STUDY ON DIFFERENT PARAMETERS OF AN INERTIA-TYPE PIEZOELECTRIC ACTUATOR IN REDUCING THE VIBRATION OF SUSPENDED HANDLE MODEL

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DECLARATION

I hereby declare that the work reported in this thesis which I submit to Universiti Sains Malaysia as part of the requirement for the degree award is the result of my personal effort and investigation except for other sources or material taken from other reference where such work has been explicitly cited and acknowledged within text. I also hereby permit Universiti Sains Malaysia to make the thesis available for outside organization use for scholarly research purpose.

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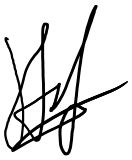

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LIST OF SYMBOLS

Symbol	Description
m	Mass
c	Damping
k	Stiffness
e	Error between desired and system outputs
F_a	Actuator force
K_I	Integral gain
K_P	Proportional gain
K_D	Derivative gain
t	Time
x	Displacement
$\dot{x}$	Velocity
$\ddot{x}$	Acceleration

LIST OF ABBREVIATIONS

Symbol	Description
AFC	Active Force Control
AVC	Active Vibration Control
EAV	Exposure Action Value
ELV	Exposure Limit Value
EMA	Experimental Modal Analysis
HAVs	Hand-arm Vibration syndrome
FRF	Frequency Response Function
PID	Proportional, Integral, Derivative
ZN	Ziegler Nichols

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ABSTRAK

Pada masa ini, kebergantungan kepada penggunaan alat kuasa pegang tangan seperti tukul bicu dan pengisar pneumatik di kalangan pekerja industri adalah sangat tinggi kerana fungsinya yang luas dan kecekapan yang hebat yang menjadikan tugas yang dilakukan menjadi lebih mudah. Walau bagaimanapun, alat ini tertakluk kepada getaran yang tidak diingini semasa operasi yang boleh menyebabkan kesan buruk kepada kesihatan pekerja selepas pendedahan yang panjang seperti perkembangan HAV. Dalam kesusasteraan yang diterbitkan, terdapat kajian simulasi yang sangat terhad mengenai pengecilan getaran pemegang yang digantung menggunakan penggerak piezoelektrik jenis inersia, di mana pelbagai kajian parametrik boleh dilakukan untuk menyiasat prestasi penggerak piezoelektrik. Oleh itu, penyelidikan ini akan menyiasat parameter yang berbeza dari penggerak piezoelektrik jenis inersia dalam mengurangkan getaran model pemegang yang digantung menggunakan simulasi dalam perisian MATLAB dan Simulink. Daripada hasilnya, sistem AVC dengan kaedah penalaan ZN adalah yang paling berkesan dalam mengurangkan getaran pemegang yang digantung berbanding dengan PID (auto dan manual) dan sistem pasif. Di antara parameter penalaan, kaedah ZN dengan parameter yang ditala 10 kali lebih tinggi daripada nilai asal mempunyai prestasi terbaik dengan pengurangan getaran 99.96% pemegang yang digantung. Sebagai kesimpulan, sistem AVC dengan kaedah penalaan ZN adalah penyelesaian yang menjanjikan untuk kawalan getaran, terutamanya dalam penggunaan alat kuasa.

ABSTRACT

Currently, the dependency on the use of handheld power tools such as jack hammer and pneumatic grinder among the industry workers are substantially high due to its wide functionality and great efficiency which make the performed tasks become easier. Nevertheless, these tools are subjected to the undesirable vibration during operation which may cause adverse effects to workers' health after a long exposure such as the development of HAVs. In the published literature, there are very limited simulation studies on vibration attenuation of suspended handle using an inertia-type piezoelectric actuator, whereby a wide range of parametric study can be done to investigate the performance of the piezoelectric actuator. Therefore, this research will investigate different parameters of an inertia-type piezoelectric actuator in reducing the vibration of suspended handle model using simulation in MATLAB and Simulink software. From the result, AVC system with ZN tuning method is the most effective in reducing the vibration of suspended handle compared to PID (auto and manual) and passive system. Among the tuning parameters, ZN method with the tuned parameter of 10 times higher than original value has the best performance with 99.96% vibration attenuation of suspended handle. As a conclusion, the AVC system with ZN tuning method is a promising solution for the vibration control, particularly in the application of power tools.

CHAPTER 1: INTRODUCTION

1.1 Overview

This chapter will discuss briefly on the following topics:

- Project background
- Problem statement
- Objectives
- Project scope

1.2 Project background

Piezoelectric actuators are well known for their compact size, high stiffness and flexibility. However, they are limited by both stroke and displacement (Instrumente, 2009; Sohn et al., 2010). They can generate high actuation force which make them suitable to be used for the vibration isolation of stiff structure such as for machine tools and automotive engines.

This actuator can be incorporated with any industrial machines specifically hand-held power tools such as orbital sander, circular saw and drill which are widely used in the industry. The use of these tools are quite demanding due to its great efficiency and high power generation. They also contribute to a better work productivity among the workers as they are actuated using external power rather than physical energy applied by operators. However, tools have some drawback in which the tools tend to produce a high level of vibration while operating. Table 1.1 shows the vibration level in magnitude generated by several common power tools (HSE, 2019).

Table 1.1: Vibration magnitude of power tools (HSE, 2019)

Tools	Vibration Magnitude (m/s^2)
Road Breaker	12
Demolition Hammer	15
Angle Grinder	2-6
Chainsaw	6
Sander	7-10
Hammer Drill	9

As stated by Health and Safety Executive (HSE), powered tools mostly induce a high level of vibration that exceeds Exposure Action Value (EAV) and Exposure Limit Value (ELV) (Scarlett et al., 2007). As a result, a prolonged exposure to these tools will lead to the development of Hand-arm Vibration syndrome (HAVs), which also known as complex vascular, neurologic and osteoarticular disorders occurring in upper limbs (Mazlan and Ripin, 2015). Table 1.2 illustrates the exposure time limit for different vibration magnitude (Pelmear and Leong, 2000).

Table 1.2: Exposure time limit for different vibration magnitude and noise level (Pelmear and Leong, 2000)

Vibration Magnitude (m/s^2)	Noise Level (dB)	Exposure Time (hours)
4	132	< 8
6	135	< 4
8	138	< 2
12	141	< 1

Basically, there are two common methods being implemented for suppressing vibration levels which are passive and active vibration control (AVC). Passive vibration control involves the use of mechanical device to attenuate the vibration level and the common example is a dynamic vibration absorber (DVA). DVA is a spring-mass system that mounted in a structure (primary mass) to eliminate the harmonic excitation at any given frequency (Sun, et. al., 2008). Nevertheless, this method is ineffective due to narrow bandwidth of frequency vibration attenuation. However, this problem can be solved with the use of AVC method in order to achieve its maximum effectiveness. For this system, it consists of a sensor, controller and actuator which works based on the applied force from the actuator in almost equal magnitude but opposite in direction to counter the vibration of the main structure (Satar, Mazlan, & Jie, 2021)

For the case of vibration generated from a suspended handle, there is very limited study on simulation of AVC method using an inertia type piezoelectric actuator. In fact, the researchers prefer to conduct their research of piezoelectric material on suspended handle using experiment as the obtained results are more accurate and reliable. However, by using simulation, more parametric studies can be done to evaluate the performance of the AVC system. Therefore, this project will study on different parameters of an inertia-type piezoelectric actuator in reducing the vibration of suspended handle model using AVC method by simulation.

