POSITIONING CONTROL OF BALL SCREW SYSTEM DRIVEN BY DC MOTOR

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by

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"I hereby declare that I have read through "*Positioning Control of Ball Screw System Driven by DC Motor*" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Control, Instrumentation and Automation)

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To my beloved father and mother.

ABSTRACT

Ball screw driven by DC motor system is an electromechanical linear actuator that translates the rotational motion into a linear motion. There many application of ball screw system in industry especially the application of Computer Numerical Control (CNC) machine. The ball screw mechanism in this project is driven by DC motor. The DC motor is use because it is easy to setup and control, has precise rotation and most importantly is low cost. As for ball screw mechanism itself, has smooth motion, not easy to wear out and high mechanical efficiency. The problem is arise when the used of conventional PID controller in the ball screw system driven by DC motor shows less adaptability to the changes of system parameter. Therefore, the objective of this project is to design an adaptive fuzzy PID controller to overcome the limitation of conventional PID controller. The performances between the conventional PID controller and fuzzy PID controller will be compared in order to validate the robustness of the fuzzy PID controller. So this project is to compare the robustness of two proposed controllers by compare the results of ball screw table position when the parameter mass of load is set to vary. The experiment is start with designing the algorithms of fuzzy PID control and conventional PID controller, then the designed algorithm is apply onto the experimental that has been setup. The performances especially the transient response and steady state error between the controllers will be collect and compare. In the end of this project the results of system performance obtained after applying with fuzzy PID controller have lower positioning error and better performances of transient responses compared to conventional PID controller.

ABSTRAK

Mekanisma skru bola yang didorong oleh DC motor adalah merupakan sistem penggerak linear elektromekanik yang menterjemahkan gerakan putaran ke gerakan linear. Terdapat banyak aplikasi sistem skru bola dalam industry terutama penggunaan Kawalan Berangka Komputer (CNC). Mekanisme skru bola dalam projek ini adalah didorong oleh DC motor. DC motor digunakan kerana ia adalah mudah untuk setup dan kawalan, mempunyai putaran yang tepat dan yang paling penting adalah kos yang rendah. Sebagai mekanisme skru bola sendiri, mempunyai gerakan yang lancar, tidak mudah haus dan kecekapan mekanikal yang tinggi. Masalah timbul apabila pengawal PID konvensional digunakan dalam sistem skru bola didoro didorong oleh motor menunjukkan kurang keupayaan menyesuaikan diri dengan perubahan parameter sistem. Oleh itu, objektif projek ini adalah untuk mereka bentuk sebuah kabur pengawal PID kabur penyesuaian untuk mengatasi had pengawal PID konvensional. Persembahan antara pengawal PID kabur akan dibandingkan bagi mengesahkan keteguhan pengawal PID kabur. Jadi projek ini adalah untuk membandingkan keputusan bola skru kedudukan meja apabila jisim parameter beban ditetapkan berubah. Eksperimen adalah bermula dengan mereka bentuk algoritma kawalan PID kabur dan pengawalan PID konvensional, maka algoritma yang direka diaplikasikan ke eksperimen yang telah siap dipasang. Persembahan terutamanya sambutan fana dan ralat antara pengawal akan ambil dan dibuat perbezaan. Di akhir projek ini hasil prestasi yang diperoleh selepas menggunakan dengan pengawal PID kabur mempunyai ralat kedudukan yang lebih rendah dan prestasi yang lebih baik daripada jawapan sementara berbanding dengan pengawal PID konvensional.

