APPLICATION OF THE ACTIVE FORCE CONTROL METHOD TO REDUCE THE VIBRATION OF THE SUSPENDED HANDLE

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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 acknowledgement by giving explicit references.

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LIST OF ABBREVIATIONS

Symbols	**Descriptions**
AFC	Active Force Control
AVC	Active Vibration Control
DVA	Dynamic Vibration Absorber
EAV	Exposure Action Value
ELV	Exposure Limit Value
EMA	Experimental Modal Analysis
FFT	Fast Fourier Transform
FRF	Frequency Response Function
HAVs	Hand-arm Vibration Syndrome
PID	Proportional-Integrated-Derivative
VWF	Vibration White Finger

PENGGUNAAN KAEDAH KAWALAN DAYA AKTIF UNTUK MENGURANGKAN GETARAN DI PEMEGANG BERGANTUNG

ABSTRAK

Dalam kajian ini, kaedah kawalan getaran aktif menggunakan dua jenis penggerak telah diaplikasikan untuk mengurangkan getaran pada pemegang yang bergantung secara eksperimen. Getaran telah diberikan oleh penggoncang kepada pemegang yang bergantung dan ukuran getaran telah diambil menggunakan dua meter pecut di mana salah satu telah diletakkan pada lokasi penggerak dan satu lagi pada lokasi pemegang. Penggerak piezoelektrik telah digunakan untuk mengurangkan getaran yang diberikan oleh penggoncang. Dua jenis kawalan telah digunakan dalam kajian ini iaitu teknik kawalan berkadar dan kawalan daya aktif untuk mengurangkan getaran pada pemegang yang bergantung. Keputusan eksperimen menunjukkan bahawa penggunaan teknik kawalan berkadar, getaran dapat dikurangkan sebanyak 42.56 % pada lokasi penggerak dan penggurangan sebanyak 39.78 % pada lokasi pemegang. Apabila kawalan daya aktif ditambah ke dalam sistem, getaran dapat dikurangkan lagi sebanyak 38.35 % pada lokasi penggerak dan sebanyak 36.95 % pada lokasi pemegang. Keputusan tersebut membuktikan bahawa menggunakan teknik kawalan berkadar dan kawalan daya aktif secara serentak dapat mengurangkan lebih banyak getaran. Selain itu, jenis kawalan ini juga boleh digunakan untuk mengurangkan getaran pada alatan kuasa tangan dalam aplikasi harian.

APPLICATION OF THE ACTIVE FORCE CONTROL METHOD TO REDUCE THE VIBRATION OF THE SUSPENDED HANDLE

ABSTRACT

In this study, active vibration control (AVC) methods with two types of controllers are applied to attenuate the vibration of the available suspended handle experimentally. The vibration is simulated to the suspended handle using shaker and the vibration measurement is taken using two accelerometers, whereby one is placed at the actuator location and another one at the handle of the suspended handle. Piezoelectric actuator is used to counter the vibration of the suspended handle that excited by the shaker. Two types of controllers are used in this study, which is Proportional-integral-derivative (PID) and Active Force Control (AFC). The result shows that, the PID controller can reduced the vibration (i.e., acceleration) up to 42.56 % at the actuator location and 39.78 % at the handle location, respectively. When AFC is included to the system, the vibration is further reduced up to 38.35 % at the actuator location and 36.95 % at the handle location, respectively. This result proved that, by using PID-AFC controller, the vibration reduction of the suspended handle can be further improved and this controller can be applied to reduce the vibration of the hand-held power tool in a daily application.

CHAPTER 1

INTRODUCTION

1.1 Background study

Excessive vibration from the power tools is one of the problem that has been faced by workers which may lead to a health problem. It is important for the workers to access the level of vibration exposure. Parliament and Commission of European Community has agreed to have a requirement on minimum health and safety for the workers that are exposed to the risks arising from vibration. In 2002, this community has defined the qualitative and quantitative requirements in the form of exposure action value (EAV) and exposure limit value (ELV) (Scarlett et al., 2007). Table 1.1 shows the limit advised of vibration exposure to prevent the risk of health associated problems.

Table 1.1: Total daily exposure duration and the value of acceleration (Pelmear and Leong, 2000)

Total Daily Exposure Duration (hrs)	**Value of RMS Acceleration Component, α (m/s^2)**
4 to less than 8	4
2 to less than 4	6
1 to less than 2	8
Less than 1	12

There are several methods to reduce the transmitted vibration from the hand-held power tool. One of the method is by using passive vibration control. This type of vibration control involves structural dynamic modification, vibration isolation and vibration absorption techniques (Golysheva et al., 2004). However, passive vibration control is not effective when the disturbances of the dynamic system varies with time. Active Vibration Control (AVC) in an alternative way to be used to attenuate the vibration from the hand-held power tool.

1.2 Problem statement

Workers are exposed to the high level of vibration from the power tools which can cause discomfort, injury and disease. Active force control (AFC) is one of the method that can be used to attenuate the vibration from the power tool. In this project, the application of the AFC method in reducing the vibration of power tool is studied using the active suspended handle.

1.3 Objective

In this project, the objectives that need to be achieved are:

- To measure the vibration level of the available power tool
- To carry out the vibration analysis of the suspended handle
- To construct the AFC programming blocks using the LabVIEW software
- To attenuate the vibration of the suspended handle using the AFC method

1.4 Scope of work

In this project, the application of AFC method in reducing the vibration from the power tool will be carried out using the suspended handle. Firstly, the vibration of power tool is measured and the modal analysis of the suspended handle is carried out. Then, the range of input spectrums with different of frequencies will be used to shake the suspended handle. Finally, the AFC programming block will be developed in LabVIEW software in order to reduce the vibration of the suspended handle.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, five topics will be presented:

- High level vibration of power tools
- Hand-arm vibration syndrome
- Passive vibration control
- Active vibration control
- Active force control

2.2 High level vibration of power tools

There are several industrial sectors that used power tools to assist their works such as drills, grinders, sanders, circular saws and several more. Excessive vibration from the power tools may lead to several health problems. The high level vibration from power tools can be defined that, the vibration level of the power tools are exceed the standard vibration exposure value of EAV and ELV values.

EAV is a daily amount of vibration exposure that workers must take an action to control and it has the value of 2.5 m/s^2 A (8). ELV is the maximum amount of vibration that workers must avoid in any single day and it has the value of 5 m/s^2 A (8). The greater the exposure level, the greater the risk to the workers and necessary action must be taken in order to avoid the risk (Griffin, 2004).

A survey has been done to determine the problems of hand-held power tools in the industry (Vergara et al., 2008). The vibration of power tools was measured for all seventy tools used in different industrial sectors. Ninety workers were interviewed about their perception of vibration level and the symptoms of diseases related to the hand arm vibration. The survey shows that four out of seventy measurements exceed the EAV value and three of them exceed the ELV value. Table 2.1 shows the result of the measurements that exceeded the ELV value.

Table 2.1: Result of the measurement that exceeded the ELV value (Vergara et al., 2008)

Tool type	Mean daily time of use (min)	Vibration level (m/s^2)
Screwdriver, wrenches	300	8.20
Driller	180	5.87
Sander, polisher, grinder	300	5.80
Hammer	14	3.81

In order to use the power tools, the precaution steps and time limitation should be taken. In addition, a necessary care should be taken by selecting the tools with low vibration levels for the jobs that required a long working hours such as screwdriver, wrenches and drills. These tools may give the same affects such as using the high level vibration power tools in a short period.