1.3 Problem statement

Nowadays, the dependency on the use of handheld power tools such as jack hammer and pneumatic grinder among the industry workers is significantly high due to its wide functionality and great efficiency which make the performed tasks become easier. However, these tools are subjected to an undesirable vibration during operation which may cause adverse effects to workers' health after a long-time exposure. For instance, this uncontrolled vibration level exposure will lead to the development of HAVs among the workers. Also, among the related journal and article available out there, there are very limited simulation studies on vibration attenuation of suspended handle using an inertia-type piezoelectric actuator, whereby a wide range of parametric study can be done to investigate the performance of the inertia type piezoelectric actuator. Therefore, this study will investigate different parameters of an inertia-type piezoelectric actuator in reducing the vibration of suspended handle model using simulation in MATLAB and Simulink software.

1.4 Objectives

I. To characterize the dynamic behaviour of suspended handle and inertia-type piezoelectric actuator using an Experimental Modal Analysis (EMA).
II. To compare the AVC performances in reducing the vibration of suspended handle model using MATLAB and Simulink software.
III. To study the effect of different vibration parameters (mass, stiffness and damping) of an inertia-type piezoelectric actuator to the performance of AVC systems.

1.5 Project scope

This final year project is a simulation-based which involves the use of MATLAB and Simulink software to obtain the performance of different vibration parameters of inertia type piezoelectric actuator in attenuating the vibration of suspended handle. For this simulation, two models will be constructed in the form of block diagram which are passive and active models. On the other hand, this project will also deal with EMA to determine the dynamic behaviour of suspended handle model (primary system) and piezoelectric actuator (secondary system). The results from the experiments will then used as the input for passive and active models. Once the results are filled into both models, the vibration level of suspended handle can be controlled by tuning different value of piezoelectric parameters (mass, spring and damping) inside the active model.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

In this chapter, five main topics will be assessed:

- Characteristic of piezoelectric materials
- Vibration of power tools
- Hand-arm vibration syndrome (HAVs)
- Passive vibration control
- Active vibration control (AVC)

2.2 Characteristic of piezoelectric materials

2.2.1 Piezoelectric effects

‘Piezoelectricity’ comes from a Greek word which defined as ‘electricity by pressure’. The name is given by Hankel in 1881 after discovering the concepts in 1880 from 2 brothers, Jacques, Pierre Curie and a group of scientists. Piezoelectric is classified as a property which exhibited in several materials such as ceramic, bones, DNA, quartz crystal and many more. The unit cell for most of mentioned material is typically symmetrical in shape. Moreover, the materials might also be in irregular structure but they are electrically neutral. The material will get deformed in response to the applied mechanical force. In other words, this leads the atoms inside the materials to move closer to each other and some will behave in the opposite way. Consequently, electric charge in the crystal will be imbalance resulting from movements of positive and negative charges which distributed on two sides of the structure. A dipole moment is created which then will produce voltage when electrical current is supplied (Kanazawa, 2008). The effect is explained by the simple molecular model in Figure 2.1

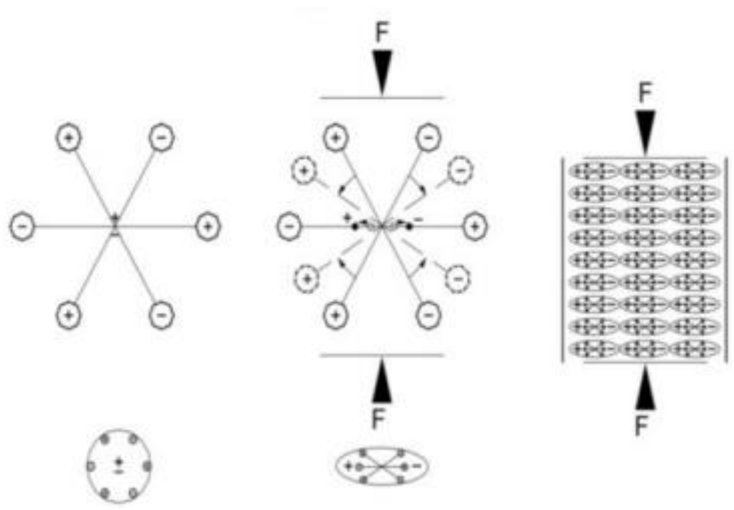


Figure 2.1: Effect of applied force to piezoelectric materials (Kanazawa, 2008)

On the other hand, the system also able to work in a reverse direction. Once the electrical energy is supplied to the crystal, it will result the crystal structure to get expand and contract. Indirectly, this causes the structure to dissipate mechanical energy in the form of moving wave. Figure 2.2 depicts the behaviour of atoms in piezoelectric materials when they are exposed to electric current.

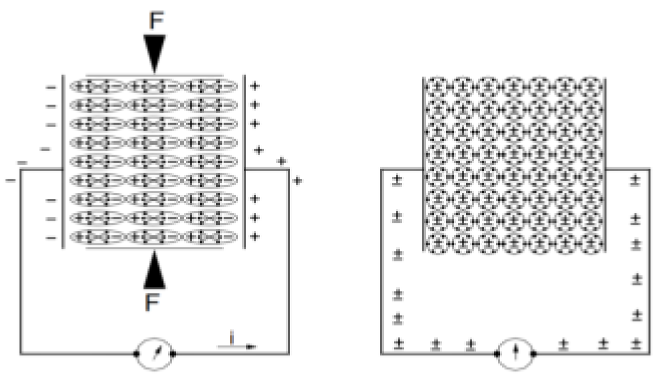


Figure 2.2: Effect of piezoelectric material in response to applied electric field (Kanazawa, 2008)

2.2.2 Piezoelectric actuator

Piezoelectric actuator is a device or transduce that converts electrical energy into a mechanical displacement or stress based on a piezoelectric effect. This device is sandwiched to a piezoelectric material for actuating capability purpose. When voltage is supplied, the expansion and contraction of piezoelectric will generate a force to the actuator which will be in the form of extension and contraction motions. It is also controllable and has a fast response, generate a low quantity of heat, compact size and light in weight. The great behaviour and performance of piezoelectric actuator makes it widely being used in the area of vibration control. In contrast to traditional actuator, the piezoelectric actuator has the following properties (Sui et al., 2012):

1) Low power consumption: The piezo effect uses electrical energy only when it converts to motion.