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M	-	Mass of table
J	-	Inertial of the motor
D	-	Viscous damping coefficient of the supporting bearing
La	-	Armature inductance
Ra	-	Armature resistance
Rc	-	Ball screw pitch
θ(s)	-	Angular displacement
X(s)	-	Displacement of the table
T(s)	-	Torque of ball screw
F(s)	-	Force exert on the table
Ea(s)	-	Armature voltage
Ia(s)	-	Armature current
Kb	-	Back EMF constant
Kt	-	Motor torque constant

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Positioning control is the process of controlling the mechanism position in term of linear displacement and angular displacement. The position control can be done by adding the controller inside the mechanism to achieve high performance in the form of precision or accuracy of output position. The position control done by human power nowadays is rare and hard to achieve the good performance of positioning. Due to the human limitation in error of measuring and time consuming, the various technology have been introduced to overcome these problems. One of the positioning systems is ball screw driven by motor. Therefore, positioning control system in the modern decade is highly demand by industries such as automobile industry, fabrication and metalworking industry, oil and gas industry and process and manufacturing industry. Due to high demand of positioning control from various industries, more and more of the advanced positioning controller has been introduced to overcome the limitation of the positioning system. This is because some of industries need to achieve very high precision, high speed, low error, stability and very high robustness in various conditions of environment to get better quality of positioning output response.

There are many designs of actuator mechanisms that are purposely designed to obtain different kind of specification which is need by manufacturers especially the cost, the working range, degree of freedom and performance of the system in order to reduce the financial resources burden. One of the design actuator is ball screw feed drive mechanism which convert the rotational motion into linear motion. The ball screw system is usually driven by DC motor, servo motor and stepper motor.

Before the ball screw mechanism was introduced, the used of traditional screw (ACME) was very poor in positioning and was quite easy to be damaged. Until in 1898 that there are people try to put the steel ball between the nut and the screw shaft to replace the sliding friction with rotational friction so as to improve the bad positioning. In 1949, a ball screw device was placed in the car and it became a great revolution in the application of the ball screw. Therefore, the sliding friction of traditional screw (ACME) was replaced. And in recent years, the ball screw mechanism becomes one of the components that are widely used in the industries.

The ball screw mechanism in this decade has been widely used in the machinery such as precision machine tools, industrial machinery, electronic machinery and transport machinery. For example, the commercial aircrafts use ball screw in mechanisms such as engine thrust reversers and propeller pitch controls. Furthermore, it also can be applied in the drive of the computer disk drive starter, the adjustment of the aircraft wings, and medical x-ray examination. All of these applications need the very high precision of the drive system such as DC motor, servo motor and stepper motor to drive the ball screw mechanism. But due to some drawback of DC motor, servo motor and stepper motor itself, the positioning controllers are apply into the ball screw system driven by motor to overcome the limitation and at the same time increase the performances of the system.

This project will compare the fuzzy PID controller with the conventional PID controller to obtain high adaptability and better performance of ball screw system driven by DC motor. The term of adaptability is referring to the system that can maintain the same performances in various condition of environment no matter the performance is in good or bad. The performance of the ball screw system will include the transient response, stability and steady state. The transient response have several criteria need to consider such as rise time, settling time and percentage of overshoot in order to compare the propose controller with conventional controller. Besides that, the steady state also needs to consider in comparing between the controllers by measure error between steady state value of reference input and steady state value of output signal. Therefore, the rise time will consider as the speed of the load of ball screw system to reach the destination and the steady state error will consider as the error of position between references input position with output position.

A fuzzy logic controller is proposing to improve the conventional PID controller by improving the adaption of the PID controller to the changes of system parameter. There are many type of fuzzy PID controller that proposes by many researchers. Especially the Fuzzy P controller, Fuzzy PI+PD controller, Fuzzy PI controller, Fuzzy PD controller and Fuzzy Gain Scheduling (FGS) PID controller. The performances of each fuzzy PID controller in previous research are depending on the suitability of controller to the system model itself. Another controller that proposes beside the PID controller is fuzzy PID controller. By applying the fuzzy PID controller, it is expected that the under variation of load mass, the good performance of the system will be maintain unlike the conventional PID controller.

