SIMULATION OF ACTIVE FORCE CONTROL USING INTELLIGENT METHODS TO REDUCE VIBRATION OF THE SUSPENDED HANDLE

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DECLARATION

I hereby declare that this thesis, which I submit to Universiti Sains Malaysia as part of the requirement for the award of degree, is based on my personal effort, except other sources where such work has been cited and acknowledged within this text. The results embodied in this thesis have not been submitted to other institution or universities for the award of any degree of diploma. I hereby authorize Universiti Sains Malaysia to make the thesis available outside organization for purpose of scholarly research.

Signed …………………………………………………………… (WONG JEN NYAP)

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LIST OF SYMBOLS

Symbols	**Descriptions**
a	Acceleration
A & B	Learning parameters
c	Damping coefficient
f^{k}	Current step value
f^{k+1}	Next step value
F^*	Estimated disturbance force
F_a	Actuator force
k	Spring coefficient
K_P	Proportional gain
K_I	Integral gain
K_D	Derivative gain
m	Mass of suspended handle
M^*	Estimated mass
N	Filter coefficient
Te_k	Current track error

LIST OF ABBRAVIATIONS

Symbols	Descriptions
AFC	Active Force Control
AFCCA	Active Force Control Crude Approximation
AFCFL	Active Force Control Fuzzy Logic
AFCILM	Active Force Control Iterative Learning Method
ATE	Average Track Error
AVC	Active Vibration Control
CA	Crude Approximation
EMF	Electro-Motive-Force
EAV	Exposure Action Limit
ELV	Exposure Limit Value
EM	Estimated Mass
FL	Fuzzy Logic
HAVs	Hand-Arm Vibration syndrome
ILM	Iterative Learning Method
IM	Initial Mass
MF	Membership Function
PID	Proportional-Integral-Derivative
SDOF	Single-Degree-of-Freedom
VWF	Vibration-induced White Finger

ABSTRAK

Kajian ini bertumpu kepada penyekatan getaran pada pemegang tergantung daripada alat kuasa melalui kaedah kawalan daya aktif (AFC) yang berbeza. Pemegang tergantung telah dimodel sebagai kebebasan system satu darjah (SDOF) dengan parameter jisim, spring dan redaman diperolehi daripada kajian yang lepas. Model bagi gangguan dalaman juga diperolehi daripada penyelidikan yang lepas manakala dua model gangguan luaran yang baru diperkenalkan semasa proses simulasi untuk menguji keteguhan sistem. Empat jenis skim kawalan telah diselidik dengan teliti dan dibandingkan dalam menekankan getaran pada pemegang, antaranya ialah pengawal berkadar-kamiran-kebezaan (PID), PID-AFC-CA, PID-AFC-FL dan PID-AFC-ILM. Daripada keputusan simulasi, skim AFCCA menjana prestasi yang paling baik apabila jisim anggaran (EM) adalah pada 0.04 kg. Manakala bagi skim AFCFL, sambutan yang paling baik dihasilkan dengan keahlian fungsi bentuk trapezoid dengan EM pada 0.040295 kg. Tambahan pula, skim AFCILM menunjukkan tindak balas terbaik dengan EM pada 0.040000261 kg dan kedua-dua parameter pembelajaran A dan B pada nilai 0.6. Antara semua sistem, skim AFCILM menunjukkan prestasi keseluruhan yang terbaik bagi isyarat input sifat manakala AFCCA memberi sambutan terbaik bagi isyarat input langkah.

ABSTRACT

This study focuses on the vibration attenuation of the suspended handle generated from the power tools using different type of Active Force Control (AFC) tuning strategies. The suspended handle is modelled as a single-degree-of-freedom (SDOF) system with the parameters of mass, spring and damping taken from the previous research. The model of internal disturbance is also taken from the previous research while two new models of external disturbances are introduced during the simulation process to evaluate the robustness of the system. Four types of control schemes are investigated and compared in suppressing the vibration of the handle, which are Proportional-Integral-Derivative (PID) controller, PID-AFC-Crude Approximation (CA), PID-AFC-Fuzzy Logic (FL) and PID-AFC-Iterative Learning Method (ILM) control schemes. From the simulation, AFCCA scheme generates the best performance when the estimated mass (EM) is 0.04 kg. While for the AFCFL scheme, the best response is generated with the membership function of trapezoidal shape with EM of 0.040295 kg. Furthermore, the AFCILM scheme shows the best response with EM of 0.040000261 kg and both learning parameters A and B at value of 0.6. By comparing the results among the systems, AFCILM scheme shows the best overall performance for the zero input signal while AFCCA gives the best response for the step input signal.