2.3 Hand-arm vibration syndrome

Hand-arm vibration syndrome (HAVs) is a common health associated problem that resulting from the long exposure of hand-held power tools with a high level of vibration. It is a complex vascular, neurologic and osteoarticular disorders that occurred at the upper limbs of the workers (Bovenzi, 1998). This problem may lead to the circulatory disorder such as Vibration White Finger (VWF) sensory, motor disorder and musculoskeletal disorder which may occur to the workers who exposed to the high vibration of the power tools.

The vascular component of HAVs received the most clinical and research attention since 1911. The precise condition of the vascular, sensorineural and musculoskeletal outcomes in the HAVs are not really known (Griffin et al., 2003). However, the best known vascular disorder is VWF and there are several studies on the vibration conditions associated with the observed incidence, prevalence and the condition.

VWF is common causes of secondary Raynaud's phenomenon. These disease occurs to the workers that exposed to the high level of vibration. Although it is recognised that vibration can cause direct damage to the blood vessels, the reason cannot be explained and only some workers are affected by this disease (Lau et al., 1992).

A study has been done on a group of workers that affected by VWF disease. These workers are former workers that using the vibrating machine in their daily work. The result shows that there is an increment of leukotriene B_4 in patient's blood vessel which means that the white blood cell is activated. This phenomenon considerably harder and may form clump which can disrupt the blood circulation. White blood cell enhances oxidative stress with a subsequent increase in a free radical activity and further tissue damage. This lead the patient to the VWF disease (Lau et al., 1992).

2.4 Passive vibration control

There are four classifications of vibration control technique. The three most common classifications are passive vibration control, active vibration control and hybrid vibration control. Passive vibration control involves the use of devices that load the transmission path of the disturbing vibration or absorb the vibration energy (Franchek et al., 1996).

One of the effective tools for the passive vibration control is the dynamic vibration absorber (DVA). It shows that, a non-linear absorber can be used to control the vibration of a non-linear system. The non-linear absorber widens its range of applications and its damping coefficient should be kept minimum for better performance (Eissa and Sayed, 2006).

However, the passive vibration control is not effective when the disturbance of the dynamic system varies with time. In this case, active vibration control has to be introduced to the system to attenuate the vibration effectively (Palm, 2006).

2.5 Active vibration control

Active vibration control (AVC) is one of the most effective way to attenuate vibration when the disturbance of the dynamic system varies with time. AVC loads the transmission path and achieves the loading through the actuating (Franchek et al., 1996). This type of control usually used in the precision industrial process to maintain the platform essentially vibration-free (Hassan et al., 2010).

Figure 2.1 shows the basic schematic diagram for the AVC system. AVC is a closed loop system which consists of sensor, controller, actuator and process. The actuator that can be used in the AVC system to attenuate the vibration of the system are piezoelectric, electric motor and hydraulic cylinder (Palm, 2006).

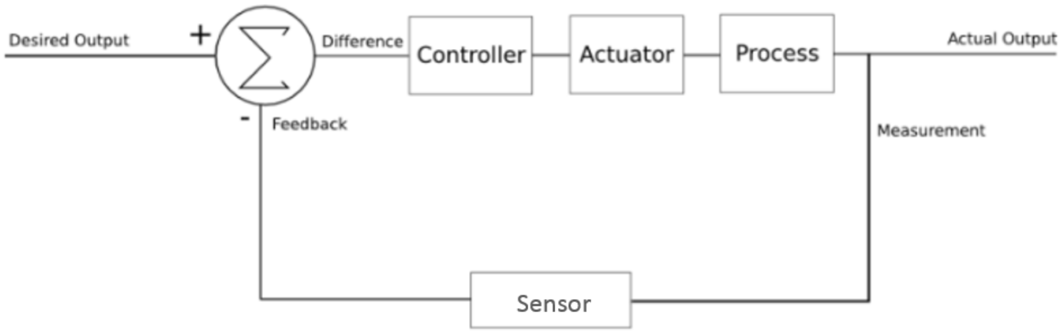

Figure 2.1: Basic diagram for the AVC system (Stienecker, 2015)

There are several control techniques that can be applied in the AVC system to attenuate the unwanted vibration. This includes Proportional-Integrated-Derivative (PID) control and active force control (AFC).

2.5.1 Active force control

Active force control (AFC) was introduced by Hewit and Burdess in year 1980. In their studies, the AFC method has been developed to solve the problem of the dynamic decoupling motion trajectories of robotic arm system (Hewit and Burdess, 1981). AFC has become one of the most efficient control technique in the AVC system.

Figure 2.2 shows the basic schematic diagram of the AVC system which included the AFC method. For the AFC, it consists of additional devices and control parameters such as force sensor, accelerometer, estimated mass and inverse of actuator.

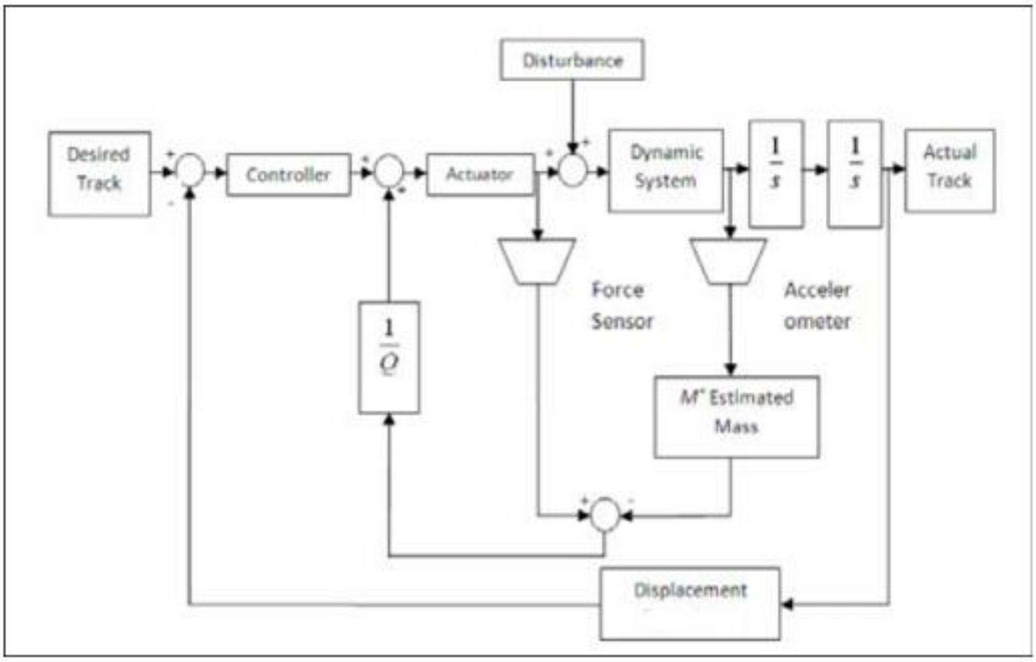

Figure 2.2: Basic diagram for the AFC (Mohamad et al., 2006)

Several experiment has been carried out and it has been proved that AFC has good stability, robustness and effectiveness to the system even though in the presence of disturbance, uncertainties and varies operating conditions (Hassan et al., 2010). For example, AFC technique has been applied for the vibration suppression of a hand-held power tool. In their studies, four type of control schemes were applied which includes PID, AFC with crude approximation, AFC with iteration learning method and AFC with fuzzy logic (Hassan et al., 2010).