2) Fast expansion: The fastest response time is provided by piezoelectric actuators, which is measured in microseconds.

3) No wear and tear: There are no gears or rotating shafts in piezoelectric actuators. Therefore, there is no wear and tear. The performance of a piezoelectric actuator has been tested after billions of cycles, and the results reveal that there is no change in performance.

In general, a single piezoelectric actuator is only capable of generating a small output displacement. Therefore, it is more practical to use a stack of piezoelectric actuator in order to meet the system requirement which typically generating a large vibration force while in operation. The stack of piezoelectric actuator is done by assembling thin wafers of electroactive ceramic material electrically connected in parallel as illustrated in Figure 2.3.

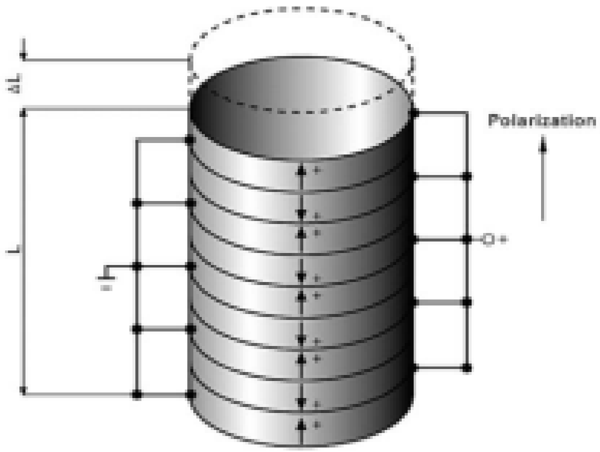


Figure 2.3: Stacked piezoelectric actuators (Sui et al., 2012)

Instead of vibration control, piezoelectric actuator also been marketed in various technologies such as in robotics, camera and biomedical applications. NEC's dot-matrix printer, which is utilised in mass production, was the first industrial application of piezoelectric actuators. This project is success through the intervention of multilayer actuator (MLA) by The Penn State University (Uchino et al., 1981). Furthermore, piezoelectric actuators are well-known for their high-speed positioning and nano-resolution capabilities. As a result, they play an important role in scanning probe microscopes and biotechnology, just like electric motors do in automobiles, and also other applications (Leang et al., 2010).

2.3 Vibration of power tools

The vibration magnitudes of power tools are basically determined using two approaches (ErgoPlus, 2019):

- Declared vibration values provided by manufacturers
- Measurement with a vibration meter

The first method is very convenience since the values already provided by the manufactures, however the values do not necessarily represent the actual values for specific work situation. For instance, the tools might be designed in a different environment and the provided data sheet value might be perfectly accurate in that specific location only. When it is used in the current location, the vibration value might be offset from stated value due to different environment while operating the tool. In general, there are many factors affecting the vibration magnitudes, such as the type of product, condition of power tool, worker's technique and many more. The best way is still depending on the experimental works in order to determine the vibration magnitude of desired power tools. The second method is more preferable as the vibration value can be obtained through measurement tools such as a vibration meter. By referring to Table 1.1 previously, we can see vividly that most of the power tools are still operating at vibration level exceeding EAV (2.5 m/s^2) and ELV (5.0 m/s^2).

As seen in Figure 2.4, it shows a relationship between vibration magnitude and exposure duration. The trend describes the higher the vibration magnitude, the lower the allowable exposure time (hours). The green region denotes the safe zone, orange zone shows high-risk and lastly, the red zone is known as the dangerous zone, which must be avoided if possible (Reactec, 2019).

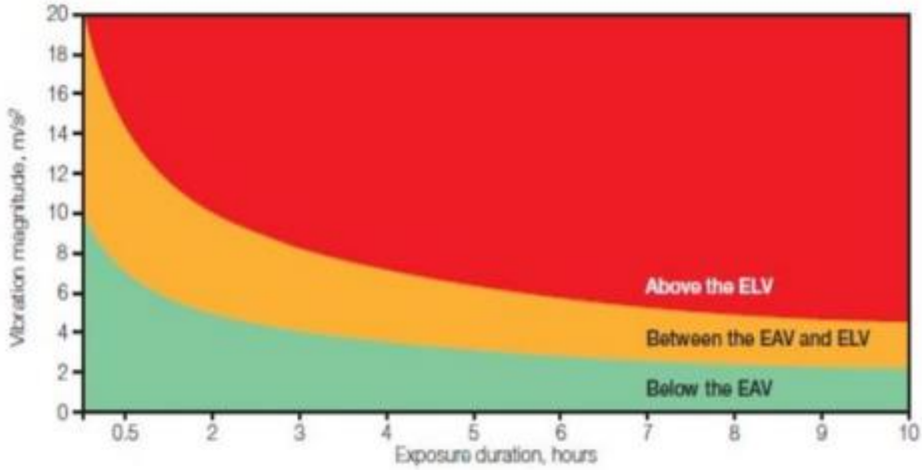


Figure 2.4: Relationship between vibration magnitude and exposure duration (Reactec, 2019)

2.4 Hand-arm vibration syndrome (HAVs)

HAVs is a common occupational disease among the workers after prolonged use of handheld vibrating tools. HAVs could affect sensory, vascular and musculoskeletal system (Campbell, et. al. , 2017). The industries such as construction, mining and forestry are more prone to the risk of HAVs as they are dealing the most with vibrating tools. The sign of the disease usually develops after long exposure to the vibrating tools which could cause permanent injury as well as long lasting pain in the hand and arms which leads to difficulties in performing daily activities (Azmir, et. al., 2016). According to Nieradko Iwanicka (2019), Raynaud's phenomenon is one of the most common vascular signs of HAVs with finger blanching and vibration white finger (VWF) as depicted in Figure 2.5 (Nieradko-Iwanicka, 2019).

Figure 2.5: Sign of HAVs (blanching)(Health and Safety Executive, 2010)

On the other hand, musculoskeletal system might also be affected as a result of HAVs disease. Musculoskeletal symptoms occur through direct vibration-induced damage to musculoskeletal tissues. The person might feel weakness, discomfort and pain on the hands, wrists, forearms and elbows.

Besides that, HAV might also develop not only due to cumulative exposure to intense vibrating tools, but also due to other factors such as age, smoking and pre-existing medical conditions. Once the person is suspected to suffer HAVs, he or she should meet a specialist so that the condition can be evaluated based on severity of signs and symptoms. Then, appropriate therapy can be prescribed based on the classification of Raynaud phenomenon as shown in Figure 2.6.