CHAPTER 1

INTRODUCTION

1.1 Background study

Vibration is a physical phenomenon where oscillation of certain object or system occurs at particular frequency. The magnitude of vibration required can be designed for specific purposes. However, its presence is typically undesirable in many applications as it would cause failure or damage to the system. Transmission of the vibration from the source to the medium in contact should also be monitored as the medium itself would experience certain degree of vibration excitation.

The usage of hand-held power tools increases significantly due to the advantage in mobility as these tools are used to carry out heavy-duty works that ease the operations, especially in the workshops, construction sites and automotive repair shops. However, the power tools can produce high level of vibration and hence the transmission of vibration to the arms is concerned for the safety of the operators. Prolonged usage of tools by the operators would lead to the health problems such as the Hand-arm Vibration syndrome (HAVs). This condition will lead to problems on hands such as numbness of fingers, muscle failure and bouts of white fingers. The HAVs is developed with a frequent use of the hand-held power tools over a long period of time, hence this syndrome is considered as occupational disease leading to invalidity. Therefore, it is very important to develop a vibration controlling system that helps in reducing the vibration of the hand-held tools.

In a vibration control, there are basically two approaches used in reducing the vibration of the system, which are passive and Active Vibration Control (AVC). Passive vibration control involves structural modification, vibration isolation and vibration approaches [1]. An example of the passive vibration control method is the use of viscoelastic material such as anti-vibration glove. However, as the dynamics of the system vary with time, passive vibration control will become inefficient and less functional.

AVC involves the generation of actuation force that is out-of-phase to the vibration phase. This will counterbalance the vibration using the active elements along with the sensors and controller and can be efficiently applied to the vibration system. There are several alternative control schemes that can be applied based on the AVC method, which can reduce the vibration of the suspended handle. This involves the Proportional-Integral-Derivative (PID) and Active Force Control (AFC) methods. AFC which has been developed for three decades, is proven to be an effective approach in suppressing the vibration system.

In this project, the modelling of four control schemes for the AVC system and AFC scheme using intelligent tuning methods of Crude Approximation (CA), Fuzzy Logic (FL) and Iterative Learning Method (ILM) will be constructed using MATLAB & Simulink software and the performance of those control schemes will be compared and analyzed.

1.2 Problem statement

The uses of power tools have now occupied an irreplaceable position in the heavy-duty industries due to its high mobility. However, the transmission of vibration from the power tool handle to the operator hand-arm system has the potential in causing health problem such as HAVs. A proper vibration control method such as AFC scheme can be designed to suppress the vibration of those power tools by using a suspended handle. In addition, the application of various intelligent control methods will assist the AFC control system in producing the best performance for the system. However, the performance between each controller is not studied for the model of power tools which is subjected with different combination of disturbance.

1.3 Objectives

In this research, the objectives to be achieved are as follow:

- To construct an active suspended handle model of power tools using intelligent control methods of AFCCA, AFCFL and AFCILM that can attenuate the vibration of the handle using MATLAB & Simulink software.
- To compare the performance of PID, AFCCA, AFCFL and AFCILM control methods in reducing the vibration of suspended handle model.

1.4 Scope of research

In this research, the active suspended handle is modelled using a PID controller and AFC with intelligent methods of CA, FL and ILM using the MATLAB & Simulink software. Then, the performance of these controllers will be compared with different combination of disturbance and input signal.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, the literature studies will be done on the subtopics of the vibration of power tools, HAVs, passive vibration control, AVC, AFC, FL and ILM.