2.6 Summary

From the literature, it can be summarized that:

- Most of the vibration of the power hand tools are high and exceed the EAV and ELV values. The daily amount of vibration exposure to the workers has to be controlled.
- HAVs is one of the health associated problem caused by excessive vibration. Necessary action has been taken in order to avoid health problem caused by excessive vibration.
- There are several methods on how to reduce the vibration. One of the method is using passive vibration control. Based on this study, passive vibration control is not applicable because of passive vibration control is not effective when the disturbance of the dynamic system varies with time.
- Another type of vibration control method is AVC. This type of method is one of the most effective way to attenuate the vibration when the disturbance of the dynamic system varies with time.
- AFC method has been introduced to solve the problem of dynamic decoupling trajectories of robotic arm system (Hewit and Burdess, 1981). In this study, AFC method has been added to the AVC system in order to reduce the vibration of suspended handle experimentally.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this chapter, the vibration measurement of power tool and suspended handle, characterization of piezo stack actuator and the setup of the AVC experiment are presented. Subsequently, the block diagram design for the PID and AFC in the LabVIEW software are also presented. The flow chart of overall methodology is shown in Figure 3.1.

3.2 Vibration measurement of the power tool

In this project, Bosch GEX 270A Professional sander has been used as a power tool for the vibration measurement. The important parts of the sander are shown in Figure 3.2.

Figure 3.2: Bosch GEX 270A Professional Sander

From Figure 3.2, the main parts of the sander are switch, latching button, front handle, rear handle, sanding plate and micro filter dust box. The vibration of the sander is measured by placing two accelerometers on the front handle as shown in Figure 3.3. The measurement was carried out using LMS Test.Lab Software.

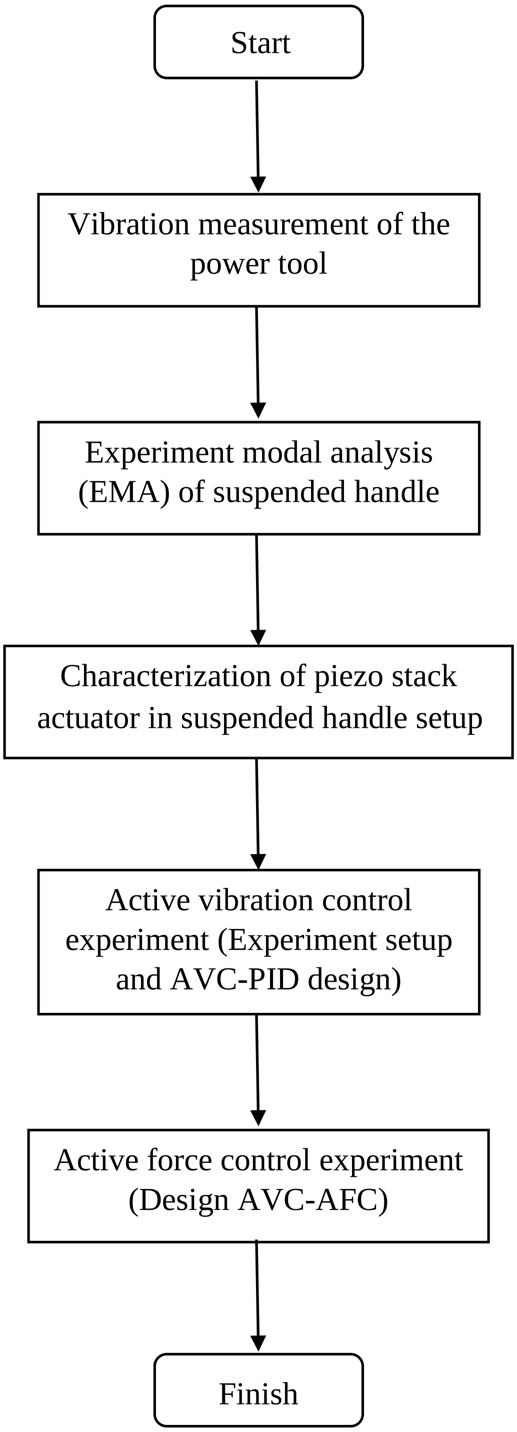

Figure 3.1: Flow chart of overall methodology

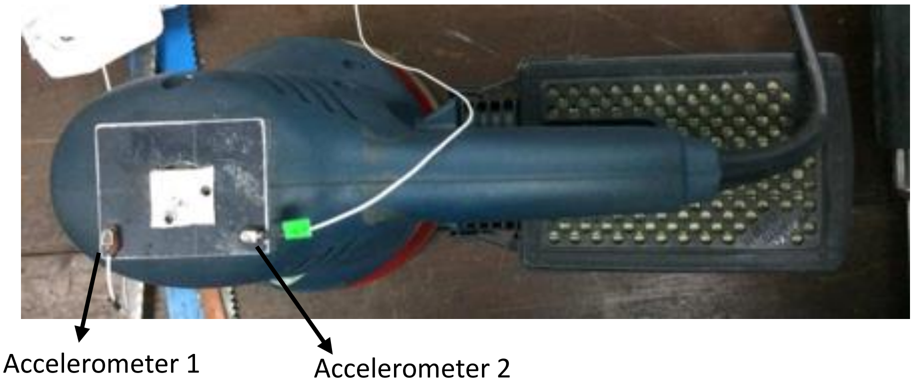

Figure 3.3: Placement of two accelerometers on sander

For this experiment, the vibration of the sander is measured during the operating condition with no load applied.

3.3 Experimental modal analysis (EMA) of suspended handle

In this study, EMA is carried out to determine the dynamic properties of the suspended handle such as the natural frequency and frequency response function (FRF) of the handle. The EMA of the suspended handle is carried out using LMS Test.Lab impact testing software.

The instrument used in this experiment including the accelerometer, impact hammer, LMS SCADAS and LMS Test.Lab software. The measurement is taken twice, firstly when the accelerometer is located at the handle position and secondly when the accelerometer is located at the actuator position.

3.4 Characterization of piezo stack actuator in suspended handle setup

In this project, the characteristics of piezo stack in suspended handle setup has been determined. Figure 3.4 shows the placement of piezo stack on the suspended handle. The piezo stack is placed in between the base of the suspended handle and the force transducer.