Table 1. Stockholm Workshop Scale; each hand should be graded separately: *A) Classification of cold-induced Raynaud phenomenon in HAVS[19]; B) Sensorineural stages of HAVS.[20]*

A)

STAGE	GRADE	DESCRIPTION
0	None	No attacks
1	Mild	Occasional attacks affecting the tips of ≥1 fingers
2	Moderate	Occasional attacks affecting distal and middle (rarely also proximal) phalanges of ≥1 fingers
3	Severe	Frequent attacks affecting all phalanges of most fingers
4	Very severe	As in stage 3, with trophic changes in the fingertips

B)

STAGE	DESCRIPTION
0SN	Exposed to vibration but no symptoms
1SN	Intermittent numbness with or without tingling
2SN	Intermittent or persistent numbness, reduced sensory perception
3SN	Intermittent or persistent numbness, reduced tactile discrimination or manipulative dexterity

HAVS—hand-arm vibration syndrome, SN—sensorineural.

Figure 2.6: A) Classification of cold-induced Raynaud Phenomenon, B) Sensorineural stages of HAVs (Pelmear and Leong, 2000)

Based on the research from Heaver (2011), HAVs is a serious and continuous disorder which need an early prevention (Heaver, et. al., 2011). A proper vibration regulation such as limited exposure duration to vibrating machine must be enforced in order to reduce the risk of HAVs among the industrial workers. Thus, employees can be protected from poor health caused by the vibration (Health and Safety Executive, 2005). Furthermore, the workers could also wear vibration-reducing gloves while operating the vibrating machine or reduce usage time on the tools to minimize the risk of HAVS.

2.5 Passive vibration control

2.5.1 Vibration isolation method

Vibration isolation is a method of object isolation from the vibration source in order to reduce the transmission of vibration energy to the primary system or object. Isolation between human hand and power tools can be achieved through the use of anti-vibration gloves which frequently used by industries. Fig 2.7 illustrates the example of anti-vibration glove.

Figure 2.7: Anti vibration glove (Stihlusa, 2021)

Apart from reducing the transmission of vibration to the hand, this glove also used for hand protection from any abrasion, extreme temperature and corrosive chemicals. In addition, the glove is also coated with vibration dampening polymer. Relying on anti-vibration glove solely is not a good solution since it does not provide a consistent protection to the user as there are many factors that could influence the transmissibility of vibration from the vibrating machinery. The example of factors are directions of applied force, frequencies of vibration, dynamic properties of materials and the interactions between the hands and tools (Griffin, 1998; Hewitt et al., 2016a). Passive vibration method also limited to the narrow bandwidth of operating frequency for the vibration attenuation. In other words, for the vibrating power tools operated outside of this range, this method will no longer useful and might leads to high vibration levels felt by the workers who handle this tool. Based on the study conducted by Hewit and his team, they found that anti vibration gloves may only be effective when operating at frequency of higher than 400 Hz (Hewitt et al., 2016b).

2.5.2 Vibration absorption method

Vibration absorption in this section is specifically refers to the function of absorber in absorbing the vibration produced by primary system. The example of the system applied this mechanism is a DVA. DVA is a secondary mass-spring system added to the primary mass which then results to 2 degree of freedom (2DOF) system. The system is designed to absorb the input disturbance by shifting the motion to the new added mass called as absorber mass. Consequently, the vibration amplitude of primary system will be ideally zero. Nevertheless, the system will only be effective if the driving frequency of DVA is close to the excitation frequency. Therefore, the application of this system is only limited to an operational range of frequency (Wagner and Helfrich, 2017). Figure 2.8 shows the theoretical model of the structure with DVA.

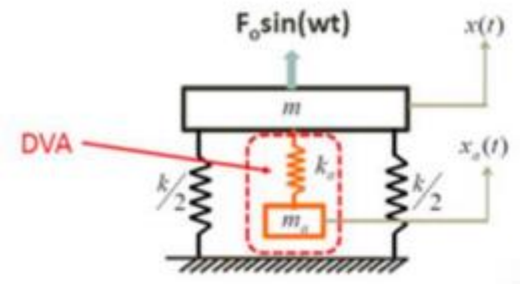


Figure 2.8: 2DOF model of DVA attached to primary system (Mazlan, 2019)

Furthermore, Patil (2019) also has studied the effectiveness of DVA in suppressing the vibration of grass trimmer. In the research, Dunkley's equation was used to design the variable stiffness with dual masses vibration absorber. The study focussed on changing the effective stiffness in the system and its natural frequency by adjusting the absorber masses along the cantilever beam. As a result, the vibration of handle has successfully reduced by 80% (Patil, 2019).

2.6 Active vibration control (AVC)

AVC is an active application of force in equal and opposite direction to imposed force. The fundamental theory of AVC is introduced by Lueg in the early 1830s (Sidoti, 2014). AVC works based on the concept of superposition and destructive interference. When an opposite and equal magnitude force is applied to the vibration source, two sources will cancel out each other and therefore, the resultant vibration will become zero in amplitude (Jovanović et al., 2013).

Consider the disturbance is in the form of sinusoidal wave as illustrated in Figure 2.9, the equation can be shown as follows:

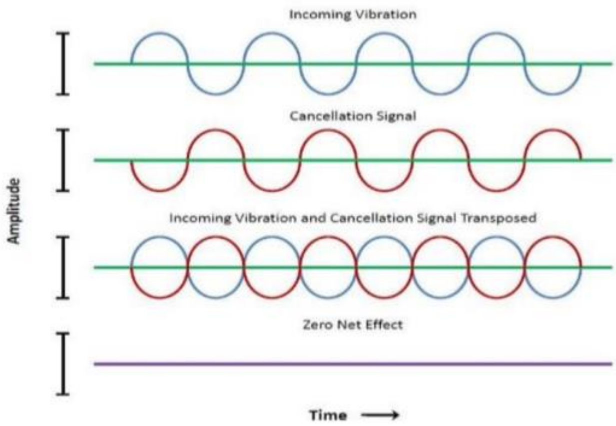


Figure 2.9: Superposition of opposite waves (Herzan, 2019)

$$F_1 = A \sin \omega t \qquad (2.1)$$

The counteract force produced is:

$$F_2 = -(A + a) \sin (\omega t + \theta) \qquad (2.2)$$

Where, a and θ represent the amplitude and the phase error between two forces respectively.

Normally, the generated source waves in actual application do not always produce a constant waveform either in sinusoidal or cosine waves. It can be in various waveform depending on various factors. The resultant force, F_1 can be minimized near to zero if amplitude and phase are closely matched. Figure 2.10 shows the general idea of AVC (Miljković, 2016).

