PERFORMANCE COMPARISON OF AFC-CA, AFC-GA, AFC-PSO AND AFC-NN IN REDUCING THE VIBRATION OF SUSPENDED HANDLE MODEL

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Description
ABC	Artificial Bee Colony
AC	Alternative Current
AFC	Active Force Control
ANN	Artificial Neural Network
AVC	Active Vibration Control
BFO	Bacterial Foraging Optimization
CA	Crude Approximation
DC	Direct Current
DOSH	Department of Occupational Safety and Health
DVA	Dynamic Vibration Absorber
EAV	Exposure Action Limit
ELV	Exposure Limit Value
EM	Estimated Mass
FFT	Fast Fourier Transform
GA	Genetic Algorithm
HAVS	Hand-Arm Vibration Syndrome
IAE	Integral of Absolute Error
ISE	Integral of Squared Error
ITAE	Integral of Time-Weighted Absolute Error

MOHR	Ministry of Human Resources
PID	Proportional-Integral-Derivative
PSO	Particle Swarm Optimization
RMS	Root Mean Square
SDOF	Single Degree of Freedom
TLV	Threshold Limit Value

LIST OF APPENDICES

LIST OF SYMBOLS

Symbol	Description
c	Damping
$e/e(t)/E$	Error difference between actual output and reference input
ET	Sum of track error of each generation
f_{GA}	Fitness score
f_{PSO}	Function value
F	Disturbance force
F^*	Estimated disturbance force
F_a	Actuator force
F_{in}	Internal disturbance
F_{eA}	External disturbance A
F_{eB}	External disturbance B
G_c	PID control function
k	Stiffness
K_D	Derivative term
K_I	Integral term
K_P	Proportional term
m	Mass
Q	Stiffness of actuator

S	Number of samples
t	Time
T_d	Disturbance torque
u	Control variable to adjust actuator force
x	Displacement

ABSTRAK

Getaran dapat dihasilkan dalam mana-mana sistem mekanikal. Sesetengah getaran yang dihasilkan bermanfaat dalam beberapa proses seperti menggerudi, memotong dan mengisar tetapi getaran akan memudaratkan pengendali yang mengendalikan alat kuasa mekanikal. Sindrom getaran tangan-lengan (HAV) ialah salah satu kesan pendedahan secara berpanjangan dengan getaran tahap tinggi. Sarung tangan anti-getaran dicadangkan dan digunakan dalam banyak industri tetapi sarung tangan anti-getaran mempunyai lebar jalur frekuensi berkesan yang terhad dan tidak berkesan dalam mengendalikan sistem dinamik. Oleh itu, Kawalan Getaran Aktif (AVC) dicadangkan dalam pengurangan getaran apabila pengendali mengendalikan alat kuasa. Daripada kajian terdahulu, AVC dengan pengawal berkardar-kamiran-kebezaan (PID) tanpa skema AFC tidak menunjukkan prestasi yang baik dalam pengurangan getaran berbanding AVC-PID dengan skim Kawalan Daya Aktif (AFC). Dalam kajian ini, pelbagai kaedah penalaan yang pintar diaplikasikan seperti penganggaran kasar (CA), algoritma genetik (GA), pengoptimuman kelompok zarah (PSO) dan rangkaian neural (NN) dalam sistem AVC-PID. Prestasi skim AFC dalam pengurangan getaran dianalisis dan dibandingkan di bawah gabungan gangguan yang berbeza. Daripada keputusan, AVC-PID dengan skim AFC telah menunjukkan prestasi yang lebih baik dalam mengurangkan getaran berbanding sistem pasif dan AVC dengan pengawal PID. Antara semua skim AFC, kaedah penalaan AFCNN mempunyai prestasi terbaik dalam mengurangkan getaran di bawah gangguan ketidakpastian. Kesimpulannya, AFC dengan kaedah penalaan pintar adalah cara yang berfaedah untuk pengurangan getaran pemegang yang digantung.

ABSTRACT

Vibration can be generated in any mechanical systems. Some of the vibration produced is beneficial in some processes such as drilling, cutting, and grinding but it will detrimental to the operator who operate the mechanical power tools. Hand-arm vibration syndrome (HAVs) is one of the consequences due to prolonged exposure of high level vibration. The anti-vibration glove is proposed and used in many industries, but it has limited effective frequency bandwidth and ineffective in handling the dynamics system. Therefore, Active Vibration Control (AVC) is suggested in vibration attenuation when operator is handling the power tool. From previous research, AVC with proportional-integral-derivative (PID) controller without Active Force Control (AFC) scheme is not perform very well in vibration attenuation compared to AVC-PID with AFC scheme. In this study, various intelligent tuning methods are applied such as Crude Approximation (CA), Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Neural Network (NN) together with AVC-PID system. The performance of AFC schemes in vibration attenuation is analyzed and compared under different combination of disturbances. From the results, AVC-PID with AFC schemes have performed better in reducing the vibration compared to passive system and AVC with PID controller. Among all the AFC schemes, AFCNN tuning methods has produced the best performance in reducing vibration even though under uncertainty disturbances. As a conclusion, AFC with intelligent tuning methods is an advantageous way for vibration attenuation of suspended handle.

CHAPTER 1

INTRODUCTION

1.1 Overview

In this chapter, project background, problem statement, objective and scope of work are going to be discussed.

1.2 Project background

Vibration is an oscillation in any mechanical systems. Vibrations are occurred in our daily life, and it can be created by a system to play a positive role on the final result. For instance, vibration involves the creation of sound, notification triggered in mobile phone, gold vibration separation process and so on. However, in some cases the vibrations can cause a problem or safety issue in the engineering systems. Undesirable vibration will waste energy, create unwanted noise and prolonged exposure to the high level of vibration when handling power tool will bring irreversible health effects.

Hand-arm Vibration syndrome (HAVs) is one of the effects from prolonged exposure to high level of vibration. Workers suffering with HAVs will experience the whitening of fingers when exposed to cold, loss of light touch, pain and cold sensations and loss of grip strength. There is a way to protect workers from these risks by introducing the exposure action limit (EAV) and exposure limit value (ELV). EAV which has the value of 2.5 m/s^2 is a daily amount of vibration exposure which the company has to take action to control them. Meanwhile, ELV is the maximum amount of vibration that employee can be exposed daily which has the value of 5 m/s^2 (Nelson & Brereton, 2005). In order to control the vibration transmitted to the workers, there are two methods that can be implemented, which are passive vibration control and active vibration control (AVC).