2.2 Vibration of power tools

Working with vibration tools is common in many industries, such as in mechanical workshops, building, construction, foundries and forestry. The power tools can be powered with electricity, plug-in or even compressed air, such as pneumatic wrench, grinding wheel, internal grinder and several more. According to industrial standard, the exposure level or intensity of vibrational power is measured as acceleration in m/s^2 unit [2].

Exposure to the high level of vibration of power tools for a prolonged period can give rise to the risk of hand injury in the form of vascular disorder and nerve malfunction that might affect on the musculoskeletal system. These damages are usually collectively referred to HAVs. Hence, there is a necessity to control the vibration at work regulations, which three important parameters to be discussed here are A(8), Exposure Action Value (EAV) and Exposure Limit Value (ELV).

A(8) is an eight-hour energy equivalent vibration magnitude value that represents the daily exposure. This means the A(8) value is the vibration magnitude that if maintained for eight hours, would be equivalent in energy terms to the actual vibration of the exposure time. EAV is a level of daily operator exposure, which require an action to be taken to reduce the exposure and risk if it is exceeded. ELV is a maximum allowable level of daily exposure that must not be exceeded. For hand-transmitted vibration, the directive specifies the EAV and ELV vibration magnitudes for eight-hour reference period (EAV = 2.5 m/s^2 A(8), ELV = 5 m/s^2 A(8)) [3].

In previous study, the range of measured vibration level of several power tools are shown in the **Table 2.1**. From the table, most of the power tools have the vibration magnitude that exceeded the specified EAV and ELV values. For example, the percussion drill has maximum vibration magnitude of 14.5 m/s^2 which exceeds the ELV value of 5 m/s^2 A(8) if the power tool is used for prolonged exposure.

Table 2.1: Vibration level of power tools. [2]

Power Tools	**Acceleration, *a* (m/s^2)**
Pneumatic wrench	0.30 ~ 11.04
Grinding wheel	1.61 ~ 8.97
Internal grinder	1.46 ~ 8.70
Percussion drill	11.10 ~14.50
Arc welding machine	0.21 ~ 2.18

2.3 Hand-arm Vibration syndrome (HAVs)

HAVs is a collection of sensory, vascular and musculoskeletal symptoms caused by repetitive trauma of vibration, which has a potential health hazard to the workers in any occupation involving repetitive use of vibrating tools [4]. HAVs symptoms includes numbness, blanching and tingling of the fingers as well as a loss of fine motor control [5].

There is epidemiologic evidence that the occupational groups using the vibrating tools will have a greater occurrence of HAVs symptoms than the control groups. Epidemiology surveys of vibration-exposed workers shown that the prevalence of peripheral sensorineural disorder varies from a few percent to more than 80 % and that symptoms and signs of sensory loss can affect the users of a wide range of tool types [6].

Cross-sectional and longitudinal epidemiology studies show that occupational exposure to HAVs from a variety of hand-held tools are significantly associated with an increase occurrence of digital vasospastic disorder called Vibration-induced White Finger (VWF). Epidemiology studies have pointed out that the prevalence of VWF is very wide, ranging from the 0 - 5 % rate observed in workers using vibrating tools in geographic areas with a warm climate to the 80 – 100 % figure seen in workers exposed to high vibration magnitudes in northern countries. This shows an association between VWF and the occupations involving with vibrating tools is further related to the exposure to HAVs [6].

The study about the exposure action and limit by David also shows the potential exposure to HAVs for manual workers who use hand-held power tools. It has proposed the change in many on-site working practice by limiting the exposure time to higher vibration tools [21].

2.4 Passive vibration control

Vibration control are generally classified into passive vibration control, AVC and hybrid vibration control. Passive control involves the use of reactive or resistive devices that either load the transmission path of the disturbing vibration or absorb vibrational energy. For the passive vibration control, isolation can be attained through the limitation of the ability of vibration to transmit in different medium. This isolation can be attained using mechanical connection that helps in dissipating the energy of vibration before it is transmitted item. Viscous dampers (dashpots), tuned-mass dampers, dynamic absorbers, shunted piezo ceramics dampers, and magnetic dampers are some elements that can be used for the passive vibration control. However, the passive vibration control has its limitations, such as low versatility to adapt to the system vibration that varies with time.