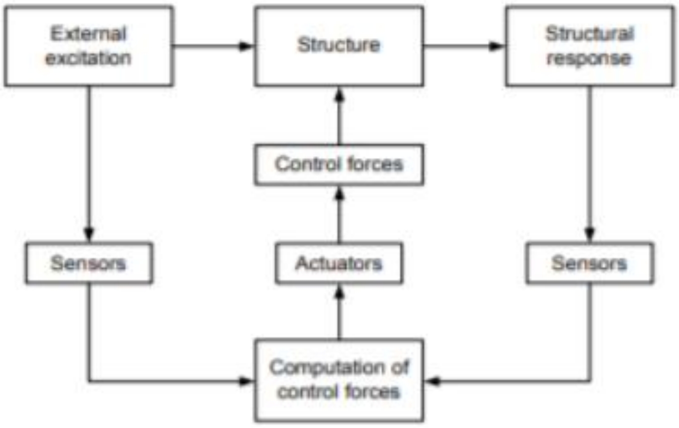


Figure 2.10: General idea of AVC system (Miljković, 2016)

As seen in Figure 2.10, AVC system basically comprises of several major components which are sensor, controller and actuators. Sensor is utilized to measure the motion of the system which typically measuring acceleration parameters. Then, the controller will interpret the sent signal and the processed signal will trigger the actuators to generate a counteract force. There are many types of actuators used in vibration control which can be designed using different principle namely as piezoelectric, electrodynamics and hydraulic actuators. A piezoelectric actuator (PZT) is a device that uses the counter piezoelectric effect to create a displacement when a voltage is applied to it, and vibrating it generates a voltage (Sui, Xiong, & Shi, 2012). It is an electric field-driven, controlled, and perfect micro-displacement actuator. PZT actuators have a fast response time, a compact volume, a tiny amount of heat, and a low mass. PZT actuators have a lot of potential in the field of AVC because of their high performance.

AVC system consists of 2 methods which are feedback and feedforward. Feed-forward system constantly senses incoming vibrations and corrects them before errors occur while feedback system adjusts the errors as they take place. In terms of complexity, feed-forward leads in the system as it requires analog filters combined with analog delay lines. Due to that, most of AVC systems used feedback systems. Figure 2.11 illustrates a block diagram of AVC feedback system (Miljković, 2016).

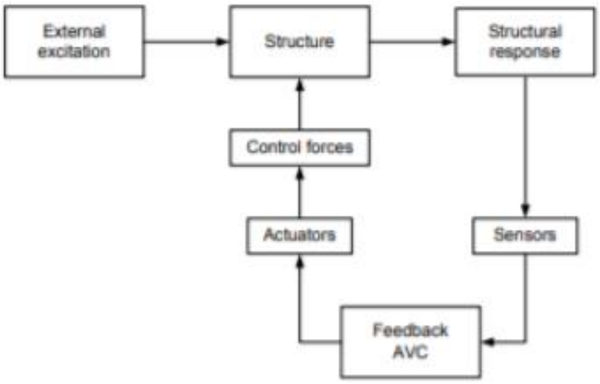


Figure 2.11: Block diagram of AVC feedback system (Miljković, 2016)

For further comparisons between the feedback and feedforward system, it can be seen from Table 2.1. The pros and cons of each system is discussed thoroughly, and the outcome is simplified in the table.

Table 2.1: Comparison between feedback and feedforward system

Type of Control	Advantages	Disadvantages
Feedback	- Simple to design - Guaranteed stability - Global method - No process model is required	- Errors can only be corrected after arised - Take input from one sensor only - Limited bandwidth - Vibration might increase outside the operational range
Feedforward	- Corrects errors prior to occurrence - No model required - Wider bandwidth	- Requires reference signal - Local method

Alkhatib and Golnaraghi (2003) in their research had stated that the performance and functionality of AVC system depend on control algorithms. The control algorithms applied for vibration attenuation has been reviewed and presented by Kumar and Narayanan in 2017. The typically used algorithm is classical control algorithm such as direct proportional feedback, constant gain velocity feedback (CGVF) and constant amplitude velocity feedback (CAVF). Furthermore, optimal control algorithm also be employed in AVC system such as linear quadratic regulator (LQR) and linear quadratic Gaussian (LQG). Next, proportional integral derivative (PID) controller is also frequently employed in AVC application due to its simplicity and robust performance (Kumar and Narayanan, 2007). The block diagram of PID controller is shown in Figure 2.12 as follows:

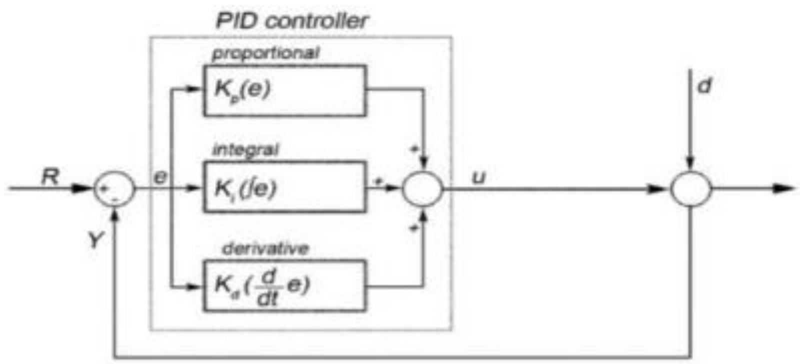


Figure 2.12: Block diagram of PID controller (Kumar and Narayanan, 2007)

The output of the PID controller is generalized as follows:

$$u(t) = k_p e(t) + k_i \int e\,dt + k_d \frac{de(t)}{dt} \qquad (2.3)$$

Where, *e(t)* is the tracking error, *Kp* is the proportional gain, *Ki* is the integral gain and *Kd* is the derivative gain. Ziegler–Nichol's method can also be applied to tune the gains theoretically to attain the desirable performance.

Table 2.2: Vibration level under different combination of gains (Gülbahçe and Çelik,2018)

K_p	K_i	K_d	Magnitude (mV)	Decrease in magnitude (%)	Decrease in magnitude (dB)
Uncontrolled			485.70	—	—
7.1	0.0061	70.46	27.72	94.29	24.8
6.1	0.0061	70.46	25.18	94.82	25.7
8.1	0.0061	70.46	31.87	93.44	23.7
7.1	0.0051	70.46	28.42	94.15	24.6
7.1	0.0071	70.46	32.64	93.28	23.4
7.1	0.0061	50.46	28.85	94.06	24.5
7.1	0.0061	90.46	34.90	92.81	22.8

Gülbahçe and Çelik (2018) had conducted an experimental study to identify the effectiveness of PID controller for AVC system, whereby the goal is to reduce the vibration level of a smart beam. Firstly, Ziegler-Nichol's method is used to determine the gain values and then different gain combinations are tuned around the theoretical values. Based on Table 2.2, it can be noticed that the highest magnitude decrement is accomplished when K_p = 6.1, K_i = 0.0061, K_d = 70.46 and the magnitude is decreased by 94.82% (25.7dB) which shows the better result compared to Ziegler–Nichol's method (94.29% (24.8 dB)). In simplest words, a little adjustment is often needed after obtaining the gains using Ziegler-Nichol's method.

Next, performance of PID, PD, PI and P controllers also can be evaluated from the previous experiment and the results are shown in Table 2.3.