1.2 Project Motivation

In this project, the positioning controllers were proposed and compared by using the ball screw system driven by DC motor as a medium of experiment. The positioning controllers that proposed in this project are fuzzy PID controller and conventional PID controller. Fuzzy PID controller is used to compare with conventional PID controller due to simplicity, easy to is use and it's have high adaptability by adding the fuzzy logic controller into the conventional PID controller. The conventional PID controller is use because of its simplicity and more familiar use in many industries.

1.3 Problem Statement

In order to control the position of the ball screw system driven by DC motor, many different controllers approach has been introduce into the ball screw system driven by DC motor to achieve a better transient performance, low steady state error and low overshoot condition. The problem arise when certain parameter of ball screw system was changed when motor load inertia is changing due to high non-linear characteristic of the ball screw system, the conventional PID controller cannot adapt to the changes of system parameter that occur on the ball screw system. Therefore, the output signal performances obtained become vary according to the change of system parameter. To improve the system using the conventional PID controller, the manufacturer or the operator has to manually change the PID gain according to the change of parameter of ball screw system. As a result, the process manually changing the PID gains would consume a lot of time when the manufacturing process is still under operation.

1.4 Objectives

The objectives of this project are:

i. To design a fuzzy PID controller for the ball screw system driven by DC motor.
ii. To examine the effectiveness of the proposed controller in PTP (point to point) positioning performance.
iii. To validate the robustness of the fuzzy PID controller under variation of load mass in the comparison to the conventional PID controller.

1.5 Scopes

The scopes of this project are:

1.5.1 DC motor

a) Maximum supply voltage is 40 Vdc .
b) Reversible direction of rotation.
c) Rated speed is 1600 rpm.
d) Rated torque is 12 Ncm.
e) Terminal resistance is 7.8 ohms.
f) Rotor inductance 5 mH.

1.5.2 Ball screw mechanism

a) Ball screw lead is 8 mm (distance travel per revolution).

b) Screw shaft diameter is 8 mm.

c) Working range of the table load along the screw shaft is 282 mm.

1.5.3 Microbox

a) Input power range is 9 V to 36 V and minimum 50 W.

b) CPU is Celeron® M 1GHz, with 256MB DDR DRAM.

c) Flash memory is 64 MB Compact Flash Card (expandable to 1 GB).

d) 8 channels Single Ended 16 bits of ADC and 4 channels 16 bits of DAC of built- in I/O with ±10 V.

e) 4 channels with 24 bit incremental encoder built-in I/O (1x, 2x or 4x).

f) 8 bits from parallel port of digital built-in I/O

g) Speed up to 1 Mbps.

1.5.4 Linear encoder

a) Working range is 300 mm.

b) Resolution is 5 um/pulse.

c) Voltage rating is 5 V.

d) Contactless.

e) Read forward and reverse direction.

1.5.5 Specification and target

a) The position control is set from point to point are 10 mm, 25 mm and 50 mm along the screw shaft.
b) The mass for the load to test the real time system are 1000g, 2000g and 3000g.
c) Design a positioning conventional PID controller using root locus, frequency response and hand tuning methods.
d) The input signals for the experiment are pulse, sine wave and step.
e) The distance range use to run the experiment is up to 174 mm.
f) The requirement for position error of the system with proposed controller that expect to maintain the maximum error up to 5um under variation of load mass.

CHAPTER 2

BACKGROUND OF STUDY

2.1 Principle of ball screw system driven by DC motor

The Figure 2.1 shows the ball screw system driven by DC motor convert the electrical voltage to mechanical torque by transfers the rotational motion in the form of angular motion from DC motor to ball screw mechanism. The conversion of angular motion from stepper motor is change into linear motion through using helical raceway of screw shaft. The amplitude of voltage that apply onto the DC motor is represent as the magnitude of angular displacement the DC motor will rotate. Therefore, the greater the amplitude of the voltage applies to the DC motor the longer the angular displacement will be rotate. Then the angular displacement will be converting into linear displacement using ball screw shaft where it has helical raceway. There are consisting of two types of helical raceway in the ball screw systems which are high helix lead and fine pitch lead. In this project the fine pitch lead is used due to high resolution since one revolution is translate to short distance of linear displacement compared to high helix lead. For example, when the motor is rotate at 90 degree, the linear motion converted by screw shaft is just move in 2 mm. Therefore, the bracket of the ball screw system can move in high precision without help from the motor with higher resolution.