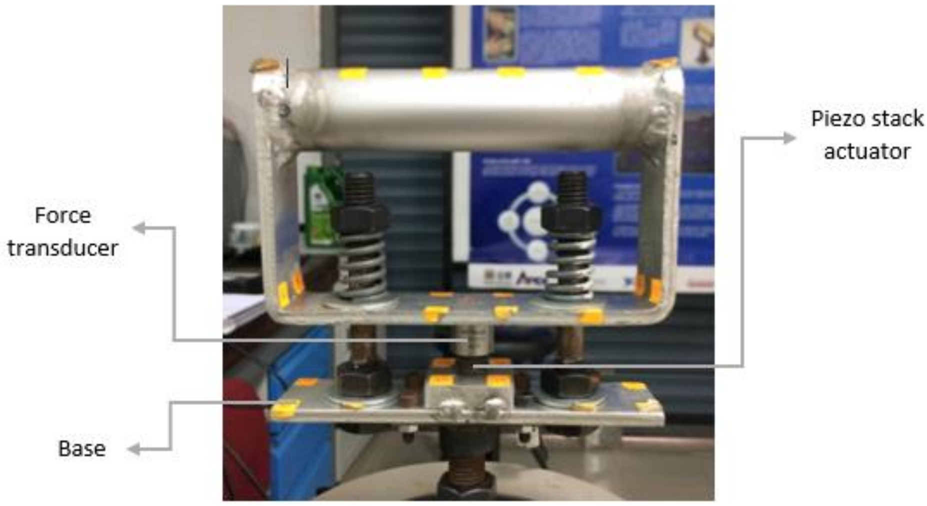

Figure 3.4: Placement of piezo stack on the suspended handle

Figure 3.5 shows the schematic diagram of the overall setup to determine piezo characteristics. From the figure, the computer with LabVIEW software is connected to the NI CDAQ 9174 chassis, where the amplitude and frequency of the piezo are manipulated in this software. The chassis is then connected to voltage amplifier. This voltage amplifier will amplify the voltage to the piezo actuator. Two accelerometers were attached at the suspended handle (actuator and handle locations). The vibration measured by the accelerometers were delivered to the computer with LabVIEW software for analysis data.

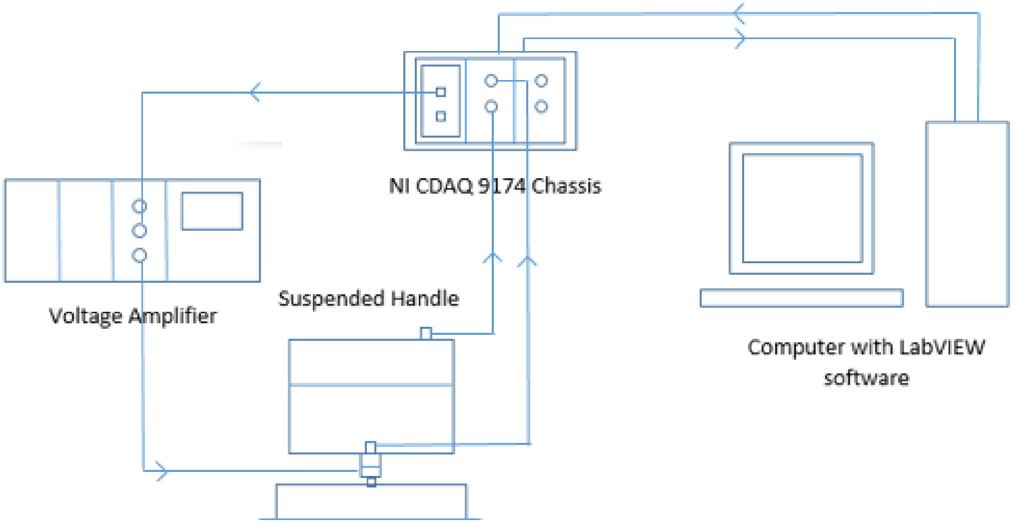

Figure 3.5: Overall experiment setup for piezo actuator characterization

3.5 AVC experiment

In this study, the main target is to reduce the vibration of the suspended handle using the AFC method. Experiment setup for AVC and design of PID in LabVIEW software has to be developed before the AFC method can be implemented.

3.5.1 Experiment setup

Figure 3.6 shows the schematic diagram of the AVC experiment setup for this study. This experiment consists of suspended handle attached on the shaker, shaker amplifier, NI CDAQ 9174 chassis, piezo voltage amplifier and computer with LabVIEW software. For this measurement, two accelerometers are used to measure the vibration at actuator and handle position of the suspended handle. Then, the piezo stack actuator is used as an actuator to counter the vibration of the suspended handle.

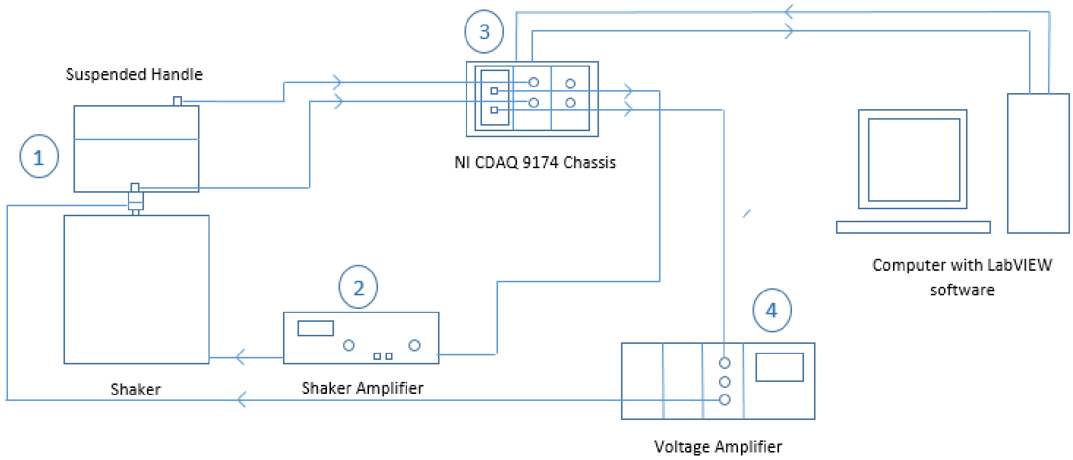

Figure 3.6: Overall experiment setup for AVC

Figure 3.7 shows the picture of attachment of suspended handle on the shaker. The important parts and features of the suspended handle are shown in this figure, such as push spring, handle, accelerometers, piezo stack actuator and force transducer.

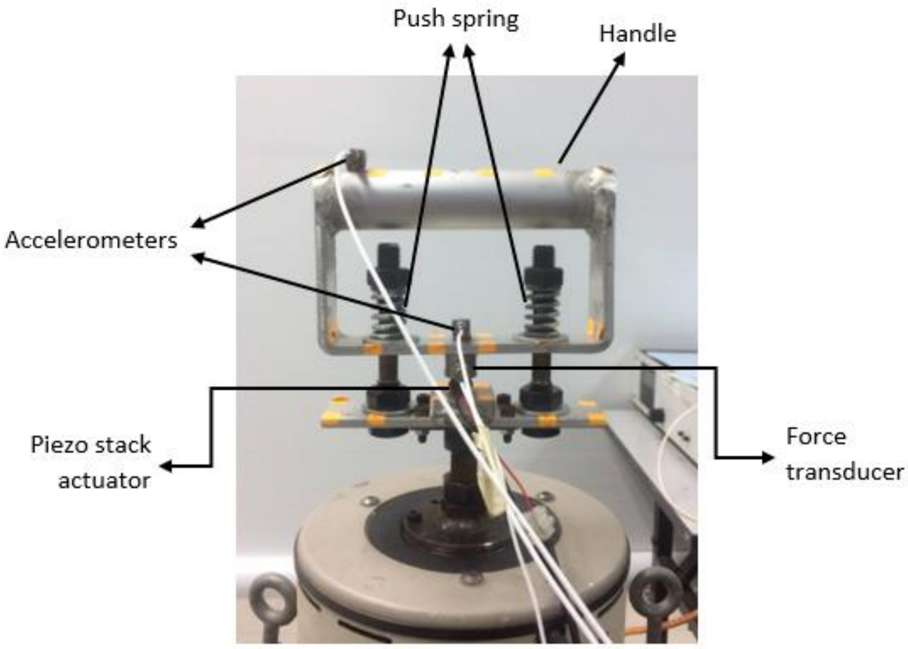

Figure 3.7: Attachment of suspended handle on the shaker

Figure 3.8 shows the picture of shaker amplifier. Signal supplied by the LabVIEW software will be amplified by the shaker amplifier for the sufficient voltage to excite the suspended handle.