Table 2.3: Performance of different controllers for vibration attenuation (Gülbahçe and Çelik, 2018)

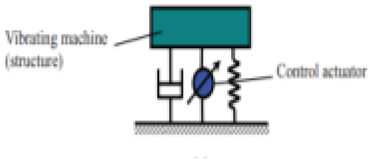
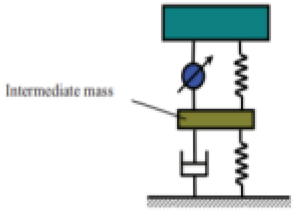
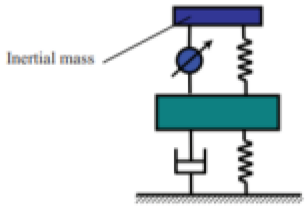
Type of Controllers	Percentage of Attenuation (%)
P	93.6
PI	93.94
PD	94.31
PID	94.82

In a nutshell, it is clear that PID controller gives the best performance of vibration attenuation among the controllers.

2.6.1 AVC using inertia-type piezoelectric actuator

There are 2 fundamental approaches when piezoelectric actuator is used. The first one is by directly bonding the piezoelectric actuator to the structure (Choi et al., 2011). By using this method, it will be convenient and works well for small-sized structures which have a high flexibility. The second method is by fabricating an active mount using a piezoelectric actuator. Generally, this active mounts for vibration control can be divided into three types which are series, parallel and inertial. There are active and passive elements in each type of active mounts which capable of generating a counter force to the vibration. Table 2.4 describes the comparison between each type of the active mounts.

Table 2.4: Comparison of active mounts for piezoelectric actuator (Choi et al., 2011)

a. Parallel Type 	b. Series Type 	c. Inertial Type 
Elements connected in parallel	Elements connected in series	Utilizes active element and an inertia mass
Requires small dynamic stiffness of active element	Better vibration isolation of passive element	Generates reaction force by the inertia mass
	Requires support of static load by active element itself	Protects piezoelectric actuator from being damaged by large force

The schematic configuration of an inertia-type piezoelectric actuator is depicted in Figure 2.13. From the figure, it can be observed that the actuator consists of an inertia mass placed on top of piezoelectric actuator, housing and pre-stress spring. The actuating force will be generated in response to the applied voltage and the force acting on the inertia mass will create a reaction force to the opposite side of the piezoelectric actuator.

Theik and Ahmad Mazlan (2020) had experimentally studied the performance of inertia-type piezoelectric actuator in AVC system using different inertia masses. In the study, three different controllers have been developed (PID auto tuning, PID manual tuning and PID-AFC controller) for the system. From the result, it was reported that larger inertia mass resulted to greater vibration attenuation for the suspended handle which lead by PID-AFC controller, followed by PID manual tuning and PID auto tuning.

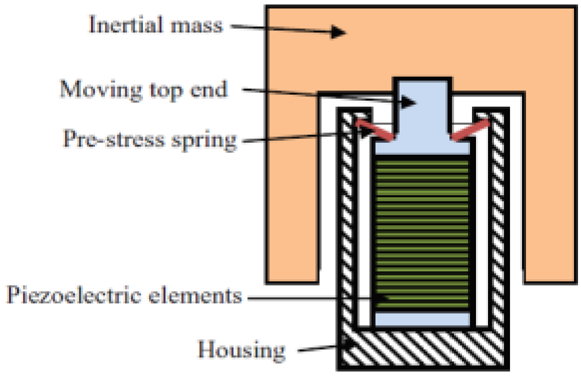


Figure 2.13: Schematic configuration of inertia type piezoelectric actuator (Choi et al., 2011)

Figure 2.14 presents the relationship of voltages and actuating force obtained from the experiment (Choi et al., 2011). The measured actuating force on different input voltages can also be expressed using Equation (2.4). From the equation, it shows that actuating force is directly proportional to the applied voltage and this relationship is verified experimentally as shown in Figure 2.14.

$$F_a(t)(N) = \alpha_1[v_P(t)]^{\alpha_2} \tag{2.4}$$

Where, α_1 and α_2 represent the proportional and exponent coefficient respectively.

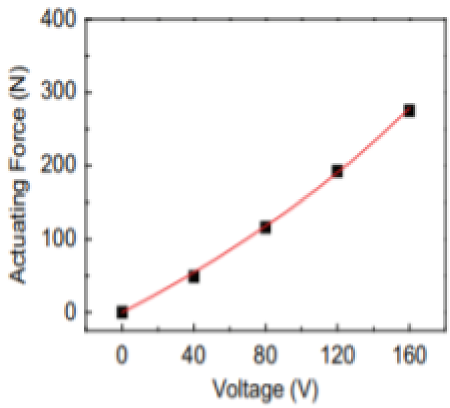


Figure 2.14: Actuating force versus applied voltage (Choi et al., 2011)

The result of vibration reduction utilising this inertia-type piezoelectric actuator is shown in Figure 2.15. The dotted line indicates that piezoelectric actuator is not switched on (uncontrolled) while the solid line corresponds to the piezoelectric actuator after activated. It can be seen clearly that accelerance values at 2 peaks of resonance frequencies are significantly reduced by the activation of inertia-type piezoelectric actuator. Thus, the effectiveness of an inertia-type piezoelectric actuator in vibration reduction has been proved experimentally.

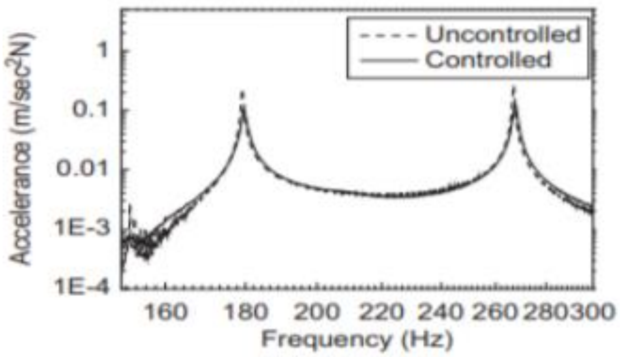


Figure 2.15: AVC using inertia-type piezoelectric actuator (Choi et al., 2011)

2.7 Summary

From the literature review, the following summary can be made:

- The unique properties of piezoelectric material make it possible to be employed in a wide range of application such as actuator and sensor.
- Most of handheld power tools in the industry are operating at the vibration level exceeding EAV and ELV.
- Uncontrolled exposure to vibrating power tools could resulted common occupational disease among the workers known as HAVs which can be felt by having pain and numbness in hands. A proper vibration regulation such as limited exposure duration to vibrating power tools must be enforced in order to reduce the risk of HAVs.
- Passive vibration control such as vibration isolation and absorption are the solutions in attenuating vibration level but this is only limited to certain range of operating frequency.
- AVC generates an active counter force to the incoming disturbance signal for vibration control. The effectiveness of an inertia-type piezoelectric actuator integrated with sensor and controller in the vibration attenuation has been proved experimentally. However, the simulation study of inertia-type piezoelectric actuator performance with different system parameters is yet been investigated.