For passive vibration control, it can be in the form of dynamic vibration absorber (DVA) or any kind of isolator that isolate human’s hand from the vibration sources. For instance, an anti-vibration glove is one of the passive vibration control devices that is commonly used daily. Anti-vibration gloves can reduce the vibration effectively at a high frequency, which more than 500 Hz (Hewitt et al., 2016), however, it is not effective for attenuating vibration below 150 Hz (Oddo et al., 2004). Anti-vibration gloves become ineffective at certain conditions and can only work in limited frequency bandwidth. In other words, the passive vibration control becomes ineffective when the dynamics of the system and frequencies of vibration vary with time.

AVC system is more preferable to be used for reduction of vibration transmitted to the human body. AVC working principle is based on superposition and destructive interference whereby it will create a new active force with same magnitude but travelling in opposite direction with the vibration force to cancel it. In AVC system, it consisted of three main elements which are sensor, actuator and controller. In this study, the available active vibration suspended handle model (Ahmad Mazlan & Mohd Ripin, 2015) is going to be applied and its performance using three different intelligent tuning methods of Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Neural Network (NN) for the Active Force Control (AFC) in reducing the vibration of suspended handle will be investigated. The suspended handle model developed by Mazlan and Ripin consists of sensor, actuator and controller as shown in Figure 1.1. The accelerometer (sensor) converts the vibration energy into electronic signals which are then transmitted to the controller.

This controller operates by computing the estimated disturbance force through measurement of acceleration and force of the actuator. The actuator provides a counter vibration as same frequency with the source but in out of phase in order to attenuate it. To compare the effectiveness of AVC system in reducing the vibration of suspended handle, the models are constructed in different schemes such as Proportional-Integral-Derivative (PID) controller, PID controller with AFC using GA Tuning Method (PID-AFCGA), PSO Tuning Method (PID-AFCPSO) and NN Tuning Method (PID-AFCNN) in MATLAB/Simulink software. The results will be compared to evaluate the effectiveness of vibration attenuation performance of the available suspended handle model (Ahmad Mazlan & Mohd Ripin, 2015).

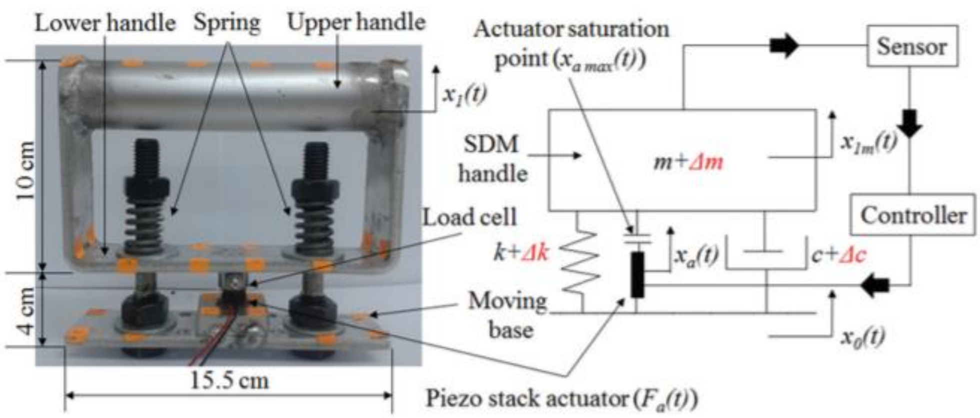

Figure 1.1 Design of an original-active suspended handle (Ahmad Mazlan & Mohd Ripin, 2015)

1.3 Problem Statement

Most of power tools and machineries that used by workers in industry can generate high level of vibration which exceeding the EAV and ELV values. This subsequently can cause catastrophic consequences to the worker's health such as HAVs due to prolonged exposure to the high level of vibration tools. Several studies showed that the passive vibration control techniques are not very effective in reducing the vibration such as the anti-vibration glove (Eissa & Sayed, 2006). AVC with the integration of AFC strategy is one of effective vibration control technique compared to the available anti-vibration gloves. In order to make the AFC perform effectively, a proper tuning method has to be investigated. There are many tuning algorithms for the AFC such as GA, PSO and NN methods. Hence, this study will investigate and compare all of them in attenuation the vibration of active suspended handle for the power tools application.

1.4 Objectives

There are two objectives to be achieved in this study which are:

- To develop the suspended handle models with AVC system using MATLAB/Simulink software
- To evaluate effectiveness of AFC scheme in reducing vibration of suspended handle model using different intelligent tuning methods such as GA, PSO and NN

1.5 Scope of Work

In this project, a simulation study of suspended handle model with AVC system can be carried out using MATLAB/Simulink software. A PID controller with AFC using different tuning algorithms such as GA, PSO and NN will be constructed, and the effectiveness of the control scheme in attenuating the vibration of suspended vibration handle will be evaluated

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, five main topics will be discussed as follows:

- High vibration of power tools
- Active Force Control (AFC)
- Genetic Algorithm (GA)
- Particle Swarm Optimization (PSO)
- Neural Network (NN)

2.2 High Vibration of Power Tools

Power tool is a type of machinery that is actuated by power source either using alternating current (AC) or direct current (DC) operation, and it is widely used in gardening, construction and industry. Power tools can be categorized into several types which are drills, saws, sanders, grinders, and many more. Power tools are widely used by workers and operators because of the multi-functioning, but in some cases, they can create unwanted and high vibration during operation. The vibration can be transmitted into workers' hands and arms, and it is called HAV (HSE GOV UK, 2019). Prolonged exposure to high level of vibration may lead to permanent health issues such as HAVs. As shown in Figure 2.1, there are several symptoms of HAVs like tingling and numbness in the fingers which can cause inability to do fine work, loss of strength in the hands and fingers and in a long time it can become red and painful. The workers whose are facing HAVs cannot work in a cold or damp conditions.