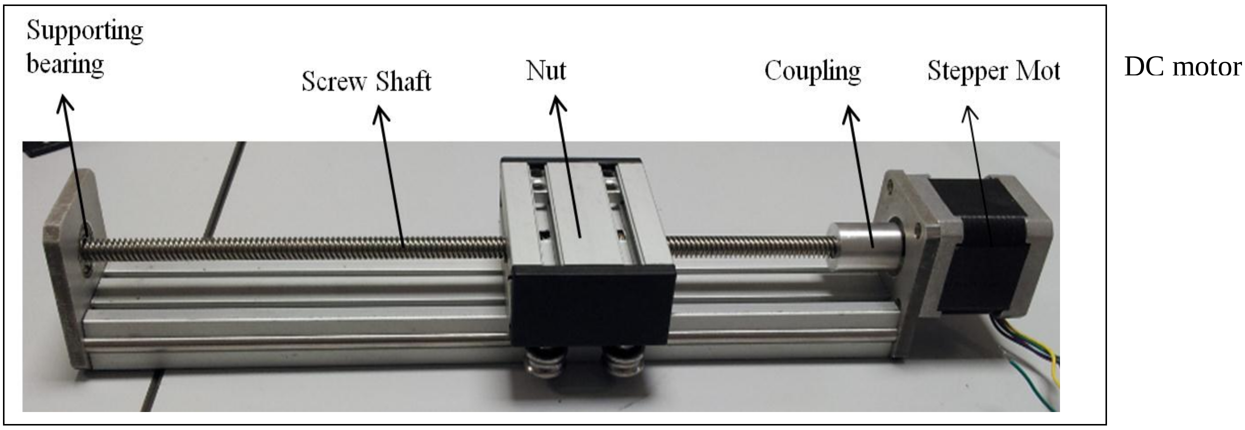


Figure 2.1: The ball screw system driven by DC motor.

2.2 Modeling of ball screw system driven by DC motor

Figure 2.2 shows the ball screw system drive by DC motor, a ball screw shaft which is use to translation of rotational motion to linear motion and mass of the table.