CHAPTER 3: METHODOLOGY

3.1 Overview

In this chapter, the EMA of suspended handle and inertia-type piezoelectric actuator, theoretical model development, and the passive and active Simulink model constructions are presented. Figure 3.1 shows the overall flowchart of the project.

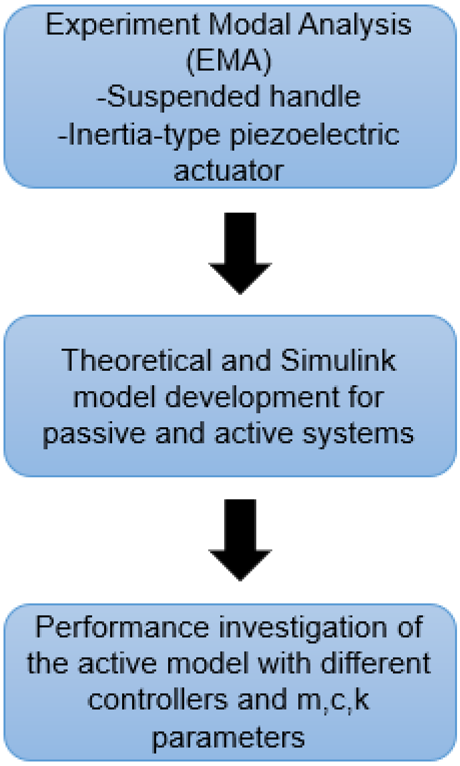


Figure 3.1: Flowchart of the project

3.2 Experiment Modal Analysis (EMA)

EMA is conducted with the purpose of determining the natural frequencies, mode shapes and frequency response function (FRF) values for each system (suspended handle and inertia-type piezoelectric actuator). The values include m_1, c_1, k_1 for the primary system (suspended handle) while m_2, c_2, k_2 for the inertia-type piezoelectric actuator. Once these values are obtained, they will be used in the Simulink model construction.

3.2.1 EMA of suspended handle

EMA of suspended handle is conducted to determine the dynamic properties of the system which includes natural frequencies, mode shapes and FRF. This is an important procedure to get an accurate approximation of natural frequencies to protect the occurrence of resonance on the handle structure. From the FRF graph, we can obtain the natural frequencies of the system which are represented by the peaks of the graph. On the other hand, mode shapes will illustrate the vibration pattern of the structure when excitation frequencies are equivalent to the natural frequencies of the system (resonance case). For the experimental setup, several equipment will be used such as LMS SCADAS, LMS Test Lab software, accelerometer, calibrator, and impact hammer, as shown in Figure 3.2.