Figure 2.1 Whiteness of fingers (*Hand Arm Vibration Syndrome – Causes and Prevention | NASP*, 2018)

In Malaysia, Department of Occupational Safety and Health (DOSH) under Ministry of Human Resources (MOHR) have provided a guideline on Threshold Limit Values (TLV) for vibration transmitted to the hand-arm. The guidelines are based on the acceleration levels and durations of exposure for workers without beyond of Stage 1 as shown in Table 2.1.

Table 2.1 HAVs classification system (DOSH MALAYSIA, 2003)

Stage	**Grade**	**Description**
0	-	No attacks
1	Mild	Occasional attacks affecting only the tips of one or more fingers
2	Moderate	Occasional attack affecting distal and middle (rarely also proximal) phalanges of one or more fingers

3	Severe	Frequent attacks affecting all phalanges of most fingers
4	Very Severe	As in stage 3, with trophic skin changes in the finger tips

Table 2.2 TLV for exposure of the hand to vibration (Edwards & Holt, 2007)

Total daily exposure duration	**Root Mean Square (RMS) acceleration (m/s^2)**	**Ratio of acceleration RMS to gravity $\left(\frac{m/s^2}{9.81}\right)$**
4 hours and less than 8	4	0.41
2 hours and less than 4	6	0.61
1 hours and less than 2	8	0.81
less than 1 hour	12	1.22

In Table 2.2, it is showing the total daily vibration exposure duration with respect to the root mean square (RMS) acceleration of vibration amplitude. It can be notable that the higher the total vibration exposure duration in daily, the lower the RMS acceleration value. The TLV were set by DOSH is to advise the workers about exposure of high level vibration over 8 hours daily.

The level of vibration power tools must be operated at a level that not exceeding the EAV of 2.5 m/s^2 or even ELV of 5.0 m/s^2 (HSE GOV UK, 2019). According to

European Union standard, EAV and ELV have been set as an acceptable levels of HAV exposure per day or 8 hours of operation (Council of the European Union, 2018).

2.3 Active Force Control (AFC)

AFC has been acknowledged by several works as an effective control scheme compared to other vibration attenuation methods. It has been created and applied by J.R Hewit to control several dynamics systems (J R Hewit, 1988). In AVC system, a new active force with same magnitude will be created and travelling in opposite direction or out phase to cancel the vibration source. By adding AFC with an appropriate tuning method, the best efficiency in attenuating the vibration of the system can be achieved.

Designing a robust, stable and effective vibration control using an AFC scheme will aid the performance of conventional PID controller which can be presented as following equation:

$$G_c = K_P e(t) + K_I \int e(t)\, dt + K_D \frac{de(t)}{dt} \tag{2.1}$$

Where, K_P is the proportional, K_I is the integral and K_D is the derivative gains. From Equation (2.1), $e(t)$ is the signal error, and can be shown as follows:

$$e(t) = Y_d(t) - Y(t) \tag{2.2}$$

Where Y_d is the desired amplitude and Y is the measured amplitude. The PID controller gains can be adjusted manually or using auto-tuning methods. However, the robustness of vibration control using PID controller can be affected and the effectiveness is limited in a certain range of frequencies. Therefore, PID control with AFC intelligent tuning algorithm can improve the robustness, stability and effectiveness of AVC system.

An active suspension control design has been investigated for attenuating vibrations caused by road disturbance (Haddar et al., 2019). The performance of AFC control schemes is determined by tracking of references trajectory, ride comfort and suspension deflection. The study shows that an *i*-PD control scheme has a better tracking of reference trajectory performance compared to others. The ride comfort performance is determined by the RMS of sprung mass acceleration as shown in Figure 2.2 and Figure 2.3. The *i*-PD and active disturbance rejection control (ADRC) showed lower value of RMS of sprung mass acceleration. Also, the *i*-PD controller has the lowest settling time among all the control schemes. This study proved that an AFC has improved the suspension deflection compared to passive controller.

$RMS = \sqrt{\frac{1}{N}\int_0^N y^T(t)\,y(t)dt}$	*Passive*	*LQR*	*ADRC*	*i-PD*
RMS of sprung mass acceleration	1.9	0.9	**0.5**	0.6
RMS of suspension deflection	0.029	0.018	0.021	0.019
Amelioration compared to passive system (%)		37%	28%	35%
RMS of normalized tyre deflection	0.177	0.124	0.145	0.122
Amelioration compared to passive system (%)		30%	18%	31%

Figure 2.2 Dynamic response performances (Haddar et al., 2019)

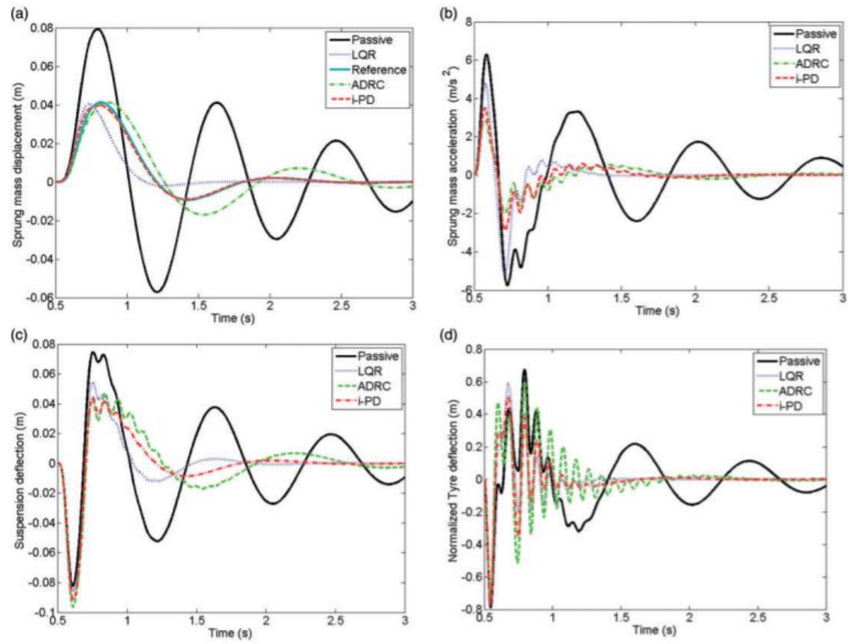

Figure 2.3 Time-domain responses of (a) sprung mass displacement (b) sprung mass acceleration (c) suspension deflection and (d) normalized tyre deflection. (Haddar et al., 2019)

2.4 Genetic Algorithm (GA)

GA is a search algorithm that created based on mechanics of natural selection and natural genetics. GA has been created by John Holland in early of 1970s. The objectives of GA development are (1) to abstract and investigate the flexible process of natural system and (2) to construct a system that is able to obtain significant mechanisms of natural systems. There are some differences between GA and other traditional ways as shown in Table 2.3.