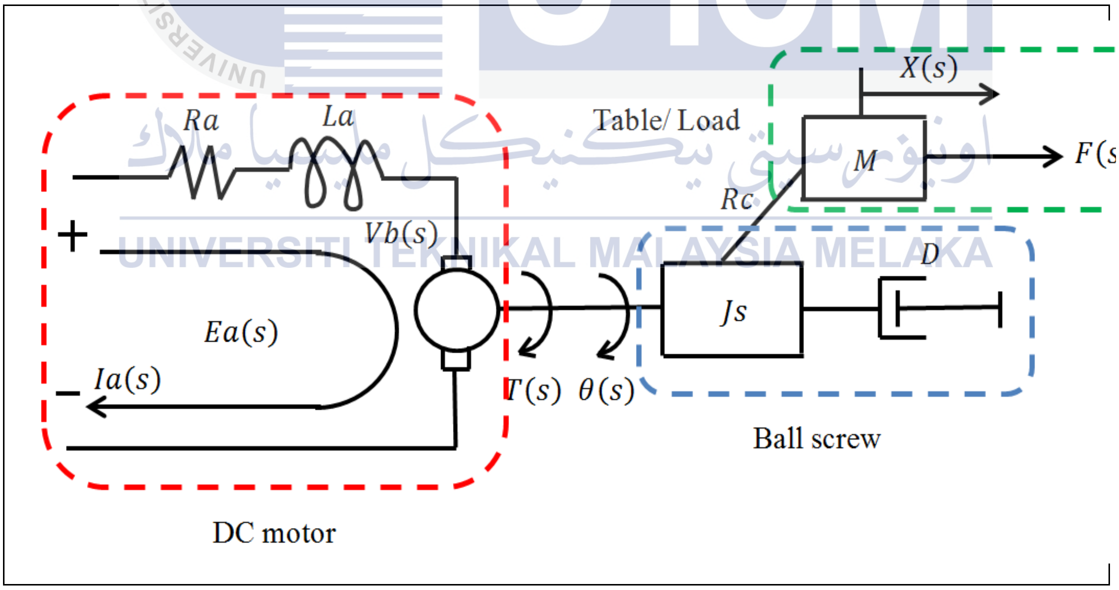


Figure 2.2: The free body diagram of ball screw drive by the motor.

Loop equation of the Laplace transformed armature circuit:

$$E_a(s) = R_a I_a(s) + L_a s I_a(s) + V_b(s) \quad (2.2.1)$$

Voltage proportional to speed:

$$V_b(s) = K_b s \theta(s) \quad (2.2.2)$$

Substitute eq. (2.2.2) into eq. (2.2.1),

$$E_a(s) = (R_a + L_a s)I_a(s) + K_b s\theta(s) \tag{2.2.3}$$

Torque developed by the motor proportional to the armature current:

$$T(s) = K_t I_a(s) \tag{2.2.4}$$

Torque developed equivalent mechanical load:

$$T(s) = (Js^2 + Ds)\theta(s) + F(s)r \tag{2.2.5}$$

From the Figure 2.2, the torque is initially generated by motor, T(s) in the direction of θ(s). The angular displacement to linear displacement:

$$X(s) = R_c\theta(s) \tag{2.2.6}$$

The force applies on the table load:

$$F(s) = (Ms^2)X(s) = (Ms^2)R_c\theta(s) \tag{2.2.7}$$

Substitute eq. (2.2.7) into eq. (2.2.5),

$$T(s) = \big((J + MR_c r)s + D\big)s\theta(s) \tag{2.2.8}$$

Substitute eq. (2.2.4) into eq. (2.2.8),

$$I_a(s) = \frac{\big((J+MR_c r)s+D\big)s\theta(s)}{K_t} \tag{2.2.9}$$

Substitute eq. (2.2.9) into eq. (2.2.3),

$$E_a(s) = (R_a + L_a s)\left(\frac{(J+MR_c r)s+D}{K_t}\right)s\theta(s) + K_b s\theta(s) \tag{2.2.10}$$

By angular displacement into linear displacement of eq. (2.2.10),

$$\frac{X(s)}{E_a(s)} = \frac{R_c K_t}{s\big[(R_a+L_a s)\big((J+MR_c r)s+D\big)+K_t K_b\big]} \tag{2.2.11}$$

The equation was derived according to the basic knowledge that has been study from the control system book [3]. From the Figure 2.3 shows that the ball screw driven by DC motor is consist of plant with speed model, angular displacement output response that generated by DC motor and the linear displacement output response that has been converted from angular displacement by ball screw mechanism. Since the ball screw mechanism is driven by DC motor, the speed model is referring to the plant that generating different speed at different amplitude of input references. The integrator is converting the speed into the angular displacement. Therefore, the longer the time taken for ball screw system operating under certain speed the longer the angular displacement as well as output linear displacement. The linear displacement will be the output response and the input will be the voltage signal.

