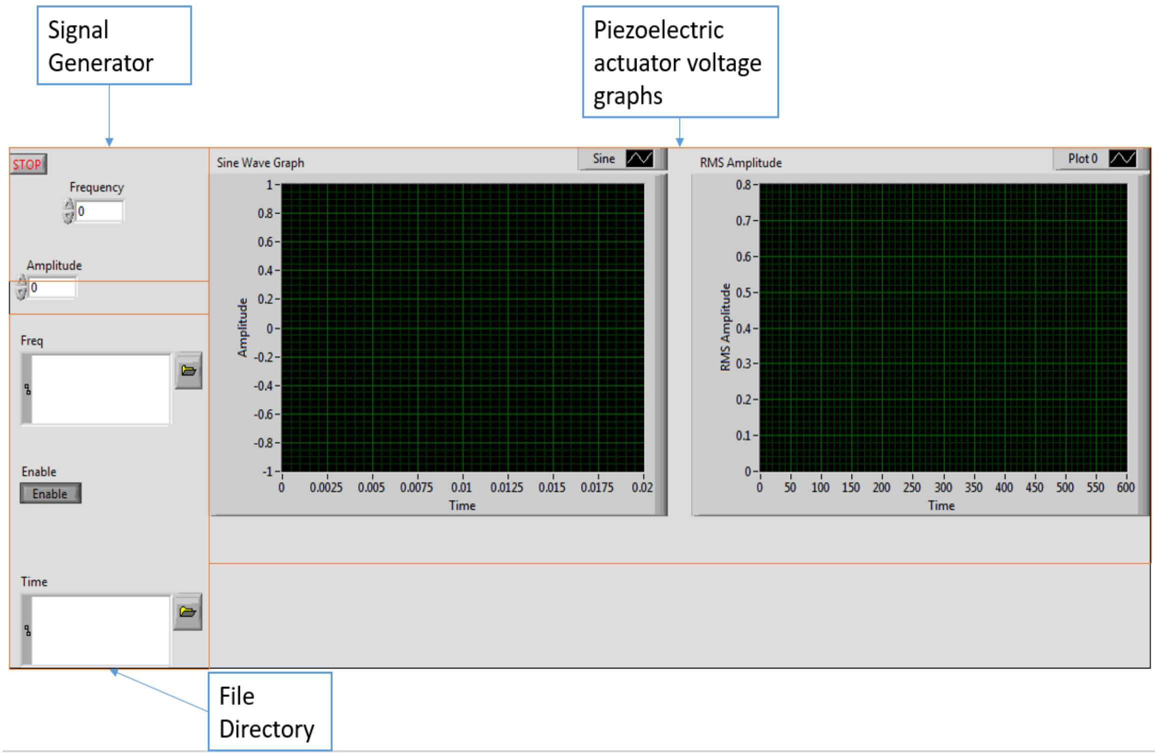


Figure 3.6 Experimental setup for inertia-type piezoelectric actuator characterization

In this experiment, LabVIEW software is used to build the controller block diagram for the characterization of the piezoelectric actuator as shown in Figure 3.7. From the figure, the region (2) of DAQ assistant block was used to produce the input sine wave signal to the piezoelectric actuator. Voltage and frequency is applied through LabVIEW software and the data is recorded in region (1) and the FFT data is converted in region (3). This experiment is conducted for frequency range of 100-500Hz from 1-4 of voltage. This experiment is conducted for all three of masses (45,63,95g), the results are plotted using Excel software. From this experiment, the force and acceleration generated by piezoelectric actuator can be determined.



(a)



(b)

Figure 3.7 (a) Block diagram and (b) Front panel of piezoelectric actuator characterization

3.5 AVC of the inertia-type piezoelectric actuator

The objective of this experiment is to eliminate the vibration of the suspended handle using AVC method. The experiment setup for AVC and the design of PID controller in LabVIEW software have been implemented.

3.5.1 Theoretical model of the AVC system with inertia type piezoelectric actuator

A theoretical model of the AVC using inertia piezoelectric actuator is shown in Figure 3.8. This figure shows the design of overall active suspended handle using two degree of freedom (2DOF) model of a suspended handle with an inertia type piezoelectric actuator that subjected moving base (shaker).

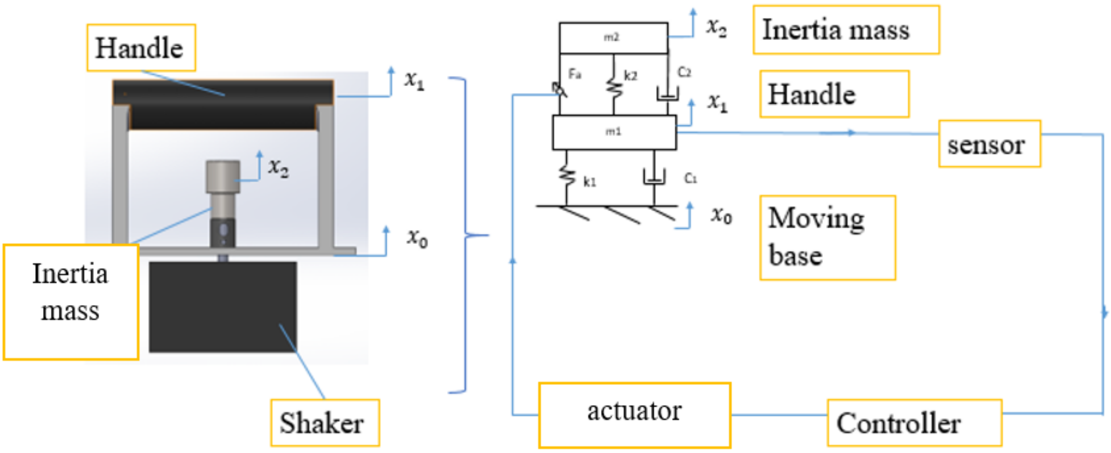


Figure 3.8 Two degree of freedom(2DOF) model of active suspended handle with inertia type piezoelectric actuator subjected to input from shaker (moving base)

In Figure 3.8, the inertia piezoelectric actuator with different masses are inserted between the handle and shaker to produce actuating force, F_a to compensate the vibration of the shaker x_0.The sensor measures the acceleration of the handle, $\ddot{x}_1$ in real time and send the signal to the controller, which can produce the feedback voltage to the actuator to diminish the disturbance produced by the shaker. The equations of motion of the active suspended handle can be written as

From 2nd Newton Law:

For Mass 1:

$$-k_1(x_1 - x_0) - c_1(\dot{x}_1 - \dot{x}_0) + k_2(x_2 - x_1) + c_2(\dot{x}_2 - \dot{x}_1) + F_a = m_1\ddot{x}_1 \quad (3.2)$$

For Mass 2:

$$-k_2(x_2 - x_1) - c_2(\dot{x}_2 - \dot{x}_1) - F_{a1} = m_2\ddot{x}_2 \quad (3.3)$$

For the total counter force of AVC with PID controller:

$$F_a = F_{a1} + F_{a2} \quad (3.4)$$

$$F_a = k_a\left(k_p e(t) + k_i \int_0^t e(t)d\,t + k_d \frac{de}{dt}\right) + m_2\ddot{x}_2 \quad (3.5)$$