Table 2.3 The differences between GA and traditional method (Goldberg & Holland, 1988)

No	**Differences**	
	Genetic Algorithm (GA)	**Traditional Method**

1	Search from a population of points	Search from a single point
2	Work with coding of the parameter set	Work with parameters themselves
3	Use payoff information	Derivatives or auxiliary knowledge
4	Use probabilistic transition rules	Deterministic rules

There are five step generations in GA which are individual population, level of fitness, selection of chromosomes, crossover and mutation as shown in Figure 2.4. GA begin at generation of initial design point. These chromosomes must be selected based on their level of fitness for production of offspring. The higher level of fitness score will lead to development of population that are suited to their environment and named it as natural adaptation. For a pair of parent the chromosomes contained are swapped at crossover site as shown in Table 2.4. A number of populations are randomly created. If the optimization standard does not meet, the new generation will be created.

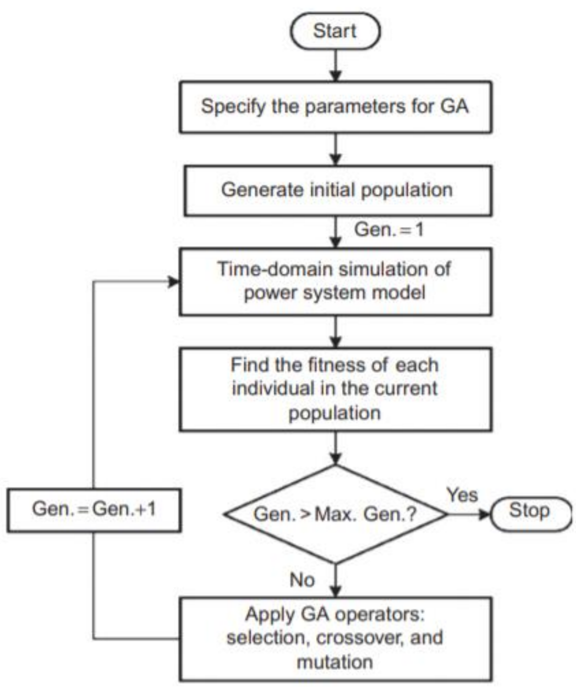

Figure 2.4 Flow chart of the genetic algorithm (Aboelela & Hennas, 2018)

Table 2.4 The one-point crossover operator (Kozek et al., 1993)

Parents	1	0	0	1	0	1	1	0	1	1	0	0	0
	2	1	0	1	1	0	0	1	0	0	1	0	1
									Crossover				
Offspring	1	0	0	1	0	1	1	0	1	0	1	0	1
	2	1	0	1	1	0	0	1	0	1	0	0	0

There are some researches that used AFC with GA scheme to reduce the uncertainties and disturbance in control system. Past research has investigated the AFC scheme of a robotic arm using GA (Mailah et al., 2002). This research is focused to estimate the inverse matrix IN of a robotic arm to achieve high robustness and accuracy control system. The effectiveness of GA in reducing the uncertainties and disturbance can be justified by the fitness, f and track error, E of the optimal individual. The results showed that by increasing of disturbance torque T_d, the effectiveness of the GA shows a decreasing trend as shown in Figure 2.5 and Table 2.5. However, the GA has successfully estimated the IN value automatically and the track error, E and best fitness, f are fall in an acceptable region (more than 0.900). Therefore, the AFC with GA is able to implement in reducing the disturbance of a robotic arm.

Table 2.5 The summary of the disturbance of torque and sum of track error against the best fitness.

T_d (Nm)	10	20	30	40	50
E(m)	0.0649	0.0717	0.0705	0.0738	0.0937

Best fitness	0.9391	0.9331	0.9342	0.9313	0.9143

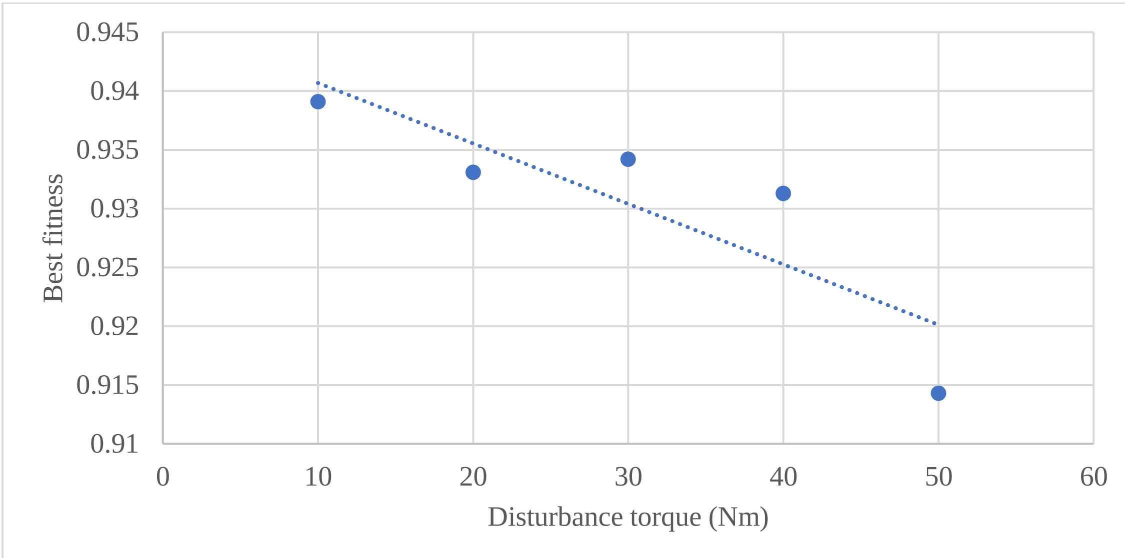

Figure 2.5 Best fitness against the disturbance torque (Mailah et al., 2002)

A car active suspension system has been tested with PID controller and tuned using GA algorithm (Aboelela & Hennas, 2018). The performance AFCPID with GA tuning approach are based on IAE, ISE and ITAE error criteria as shown in Figure 2.6. The results showed that the settling time with FOPID and GA is lesser than the controller without GA tuning.