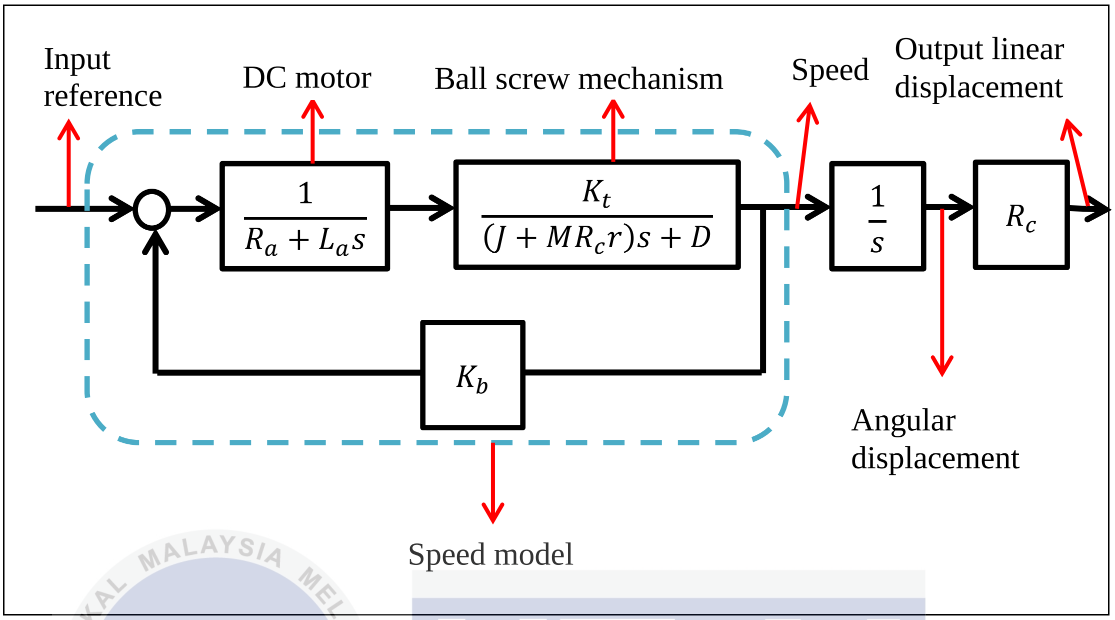


Figure 2.3: The block diagram of open loop ball screw system.

2.3 Type of controllers

For position control of ball screw system drive by any motor, numerous of controller approach is been suggest to achieve better transient performance of output response. Therefore, the study of research been done by other researcher is important to get a rough idea of using controller. In paper [1], the problem that arises is the vibrations of ball screw drives during operate in high acceleration and high velocity which results in excitation of structure's axial and torsional vibrational modes. Thus, the pole-placement technique is proposed. The reason of using pole-placement technique rather than others technique is because it is more robust and effective designs compare to the others techniques. The solution of pole-placement technique over the vibration modes occurs is vibration cancellation inside the position or velocity feedback loops or placing the zeros nearby the oscillatory poles in order to shift the root locus away from problematic. But addition of the robust feedback loop is capable of attenuating disturbances and structural vibration. Besides that, an appropriate feedforward controller and/ or a trajectory prefilter in order to improve the command following properties of the drive system. The pole placement controller (PPC) and combination with prefilter is comparing with the approach of P-PI position- velocity cascade usually use in industrial to control the velocity and acceleration feedforward terms. As a result, the proposed scheme is significantly more effective in disturbance rejection and command tracking compare to P-PI position –velocity cascade control.