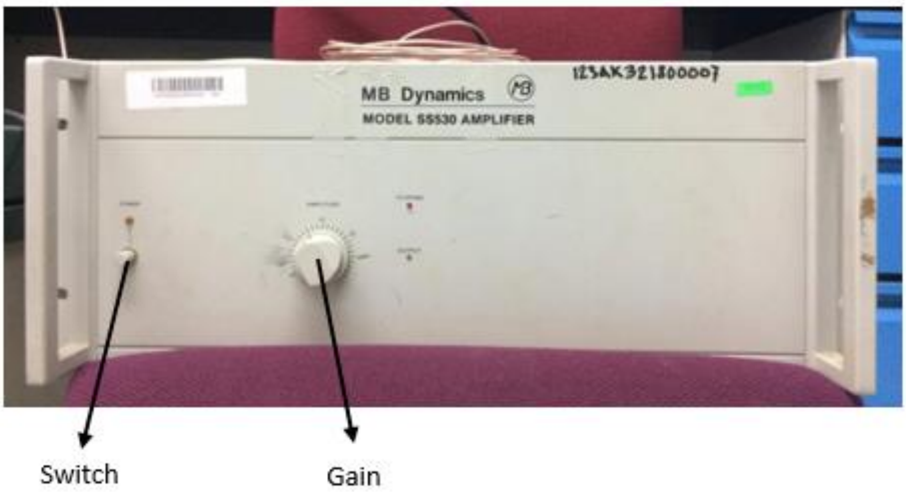

Figure 3.8: Shaker amplifier

Figure 3.9 shows the picture of National Instrument (NI CDAQ 9174) chassis. This chassis has three slots of analogue input and output modules that connected to the computer with the LabVIEW software. Using this software, the amplitude and frequency of the voltage can be controlled and supplied to the shaker amplifier. Accelerometers are placed on the suspended handle and connected to the input module for acceleration measurement. The counter signal from the PID controller in the LabVIEW software will be supplied through the output module to the piezo voltage amplifier.

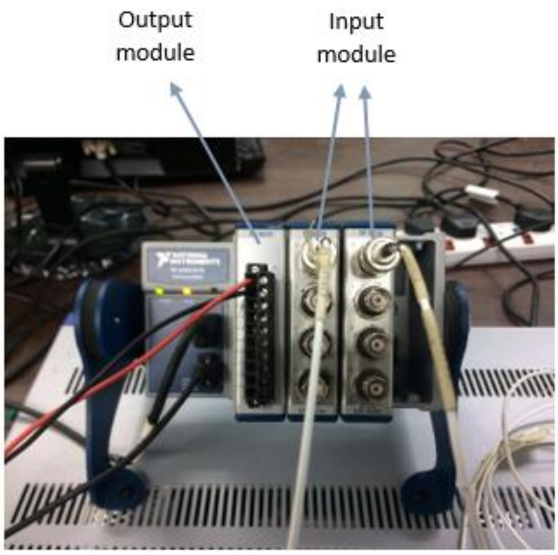

Figure 3.9: NI CDAQ 9174 Chassis

Figure 3.10 shows the piezo voltage amplifier. The output module of NI CDAQ 9174 chassis will be connected to this voltage amplifier and the amplified the voltage to a piezo stack actuator to counter the vibration of the suspended handle.

Figure 3.10: Voltage amplifier

3.5.2 Design of AVC-PID in LabVIEW

The block diagram of AVC system is developed using the LabVIEW software. Figure 3.11 shows the front panel and Figure 3.12 shows the block diagram of the AVC system in the LabVIEW software. From these figures, sub-diagram number 1 shows the signal generation for the shaker, which the value of the frequency and the amplitude of the shaker can be manipulated. The signal is then sent to the DAQ analogue output which will be connected to the shaker amplifier. Sub-diagram number 2 shows the acceleration measurement blocks of the suspended handle. There are two accelerometers have been attached to the suspended handle at the handle and actuator locations. The time domain acceleration measurement is then converted to the frequency domain (FFT) graph for easier interpretation. Sub-diagram number 3 shows the PID controller for the AVC system. PID controller is used in this AVC system to provide the counter vibration for the suspended handle. The voltage generate by the PID controller can be shown as following equation:

$$Vol_{PID}(t) = K_P\, e(t) + K_I \int e(t)\, dt + K_D \frac{de(t)}{dt} \tag{3.1}$$

where, K_P = Proportional gain

K_I = Integral gain

K_D = Derivative gain

$e(t)$ = Error signal (m/s^2)

Sub-diagram number 4 shows the counter voltage signal from the PID controller to the piezo actuator. The signal from the PID controller is then transferred to the DAQ analogue output which will be connected to the piezo voltage amplifier and piezo actuator. Lastly, sub-diagram number 5 shows the data saving blocks for this experiment.