Error Criteria		Tuned Parameters of FOPID				
		K_p	K_i	K_D	λ	δ
IAE	Value of IAE 5.6103	8.1472×10^3	2.7603×10^3	1.6218×10^3	0.1	0.1
ISE	Value of ISE 0.1754	8.1472×10^3	2.7603×10^3	1.6218×10^3	0.1	0.1
ITAE	Value of ITAE 3.3375	8.1472×10^3	2.7603×10^3	1.6218×10^3	0.1	0.1

Figure 2.6 Car suspension simulation result with FOPID GA (Aboelela & Hennas, 2018)

2.5 Particle Swarm Optimization (PSO)

PSO was firstly introduced by Eberhart and Kennedy in 1995. PSO algorithm is an adaptive algorithm based on the movement of bird and fish schooling (Julai et al., 2009) ; (Settles, 2005). PSO consists of two major operators which are velocity and position. The new generations of each particle will fly to the previous particles with best position. The generation of new velocity will according to the current velocity of the particle with the previous global position, and the latest velocity will calculate the global best position.

There is a study that designed a PID controller with PSO tuning method to maintain the chemical reaction temperature in reactor at 350 ^{o}C. The PID-PSO scheme is to refine the integral of absolute error (IAE), integral of squared error (ISE) and integral of time-weighted absolute error (ITAE) as shown in Figure 2.7. Through the simulation result from the model, the PID-PSO scheme is more suitable for refining the ITAE. This is because the settling time for ITAE criteria is the lowest compared to IAE and ISE. In other study, the car suspension system is designed for better ride comfort of passengers by reducing the vibration according to different disturbances. The traditional car suspension used a mechanical spring for absorption the energy, however, this passive vibration system has limited effective range of frequency isolation. Aboelela & Hennas (2018) has implemented the AFC with PID-PSO to minimize the deflection of vehicle body and tire body. The simulation result in Figure 2.8 showed that the AFC with PID-PSO is able to obtain less than 1.5s settling time for all IAE, IAE and ITAE.

Description	IAE	ISE	ITAE
Settling time	7.7262	3.5344	3.1468
Undershoot	No overshoot	No overshoot	No overshoot
K_p	8.1472	8.5234	1.5354
K_i	2.7603	5.8639	4.1431
K_d	1.6218	0.3033	2.5249

Figure 2.7 Reactor simulation results with PID-AWPSO (Aboelela & Hennas, 2018)

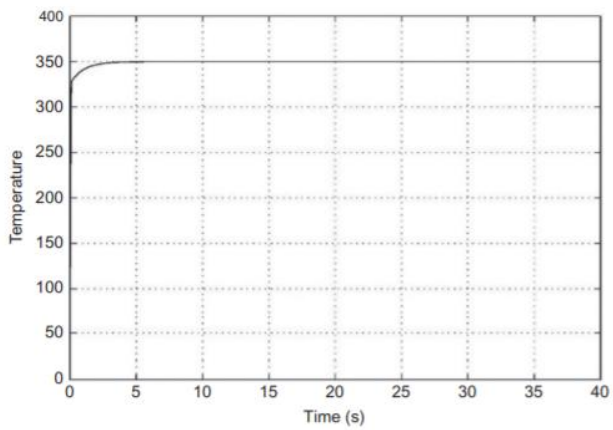

Figure 2.8 Reactor temperature with PI-AWPSO based on ISE (Aboelela & Hennas, 2018)

2.6 Neural Network (NN)

NN algorithm tuning method is very useful for the closed loop system (Milovanović et al., 2016) . NN is able to adapt on multipurpose and different conditions. Multilayer of perceptron NN structure contains an input layer, a hidden layer and output layer as shown in Figure 2.9 (Dahunsi et al., 2010). There could be large number of nonlinear neurons in the hidden layer and this will cause an increase of computational time. Therefore, Levenberg-Marquardt minimization algorithm was introduced to train the network layer due to its rapid convergence and stability. The proper weights and biases can be obtained from the error between the output and network.

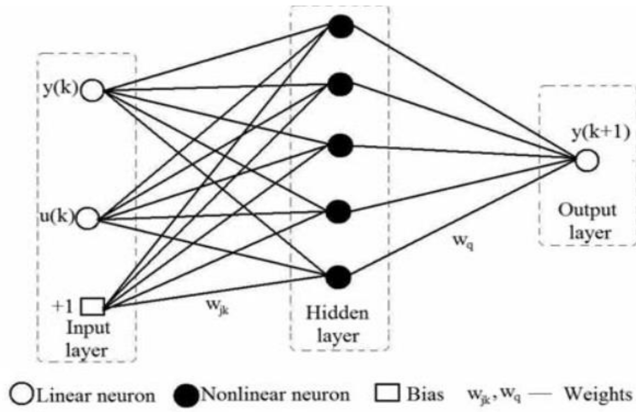

Figure 2.9 Neural network layer structure (Milovanović et al., 2016)

Priyandoko et al. (2009) have proposed NN algorithm in controlling the vibration of bus suspensions. From the study, the AFC with PID-NN performs more excellent result in controlling the vibration with only simple PID controller with inherent gains as shown in Figure 2.10.

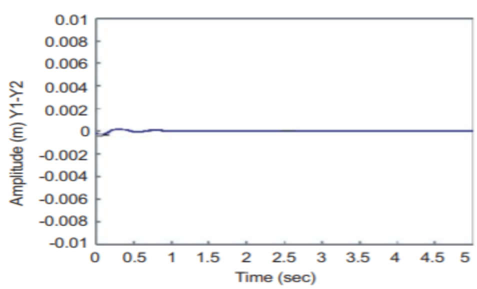

Figure 2.10 The amplitude result using neural controller in bus suspension system (Priyandoko et al., 2009)

Past research shown in Figure 2.11 has investigated AFC method with artificial neural network (ANN) tuning algorithm to find estimated mass of the seat and human body for the designed controller (Gohari & Tahmasebi, 2015). In this research, Levenberg-Marquardt training option is selected to analyse robustness of the controller with implementation of neuro-AFC control. Neuro-AFC scheme is used to test the seat vibration in various road profiles and compared with the pure PID controller. Based on the results, a feed-forward NN structure with single hidden layer that contain 10 neurons showed the best performances. They has found that the performance of neuro-AFC can reduce the vibration better than pure PID, as shown in Figure 2.12.