There is a new type of passive vibration control technique based on the concept of electromagnetic shunt damping, which is similar to piezoelectric shunt damping. By attaching an electromagnetic transducer to a resonant mechanical structure and shunting the transducer with an electrical impedance, the kinetic energy from the resonant structure can be dissipated. As the mechanical structure displaces, an opposing Electro-Motive-Force (EMF) is induced in the transducer. Using an appropriately design of electrical shunt, the transducer is capable in significantly reducing the mechanical vibration [7].

2.5 Active Vibration Control (AVC)

AVC is defined as a system with an active power sources such as actuator to control and attenuate the vibration of the system [8]. When dealing with a dynamic system that the disturbance will vary with time, AVC is more effective in attenuating the vibration compared to the passive vibration control.

In general, AVC has two types of control, which is open loop and closed-loop. Typically, the open loop control is controlled using a switch (on and off) while the closed-loop needs a specific controller to process the feedback signals and translate it into a control action [9]. **Figure 2.1** shows the basic feedback control diagram of the AVC system.

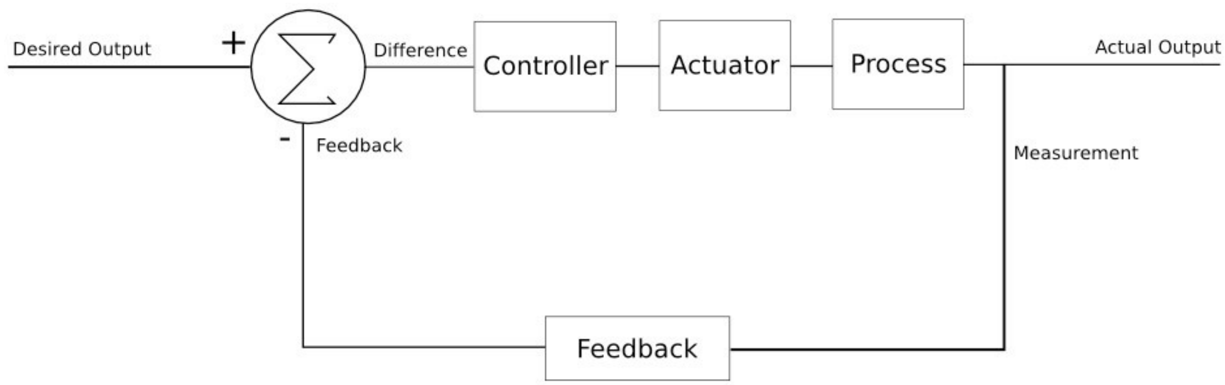

Figure 2.1: Basic feedback control loop diagram [10].

From the figure, the control system has a sensor that used to feedback the measured signal to the controller system. The actual value and desired value are then compared and analyzed to obtain the differences between both signals to produce a counter signal. The counter signal is then used to attenuate the disturbance of the system and thus reduce the vibration.

Among the controller techniques applied in AVC system, PID controller is one of the most widely used. It can provide fast response, good system stability and small steady state errors in a linear system with known parameters. As its name implies, a PID controller consists of three parts, which are proportional (K_P), integral (K_I) and derivative (K_D). Assuming that each amplitude is completely decoupled and controlled independently from other amplitudes, the control output is given by:

$$V(t) = K_p e(t) + K_i \int e(t)dt + K_d de(t)dt \tag{2.1}$$

A comparison of performance using a neural network scheme for controlling a bus suspension system with the PID, PI and PD controllers is done by Yildirim [11]. Results for four different controllers is shown in **Table 2.2**. From the study, the neural network scheme works well and give a better control performance than a simple PID scheme when accurate dynamics model of system is available. However, in practical simulations, the parameters associated with the suspension system model are very difficult to be determined exactly. Thus, the proposed neural network has to be proven in terms of stability characteristics for theoretically as well as experimentally in order to have a better performance than PID controller.

Table 2.2: Comparison of neural network, PI, PD and PID controllers [11].