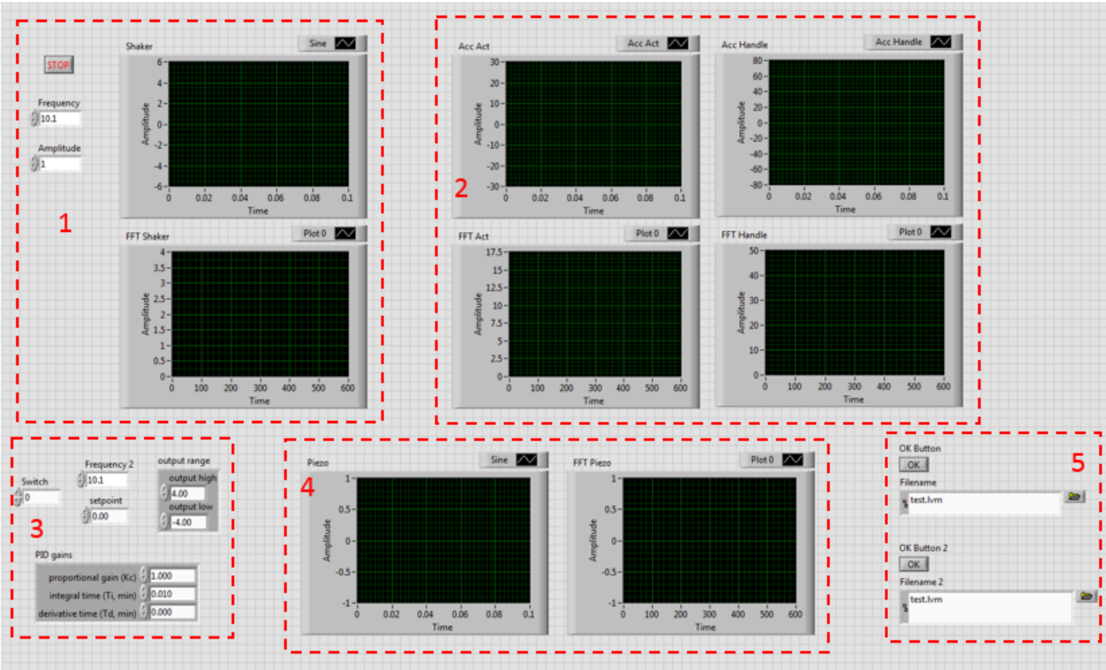

Figure 3.11: Front panel of the AVC-PID system in LabVIEW software

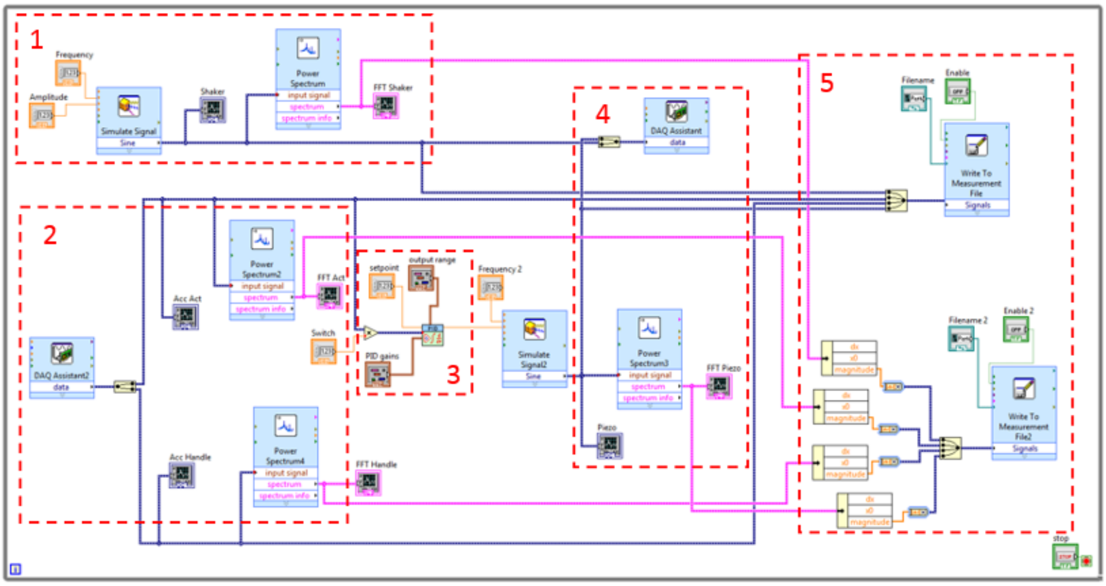

Figure 3.12: Block diagram of the AVC-PID system in LabVIEW software

Table 3.1 shows the overall sub-diagram numbers and the description of the front panel and block diagram of the AVC system in Figure 3.10 and 3.11.

Table 3.1: Overall sub-diagram numbers of the front panel and block diagram in LabVIEW

Number	Description
1	Signal generation for the shaker
2	Acceleration measurement
3	PID controller
4	Counter signal to the piezo actuator
5	Data saving

This experiment is carried out for the frequency range of 100Hz, 200Hz, 300Hz, 400Hz and 500Hz. Firstly, the measurement is taken without the activation of PID controller. Then, PID controller is activated by changing the switch for PID controller. The set point for PID is set to 0 which means that the target is to eliminate the vibration of the suspended handle. The voltage output range is set between -4.00 V to 4.00 V, so that the piezo amplifier can generate the maximum voltage of ±400 V to the piezo. Lastly, the values for P, I and D are tuned to be K_P = 1000, K_I = 1 and K_D = 1. This PID values are taken from the previous study done by Mazlan et. al (2016).

3.6 AFC experiment

After the AVC experiment with PID controller has been conducted, an AFC method is constructed in the LabVIEW software. For the AFC, force transducer has been added as an additional sensor for the AVC system.

3.6.1 Design of AVC-AFC in LabVIEW

The AFC block diagram is added to the AVC-PID block diagram. Figure 3.13 shows the front panel and Figure 3.14 shows the block diagram of the AVC system with AFC method in the LabVIEW software. The red dotted box in the figures show the additional part designed for the AFC. It shows that another DAQ input module has been added. This module is connected to the force transducer to measure the real-time force of the piezo actuator. The voltage generate by the AFC controller can be shown as following equation:

$$Vol_{AFC}\ (t) = \ K_{AFC}\ (\alpha^{-1})\ (F_{act} - M^{*}a)\ (t) \tag{3.2}$$

where, K_{AFC} = AFC percentage constant

α^{-1} = force transducer inverse sensitivity (V/N)

F_{act} = force at piezo actuator (N)

$M*$ = estimated mass (kg)

a = acceleration of actuator (m/s^2)

The acceleration (a) at the actuator location is multiplied with the estimated mass (M^*), which need to be tuned to determine the most optimum mass in order to counter the vibration. The resulting M^*a value is then subtracted to the real-time force measurement from the force (F_{act}) transducer. Then, the value is multiplied with the inverse sensitivity of the force transducer in order to make the value in voltage unit. The total voltage is then multiplied by the AFC 100% constant = 1 to show that 100% of the voltage value is going to be supplied. Finally, the AFC voltage value is added to the PID voltage value and sent to DAQ output module to the piezo actuator.