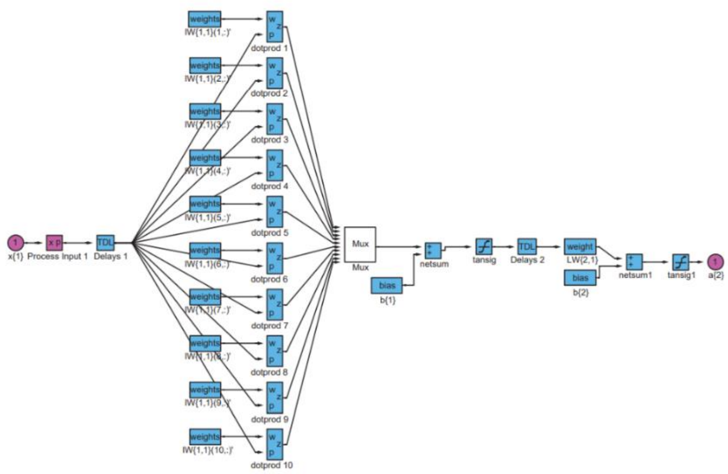

Figure 2.11 Hidden layer of ANN (Gohari & Tahmasebi, 2015)

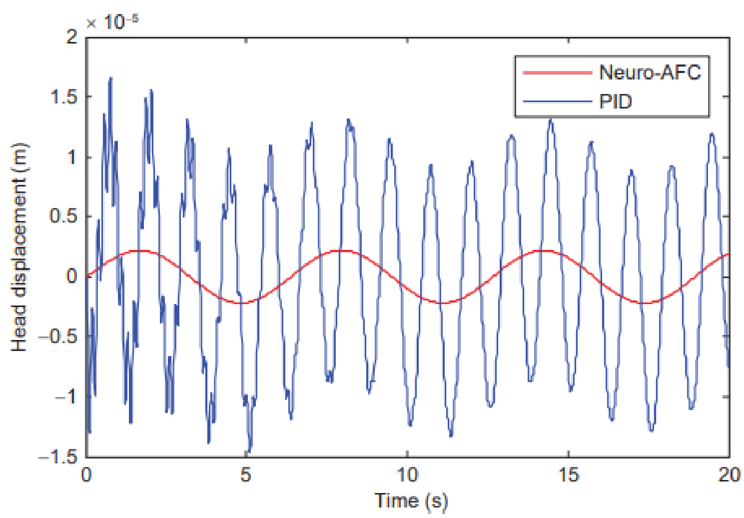

Figure 2.12 Head displacement response for Neuro-AFC and pure PID in time domain. (Gohari & Tahmasebi, 2015)

2.7 Summary:

- The high-level vibration of power tools has been reported in many working sectors and DOSH has proposed the TLV as guideline for exposure hand-arm to the vibration. The prolonged exposure to power tools can resulting the health effects such as HAVs
- AVC has provided better performance in attenuating the vibration compared to passive vibration control method. The introduction of AFC can improve the performance of the AVC system significantly.
- GA, PSO and NN are the intelligent tuning methods for parameter optimization of the AFC. The AFC with intelligent tuning algorithm has been applied in vehicle suspension system but rarely for the suspended handle that related to power tools applications.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this chapter, a single-freedom-of-freedom (SDOF) of suspended handle model is constructed in MATLAB/Simulink environment. The motion equation of suspended handle is mathematically developed. Two types of disturbances are introduced to investigate the robustness of this suspended model and its effectiveness for vibration control. Lastly, the combination of different input signals as well as disturbances are applied to study the performance of AVC models with different control schemes and intelligent tuning algorithms. Figure 3.1 shows the overall flow-chart of methodology in this study