	Neural Network	**PI**	**PD**	**PID**
Settling time	< 1s	< 1.5s	Long and not stable	> 3s
Overshoot	< 1%	< 2%	> 10%	> 5%

2.6 Active Force Control (AFC)

The concept of AFC has been introduced and applied by Hewitt and fellow researchers in 1981. It is a well-known strategy for eliminating the disturbances that affected the dynamic system. A dynamic system control experiment has proven that this strategy gives stability, robustness and effectiveness to the system even in the presence of known or unknown disturbances with various operating condition [12].

The essence of AFC strategy is to obtain the estimated disturbance force, F^* through the measurement of mass acceleration a, and actuator force F_a and an appropriate estimation of the estimated mass M^*, as described in the following equation:

$$F^* = F_a - M^* a \tag{2.2}$$

The Eq. (2.2) is very simple and computationally light, which therefore becoming a very attractive option for real-time or on-line implementation. **Figure 2.2** shows the schematic of an AFC scheme applied to the dynamic system. The actuating force F_a, and the acceleration a, are measured through the sensing elements. The estimated mass of the system M^*, with the presence of the disturbances that partially contribute to the acceleration would be estimated appropriately by using CA method or other intelligent methods such as FL and ILM.

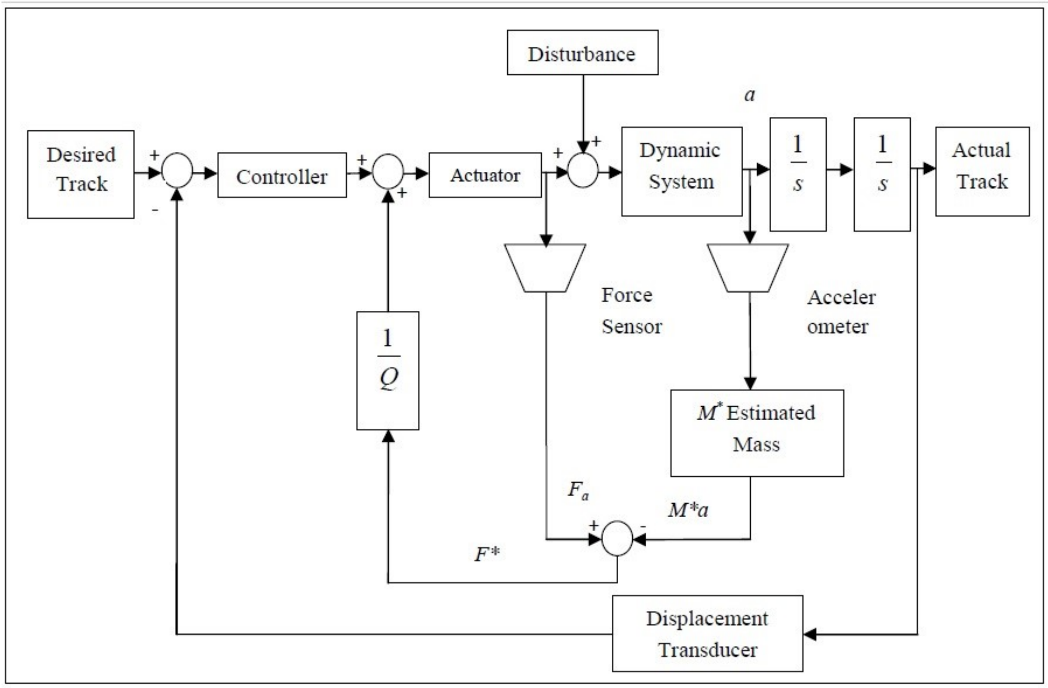

Figure 2.2: Schematic diagram of AFC. [13]

The efficiency of AFC is studied with different strategies for the biped robot and has been proven as robust and stable [14]. Three different control schemes are applied, which are PD control scheme, PD-AFC-CA and PD-AFC-ILM. The overall performance of control schemes applied to the biped is compared by considering the average tracking error (ATE) generated by all of the 4 joints during the simulation. The results are summarized in **Table 2.3**. The results show that the overall performance of the AFC schemes outperforms the PD scheme in all cases. The proposed AFC demonstrate a high degree of accuracy and robustness even under the influence of various disturbance [14, 15].

Table 2.3: Summary of ATE result for biped.