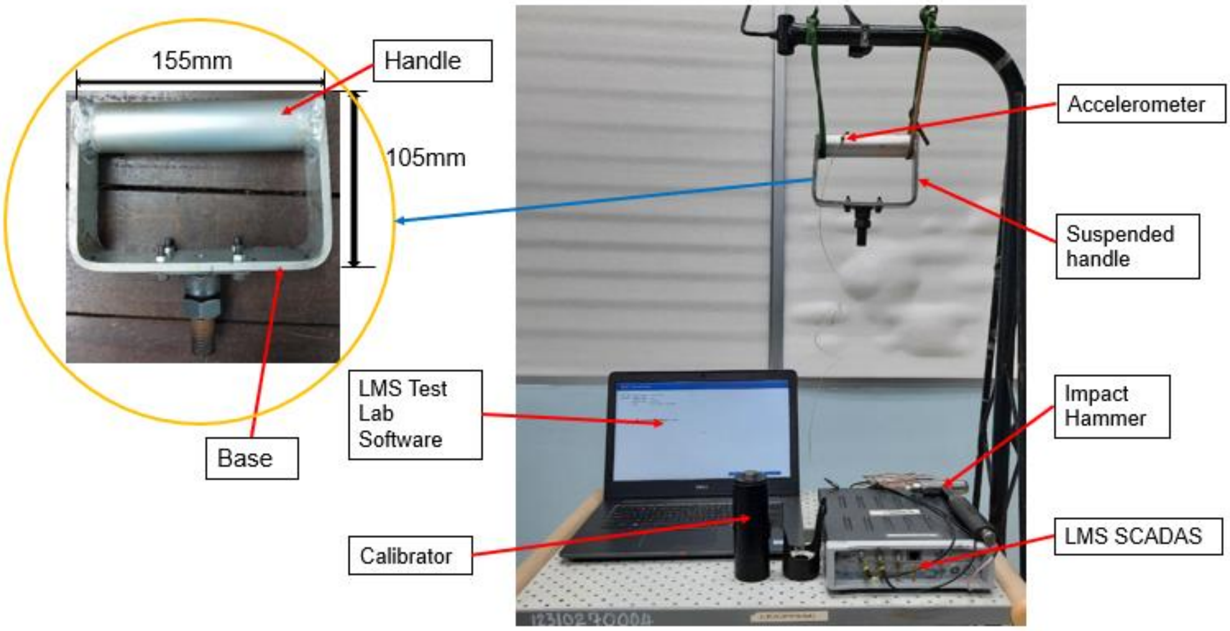


Figure 3.2: Experiment setup of EMA for suspended handle

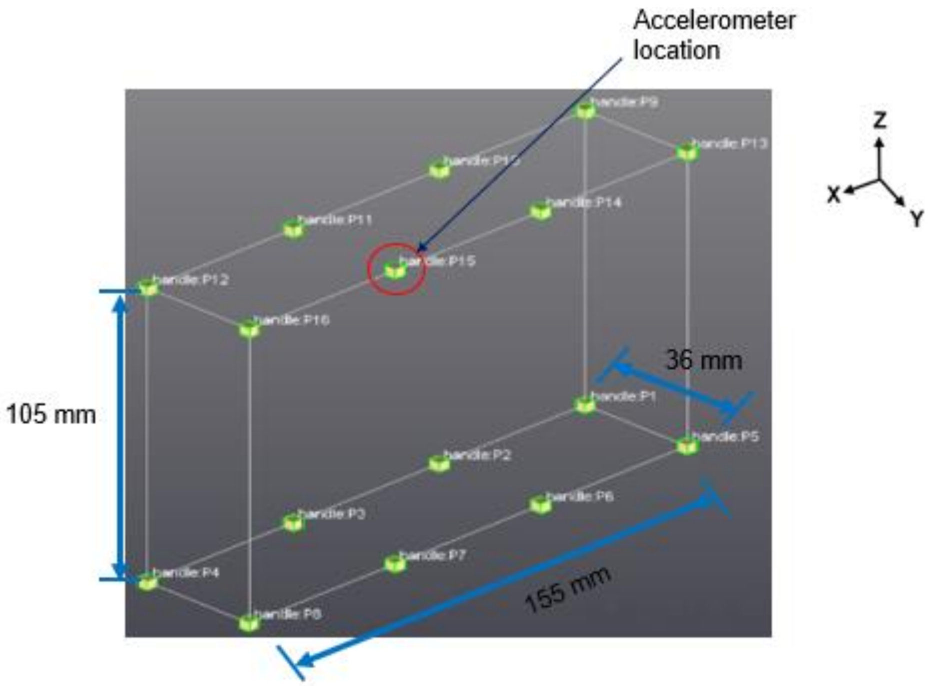


Figure 3.3: Geometry of suspended handle with 16 nodes

Firstly, the geometry of the suspended handle is drawn in three-dimensional (3D) using LMS Test Lab software as shown in Figure 3.3. The drawn geometry is 155.0 mm length,105.0 mm height and 36 mm width. On the top and bottom surfaces, a total of 16 nodes are uniformly distributed and the point numbers are marked using marker pen at the real handle. The accelerometer is then calibrated using a calibrator based on its sensitivity. It is located at node 15 to measure the acceleration of suspended handle. The impact hammer is used to induce an input force vertically (z-axis direction) by knocking on the stated nodes. The parameters of natural frequencies, FRF and mode shapes of the handle can be acquired in the LMS Test Lab software.

3.2.2 EMA of inertia-type piezoelectric actuator

For the inertia-type piezoelectric actuator, the aim of EMA is similar to the case of suspended handle which is to determine the dynamic properties of piezoelectric actuator without the suspended handle attachment. The m_2, c_2, k_2 values obtained from this experiment will be utilized as an input parameter to the Simulink model. The experimental setup of the inertia-type piezoelectric actuator is illustrated in Figure 3.4.

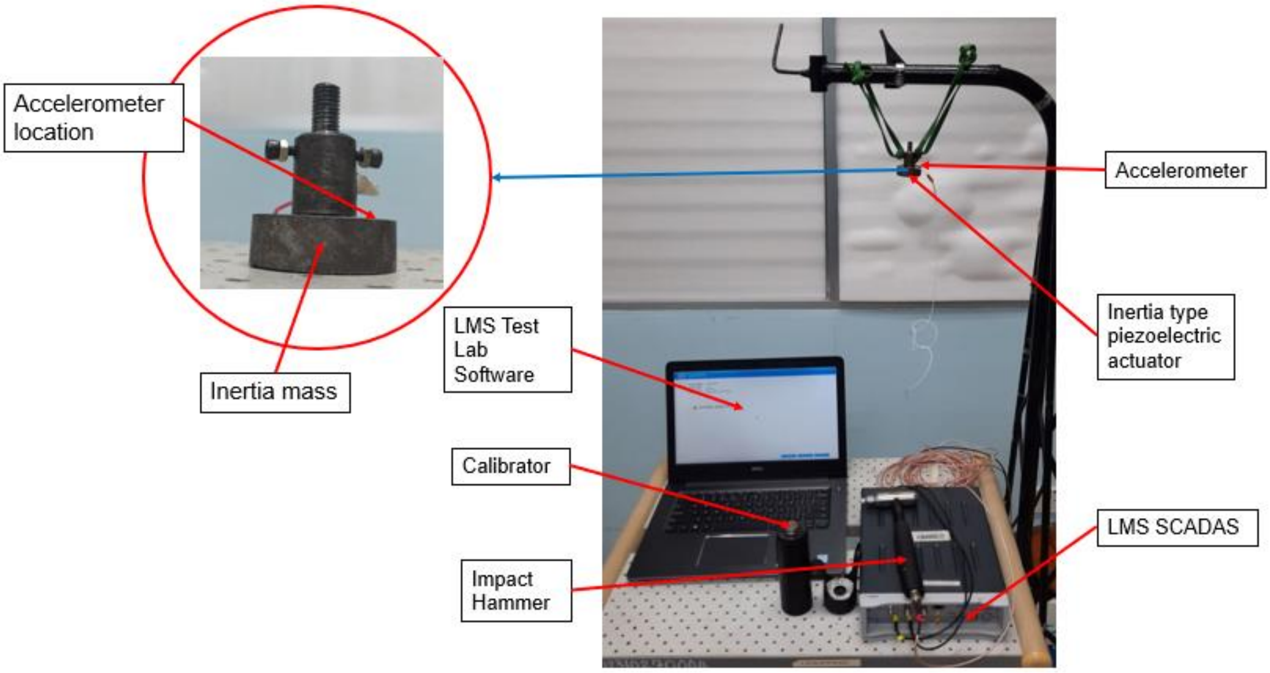


Figure 3.4: Experiment setup of EMA for an inertia-type piezoelectric actuator

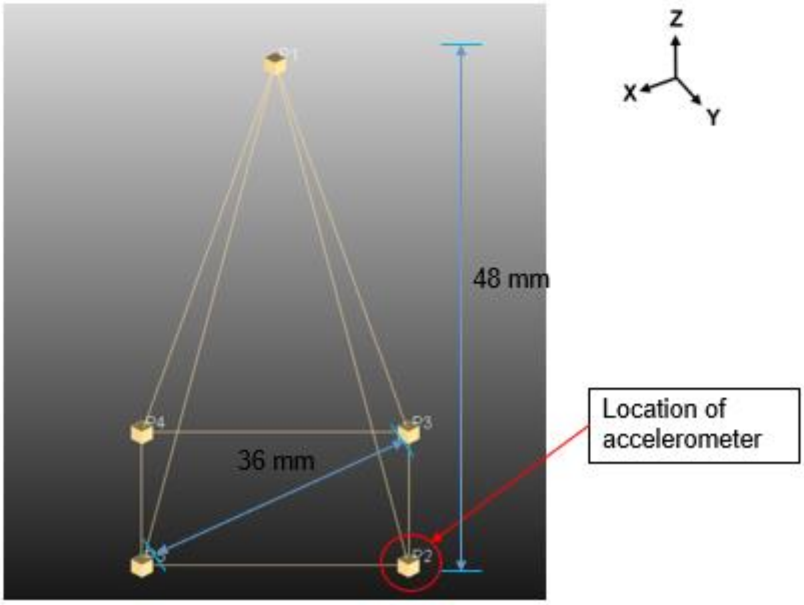


Figure 3.5: Geometry of piezoelectric actuator with 5 nodes

Similarly, the first step of this experiment is to draw a 3D geometry of piezoelectric actuator in the LMS Test Lab software as shown in Figure 3.5. The drawn geometry is 48 mm height with 36 mm diameter of the top circle. There is total of 5 nodes have been assigned evenly on top and bottom surface of the drawing and the point numbers are marked using marker pen at the actual piezoelectric actuator. After calibrating the accelerometer, it is then