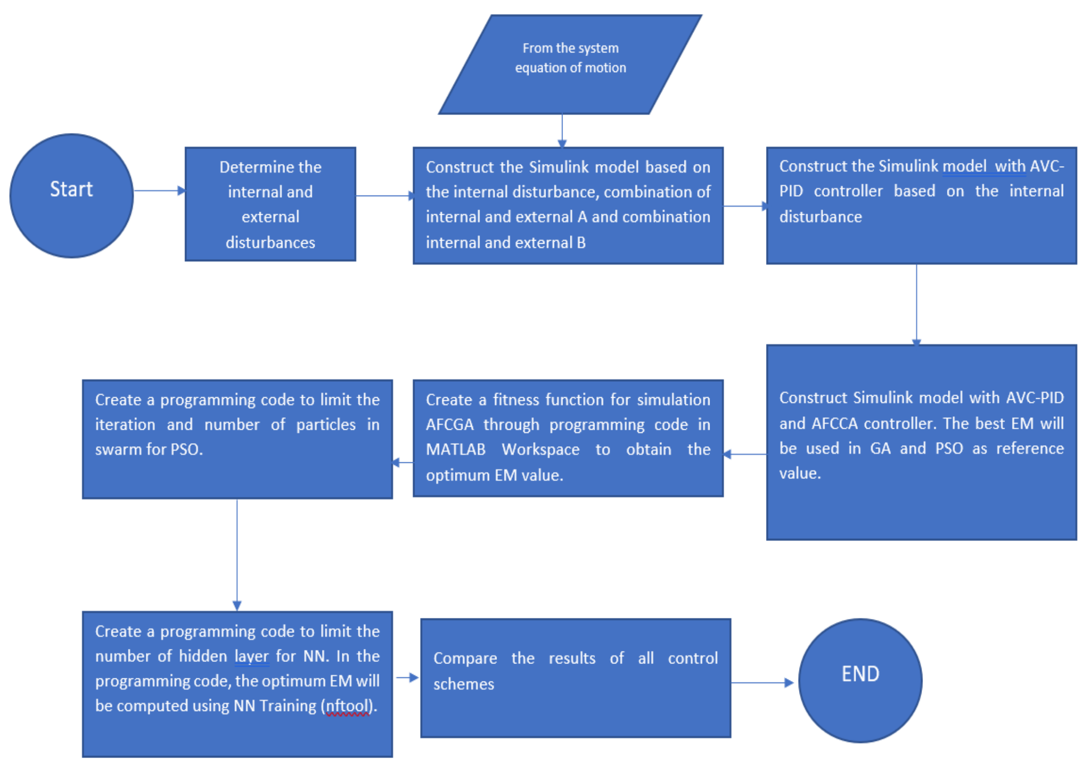

Figure 3.1 Flow chart of methodology

3.2 Model of AVC System for Suspended Handle

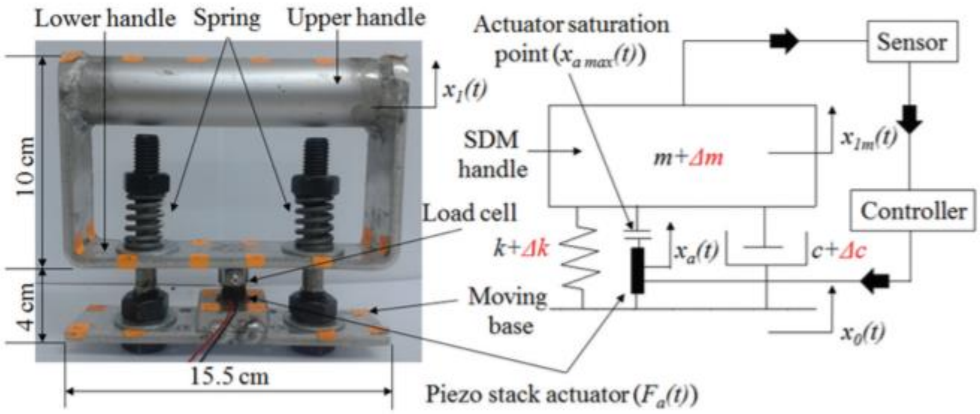

Figure 3.2 Actual and model of active suspended handle. (Ahmad Mazlan & Mohd Ripin, 2015)

Figure 3.2 shows the actual (left) and model (right) of the suspended handle with AVC system that been developed by Mazlan & Ripin (2015). This suspended handle is a SDOF system with mass *m*, spring *k*, damper *c* and a piezoelectric actuator to produce the attenuation force, $F_a(t)$ and to counteract the vibration produced by the disturbance force, $F_s(t)$. The equation of motion for the suspended model can be expressed as follows:

$$m\ddot{x}(t) + c\dot{x} + kx(t) - F_a(t) = F_s(s) \tag{3.1}$$

A piezo-actuator (P-010.00) is used in this AVC system which can exerted 1400 N of maximum force. This force is equally distributed in two directions (sinusoidal wave) which makes the amount of force in each direction to be maximum 700 N (saturation force) and the stiffness of actuator is $Q = 2.7\ \times 10^8 N/m$.

3.3 Disturbance Models

In this study, the disturbance forces are classifying into internal and external forces to evaluate the performance of different control schemes in reducing the vibration. Internal disturbance is referring to the power tools while external is representing the disturbance generation during the operational of power tools. The internal disturbance is evaluated using the following equation:

$$F_{in} = 20 \sin \left(2\pi(200)t\right) \tag{3.2}$$

There are two types of external disturbance that can be expressed for which are the disturbance creating due to the effect of hard stop (External disturbance A) and disturbance due to effect of imbalance of motor (External disturbance B). The equations for both external disturbance A and B are shown as follows:

$$F_{eA} = 4 \sin(628.32t + 1.57) \tag{3.3}$$

$$F_{eB} = 20 \sin(314.16t + 1.57) - 5 \sin(2513.27t) \tag{3.4}$$

The internal disturbance is firstly simulated without the external disturbance in order to obtain appropriate control parameter for the system. The external disturbances are simulated together with internal disturbance to investigate the robustness of AVC system for different controller tuning methods.

3.4 Simulink Model of Passive System

In a passive system, the suspended handle consists of a spring, mass, damper and the disturbances. The purpose of constructing the passive system is to determine the original system response under the disturbances. Table 3.1 listed the *m*, *c* and *k* parameter values that been experimentally determined previously (Ahmad Mazlan & Mohd Ripin, 2015). Figures 3.3 to 3.5 show the Simulink model of suspended handle with internal disturbance, external disturbance A and external disturbances B, respectively.

Table 3.1 Parameter of suspended handle model.

Parameter	Value
Mass, m (kg)	0.04
Stiffness, k (N/m)	3.78×10^5
Damping coefficient, c (kg/s)	33.45