ATE	PD scheme	AFC-CA scheme	AFC-ILM scheme
Without disturbance (rad)	0.079263	0.078574	0.078703
With disturbance (rad)	0.427657	0.079798	0.081157

2.7 Fuzzy Logic (FL)

The concept of FL was first pioneered by Professor Lotfi Zadah from the University of Califonia in 1965. This method has been widely used in recent year due to its advantages in dealing with the environmental factors during operation. Therefore, it is common nowadays that FL method is being employed in the AVC system.

FL controller is an intelligent system that is capable in interpolating the parameters between the boundary crisp rules. The basic steps of operation for FL is shown in **Figure 2.3** below.

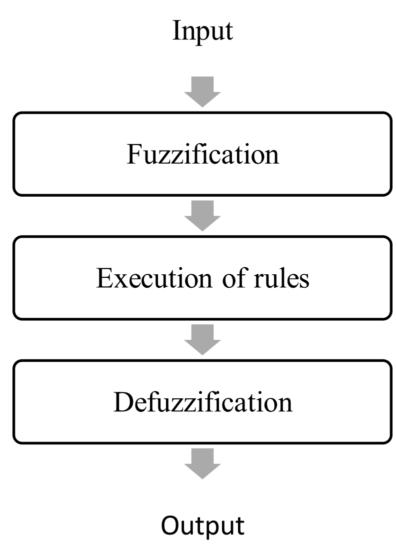

Figure 2.3: Concept of FL operation.

The first step is the fuzzification of input which is the process of decomposing the system input and transforming into fuzzy input with the construction of suitable membership function (MF) that represent the fuzzy set. This is followed by the execution of rules which are normally linguistic statements (e.g., *if-then* rules) which would response to the given fuzzy input. The final step of FL is the defuzzification that interpolate the response to produce crisp output values.

The efficiency of the FL controller is studied by Mailah [15] with the corparation of AFC controller for robotic application and it is compared with other intelligent methods and the results show that FL has high degree of robustness even with the presence of disturbance [17]. The AFCFL scheme is able in tracking the reference trajectory with high accuracy even with the spring and pulsating force applied onto the system. The proposed AFCFL performed excellently even under the influence of external disturbance.

2.8 Iterative learning method (ILM)

The concept of ILM was brought by Uchiyama in 1978 and the idea was developed by Arimoto and his co-worker later in English [16]. The concept of ILM is about the iterative approach to generate the optimal input so that the system can process for output that close to the desired value. It takes advantage of the repeated behavior of the system that converge all systematic errors to a zero datum. The basic algorithm of the ILM is shown in Eq. (2.3) below:

$$f^{k+1} = f^k + \left(A + B\frac{d}{dt}\right)Te_k \tag{2.3}$$

Where,

f^{k+1}	=	Next step value (Estimated Mass, EM)
f^k	=	Current step value (Initial Mass, IM)
A & B	=	Proportional & derivative learning parameters, respectively
Te_k	=	Current track error

From the studies done by Kwek et al. [14] the average tracking error (ATE) obtained by AFCILM is larger by 1.7 % as compared to AFCCA for all cases when the initial setting is incompatible. The AFCILM is tested without the prior knowledge of the system, which is an attractive feature of AFCILM. This is because other schemes such as AFCCA can be used provided with the prior knowledge of the system, which is impractical for most of the cases.

2.9 Summary

From the literatures, it can be summarized that:

- The vibration of power tools is high and may cause health problems such as HAVs if exposed for a prolonged period of time.
- Vibration of power tools can be reduced through two approaches, which are passive vibration control and AVC. The overall performance of AVC is better compared to the passive vibration control.
- There is no report on the performance comparison using the AFC control with different intelligent methods for a suspended handle system. The intelligent methods such as CA, FL and ILM that will be studied in this research.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this chapter, the methodology in constructing an active suspended handle model is presented. The AVC model is tested using PID and AFC with intelligent methods of AFCCA, AFCFL and AFCILM using MATLAB & Simulink software. Then, the performance of these controllers will be compared to determine which intelligent method has the best performance. **Figure 3.1** shows the overall flow chart of the research.