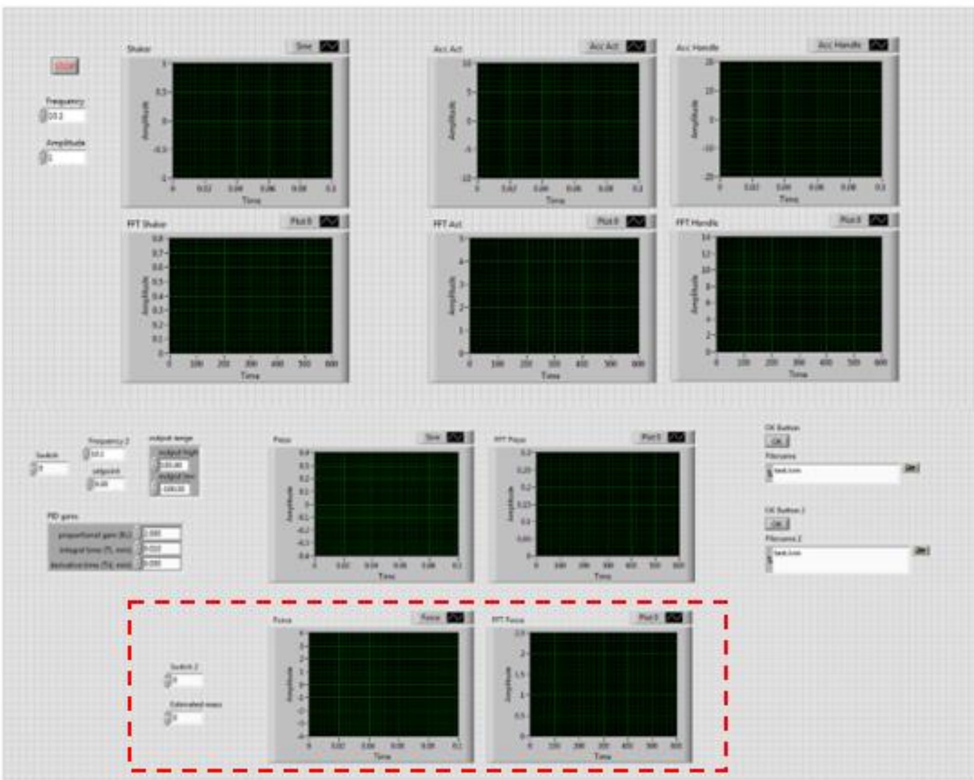

Figure 3.13: Front panel of the AVC-AFC system in LabVIEW software

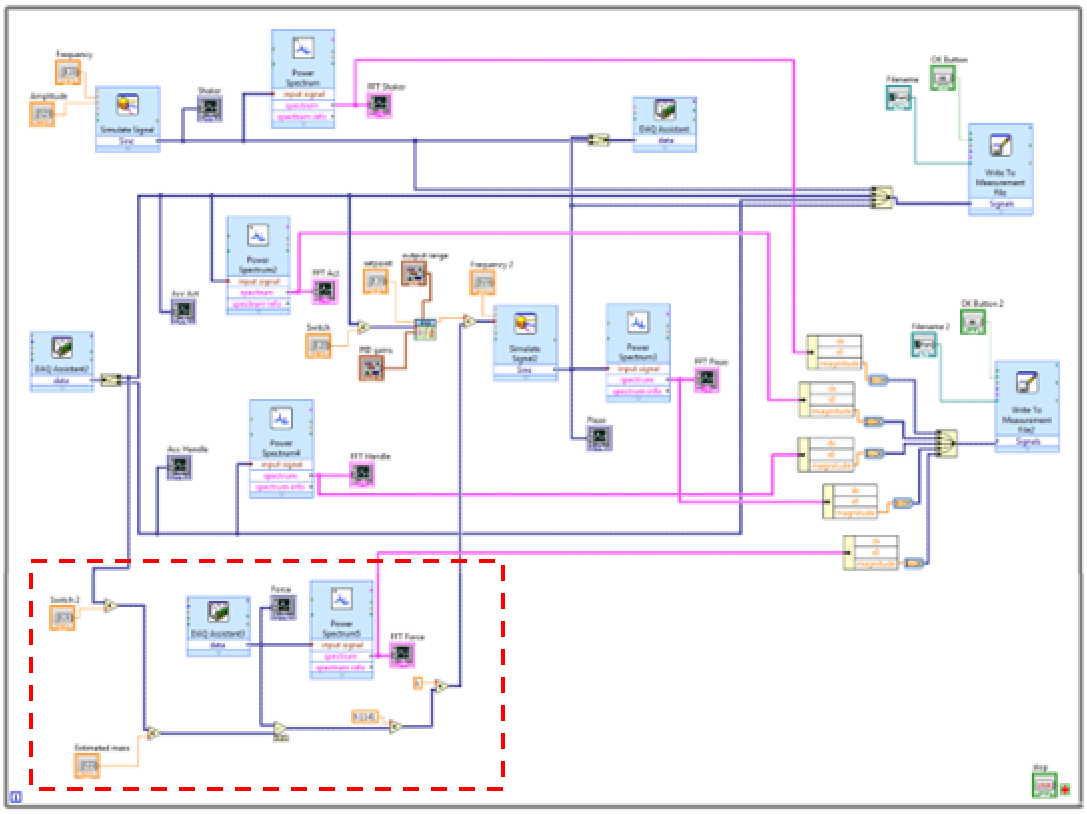

Figure 3.14: Block diagram of the AVC-AFC system in LabVIEW software

3.7 Summary

In this chapter, the methodology for this study is explained. Starting with the vibration measurement of power tool and the suspended handle, then the characteristics of the piezo stack actuator in handle setup is studied. The experiment setup of the AVC system has been explained in detail with the block diagram designed in the LabVIEW software. Finally, the addition of AFC method to the AVC system is explained.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

In this chapter, the result obtained from the vibration measurement of the power tool and the suspended handle are presented and discussed. Then, the results of AVC with activation and without activation of PID controller are presented and discussed. Finally, the results of the AFC technique with the integration PID controller are presented and discussed.

4.2 Vibration measurement results of the power tool

Figure 4.1 shows the result of the input spectrum in acceleration at both measured locations (1 and 2) of the sander that obtained from LMS Test.Lab software. Form the figure, the acceleration obtained at the location 1 and 2 are 4 m/s^2 at 164.32Hz and 3.6 m/s^2 at 167.70Hz respectively. The result shows that, the acceleration at point 1 is more significant than at point 2.

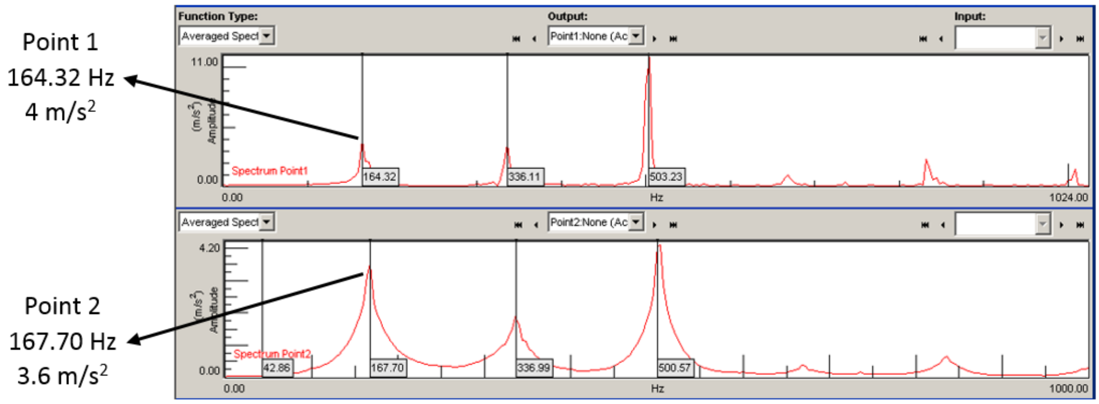

Figure 4.1: Result of vibration measurement of the power tools

4.3 EMA results of suspended handle

Based on EMA that has been carried out, the natural frequency and the FRF of the suspended handle has been determined. Figure 4.2 shows the FRF of the suspended handle obtained from the LMS Test.Lab software.