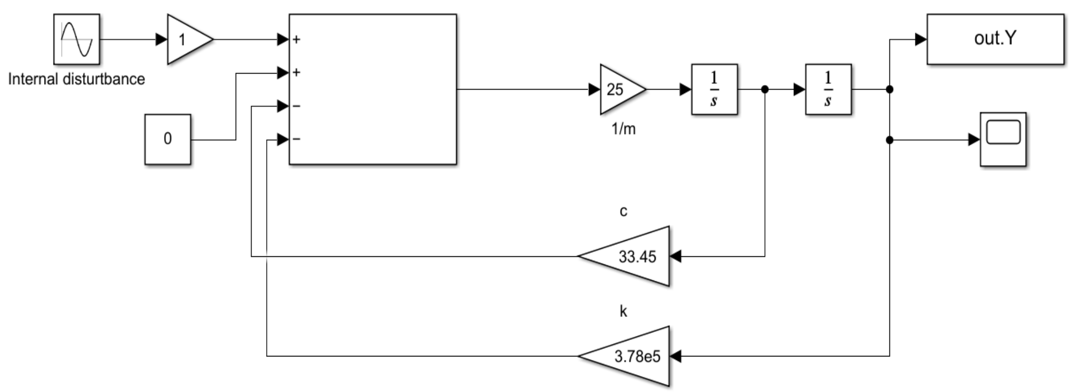

Figure 3.3 Simulink model of suspended handle with internal disturbance

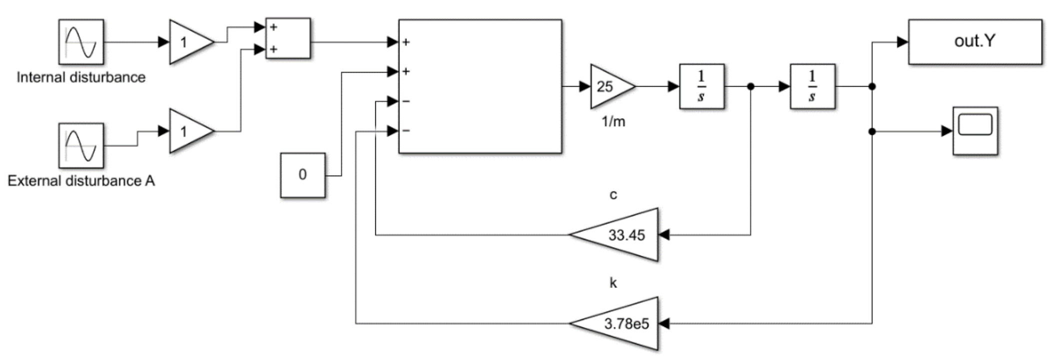

Figure 3.4 Simulink model of suspended handle with internal disturbance and external disturbance A.

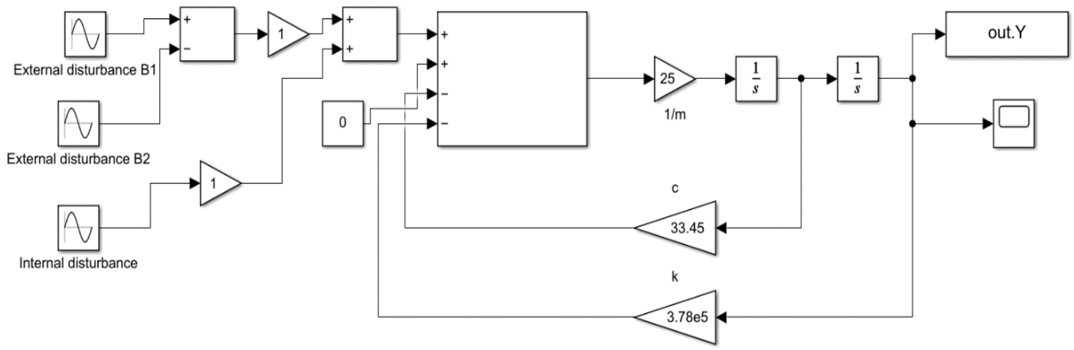

Figure 3.5 Simulink model of suspended handle with internal disturbance and external disturbance B.

3.5 Simulink Model of AVC System with PID Controller

In AVC system, a PID controller is applied to study the effectiveness of vibration control. In this system, a feedback control loop is used to measure the difference between the actual output and reference input of the system. The difference is then sent to the PID controller to adjust the force signal of an actuator to counteract the disturbance vibration. The parameters of PID controller (K_p , K_I, K_D) are required to be tuned and in this study a Transfer Function Based method (PID Tuner App) is utilized using the following equation:

$$P + I\frac{1}{s} + D\frac{N}{1 + N\frac{1}{s}} \tag{3.5}$$

Where *P* is proportional, *I* is integral, *D* is derivative, *N* is filter coefficient and *s* is sample time (-1 for inherited). The AVC-PID Simulink model of suspended handle with the internal disturbance is showing in Figure 3.6.

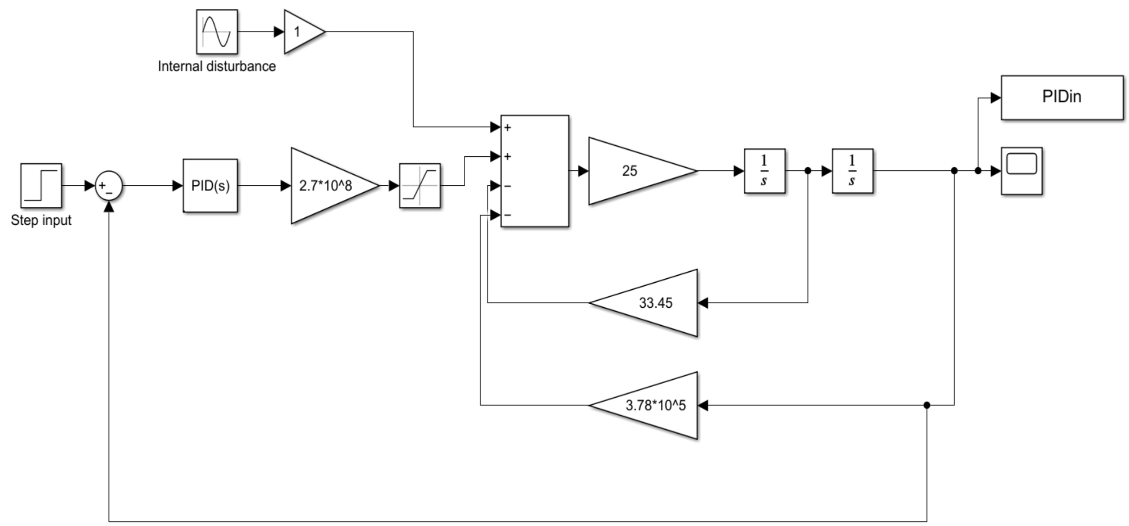

Figure 3.6 AVC-PID Simulink model of the suspended handle with internal disturbance

3.6 Simulink Model of AVC System with PID and AFCCA Controller

In order to produce a system that can counteract the force accurately, the AFC method is introduced using the following equation:

$$F^*(t) = F_a(t) - EM\ddot{x}(t) \tag{3.6}$$

Where, $F^*(t)$ is the estimated disturbance force, $F_a(t)$ is the actuator force, EM is the estimated mass and $\ddot{x}(t)$ is the acceleration of the system.

For a crude approximation (CA) tuning method, the trial-and-error process is applied to estimate the EM. The EM is set between 0.02 kg to 0.08 kg with the interval of 0.01 kg. Referring to the displacement versus time graph, the EM that produces an optimum result will be used in the others intelligent tuning methods such as GA, PSO and NN. Besides that, the settling time, overshoot and rising time are the factors to select the most optimum system. Figure 3.7 shows the Simulink model of the AVC system with PID and AFCCA tuning method.