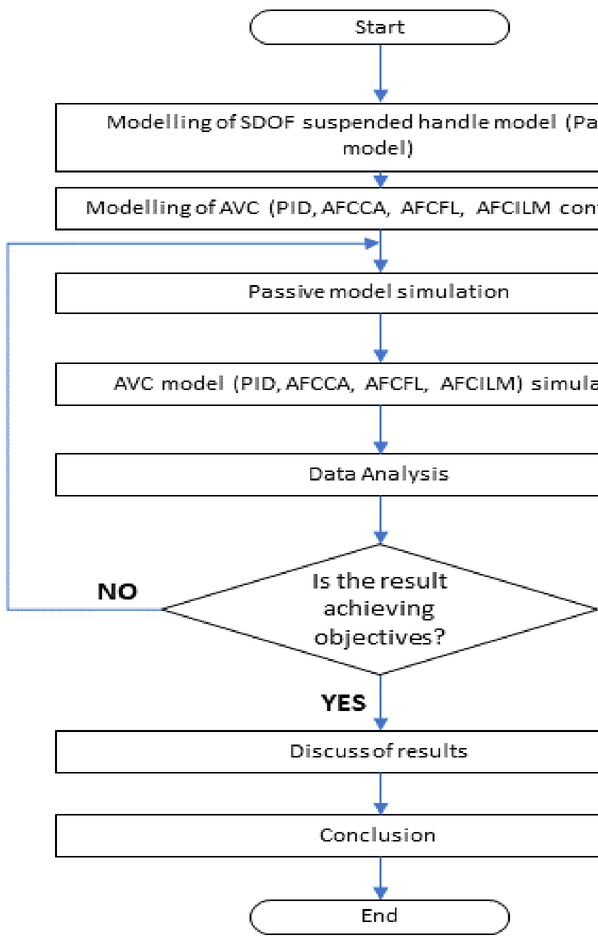

Figure 3.1: Flow chart of overall methodology.

3.2 Mathematical model of the AVC system

In this research, the mathematical model of the active suspended handle is represented by a mass(m)-spring(k)-damper(c) system in a single degree of freedom (SDOF) system. The reference of model is taken from the previous study done by Mazlan [17]. The suspended handle is designed to attenuate the transmitted vibration using a piezo stack actuator of the SDOF system as shown in **Figure 3.2**.

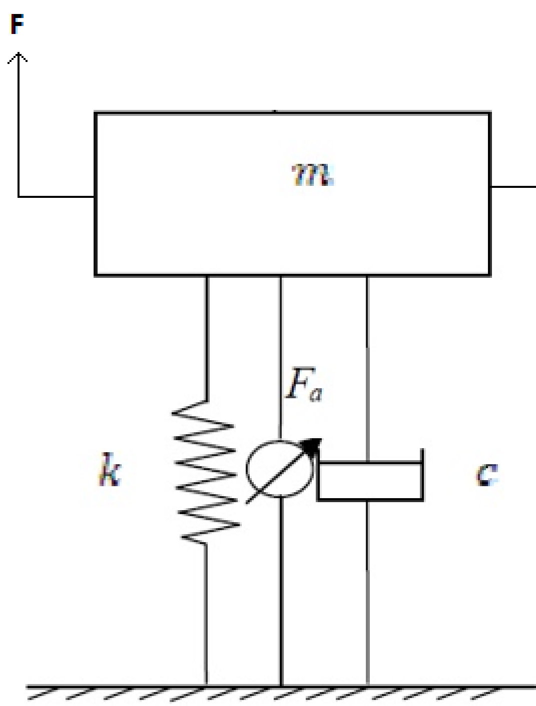

Figure 3.2: Mathematical model of the active suspended handle.

The AVC system was modelled by adding an actuator to the passive system to exert a counter force F_a, to compensate the disturbances F, that acts on the mass. The equivalent counter force acts based on the response measured by the sensors on the mass. The equation of motion for the suspended handle with AVC system can be represented as the follows:

$$m\ddot{x} + c\dot{x} + kx - F_a = F \qquad (3.1)$$

From Equation 3.1, the F_a value generated through a PID and different AFC strategies would vary and will be simulated using MATLAB & Simulink software.