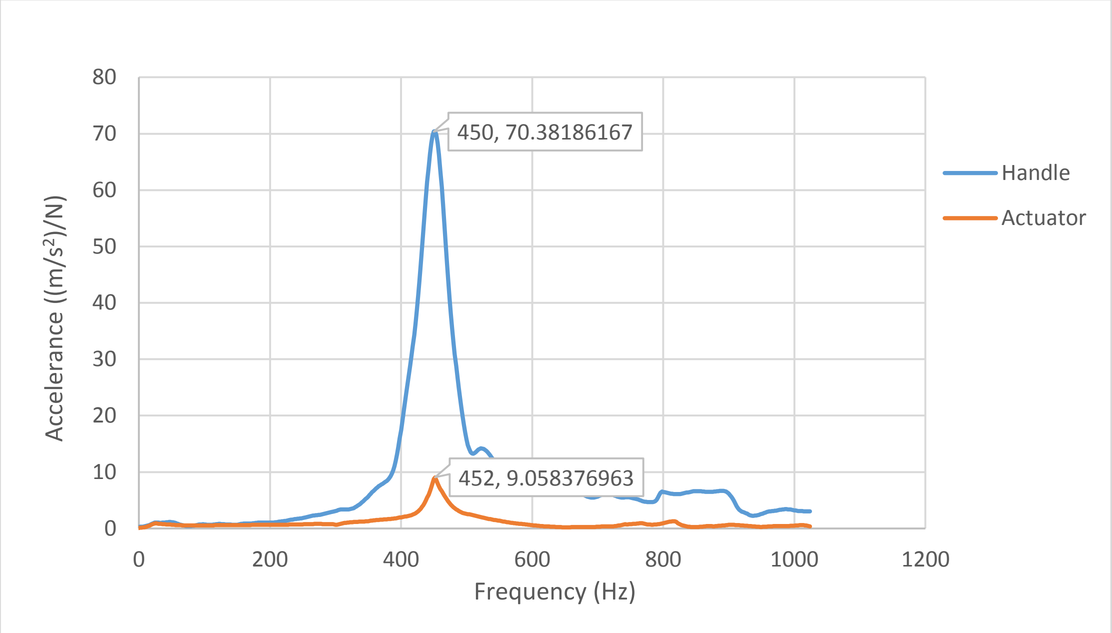

Figure 4.2: FRF of the suspended handle

From Figure 4.2, the natural frequencies of the suspended handle that have been obtained at actuator position is 452 Hz with 9.06 ms^{-2}/N of amplitude while at the handle location is 450 Hz with 70.38 ms^{-2}/N. The result shows that, the amplitude of natural frequency at the handle location is more significant than at the actuator location.

4.4 Piezo characteristics in handle setup

For the piezo actuator characterization, the experiment was conducted for the frequency of 100 Hz, 200 Hz, 300 Hz and 400 Hz, with varies voltage amplitudes of 1V - 4V. Table 4.1 (a) and (b) shows the acceleration at actuator and handle locations excited by the piezo actuator.

Table 4.1 (a): Acceleration at actuator location

Frequency (Hz)	Acceleration (m/s^2)			
	1 V	2 V	3 V	4 V
100	0.005896	0.01392	0.02305	0.03304
200	0.014	0.03578	0.06117	0.08508
300	0.03892	0.08448	0.11175	0.13789
400	0.01853	0.06839	0.13398	0.20896

Table 4.1 (b): Acceleration at handle location

Frequency (Hz)	Acceleration (m/s^2)			
	1 V	2 V	3 V	4 V
100	0.004741	0.02781	0.01313	0.01767
200	0.03041	0.06121	0.09898	0.1277
300	0.06434	0.14735	0.1832	0.2034
400	0.04545	0.0832	0.2656	0.4542

Figure 4.3 (a) and (b) show the graphs of the measured acceleration at actuator and handle locations respectively. For both graphs, the accelerations are increasing with the frequency of 100 – 400 Hz with the increase of voltage from 1 – 4 V. From these results, the higher the voltage supplied to the piezo actuator promises a higher chance in attenuating the vibration of the suspended handle using the AVC method. The highest acceleration for both locations at 400 Hz with the maximum voltage of 4V are due to the natural frequency of the suspended handle shown in Figure 4.2, where the amplitude of the handle is more significant than actuator location

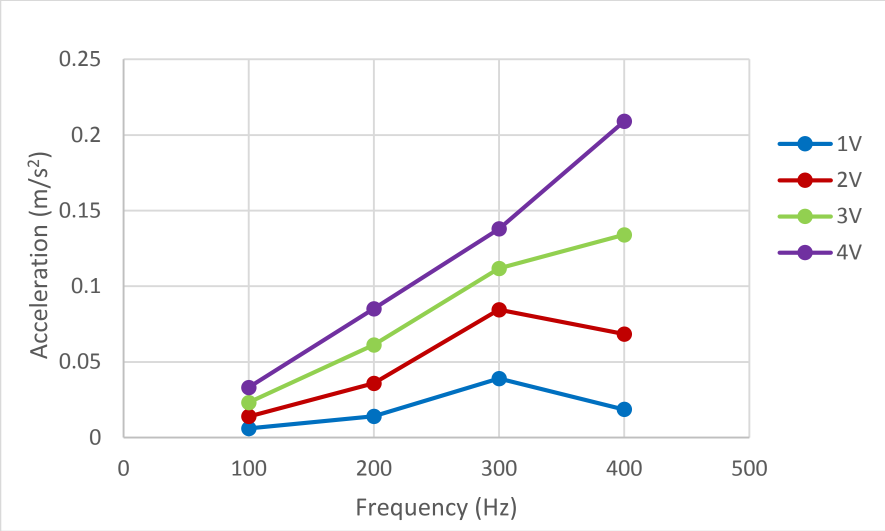

Figure 4.3 (a): Graph of acceleration at the actuator location excited by piezo actuator

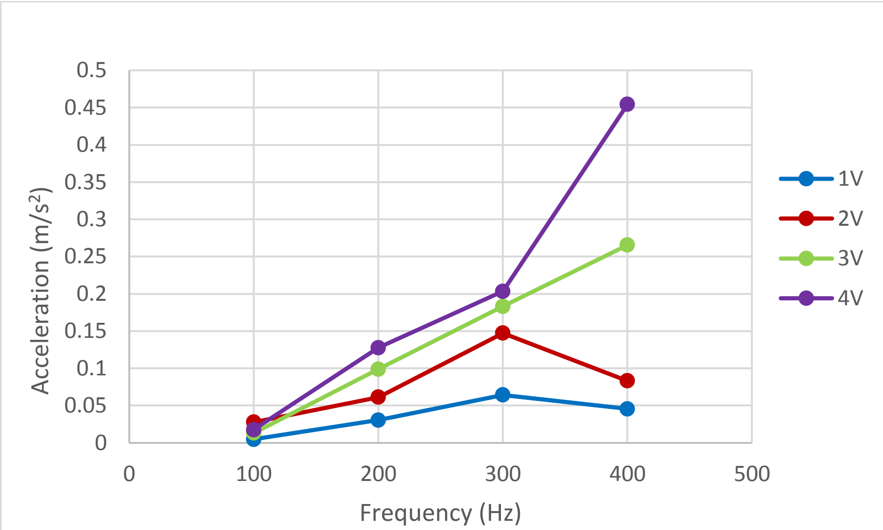

Figure 4.3 (b): Graph of acceleration at the handle location excited by piezo actuator

4.5 Vibration of the suspended handle with PID controller

In this section, the acceleration of the suspended handle at both handle and actuator locations have been recorded. The amplitude of the acceleration of the suspended handle without activation of PID controller and with activation of PID controller has been taken. The measurement taken from the accelerometers are in time domain and then converted to frequency domain to show the amplitude versus