Not only the ball screw can be applied with controller, the controller use to control the position of the stepper motor is considered. The adaptive PID controller is applied on the stepper motor driving a flexible rotor was done by previous researcher [2]. In this paper, the fuzzy gain scheduling control for stepping motor is proposed by Nehal and Sohair [2] under mechanical variation of rotor stiffness and load inertial. The purpose of conducting this research is due to static parameter limitation of conventional PID controller compare to dynamic controller of Fuzzy PID controller. The fuzzy logic gain is able to adapt the controller gains to track the desired load and speed response. There are two categories of fuzzy logic. The first categories is no PID instead the control signal is directly deduced from knowledge base and fuzzy inferences and second categories is fuzzy scheduling of conventional PID gains. The fixed gain of PID controller is not satisfactory and the system is unstable at different value of stiffness and load inertia. There are two main aims to do before fuzzy scheduling is applied onto the mechanism. First is to determine the control parameters which are robust to this varying operating condition. The second part is to identify the indices that will drive gain scheduling mechanism. In the end of this research, the output control voltage of Fuzzy PID controller is more stable, smoother and faster than that resulted from PID controller. This study also relate to the paper of [11], the conventional PID controller is compare with the propose fuzzy self-tuning controller by using computer numerically controlled (CNC) feeding servo system (FSS) of machine tools to achieve minimum overshoot, minimum transient and steady-state condition.

Furthermore, the reduction of tracking error under dynamic variation is presented in [4]. The dynamic variation usually related to mechanical flexibility, runout of the ball screw shaft and workpiece mass. The servo controllers are designed to deal with this uncertain of dynamic variation to improve the tracking performance and able to maintained robustly over uncertain mass variation. In paper [13], the research present a new approach for position control which is 'conditional' servocompensators. This controller improves the transient response over the conventional servocompensator.

Another controller also proposes for the PM stepper motor which is switching- angle controller [14]. This kind of controllers is having voltage to the phases applied earlier relative to the rotor position in order to allow the current in the phase enough to build up.

Based on another approach, the nominal characteristic trajectory-following (NCTF) controller is designed for fast positioning without exact value. The NCTF controller consists of nominal characteristic trajectory (NCT) as the movement reference and a PI compensator making object movement follow the NCT [5-7]. This controller is designed to overcome the difficulties in design of robust PID controller with disturbance observers or friction estimators and the grown of sliding-mode controllers. For improve the tracking accuracy, the feedforward friction compensation is added. The NCTF controller also can improve the positioning, tracking accuracies, high overshoot reduction and low sensitivity disturbance [7]. The NCTF controller known to be user-friendly compare to conventional controller [8].

The precision control of high speed ball screw also can be applied with Adaptive Sliding Mode Controller (ASMC) which is designed based on the rigid body dynamics and notch filters are used to attenuate the effect of structural resonances [9]. Whereas the output feedback Sliding Mode Control (SMC) is able to demonstrate the disturbance rejection by implementing High Gain Observer [10]. Besides that, the paper [12] proposes the new control design of Discrete-Time Sliding Mode Controller (DSMC) to overcome the uncertainties especially the friction parameter of ball screw. The Discrete-Time Sliding Mode Controller with one step delay disturbance compensations provides an excellent method for disturbances rejection and chattering attenuation. In paper [15], the sliding mode position controller (SMC) of stepper motor is presented. This SMC controller is develop to optimize the torque output, maximize acceleration and deceleration rate and avoid the loss step of stepper motor.

From literature review as above, the fuzzy logic control for PID gains are choose in this project to deal with limitation of conventional PID controller. The reason of using fuzzy PID controller is because it is common controller that used as advanced PID controller. Based on the paper [16][17], the fuzzy logic control method is easy to implement in the conventional PID controller compare to other advance controllers like adaptive Sliding Mode to trigger. Although, the NCTF controller is also good in terms of performances, easy to implement and no need extra knowledge of in parameter of the system. But many industries is familiar and used conventional PID controller in their system, so it is recommend to use fuzzy PID controller that can directly add the fuzzy logic control onto the conventional PID controller than directly change whole controller with new controller to prevent the wasting.

2.4 Basic knowledge of fuzzy controllers

Fuzzy logic system is known as artificial intelligence system where this system is capable to making decision depend to the change of input parameter. The input and output parameter in fuzzy logic control system is representing as the linguistic variable and a several set of membership function. There are different types of membership function can be use likes triangular, trapezoidal, Gaussian, generalized bell and singleton. The shape of membership function can be modified by implement the mathematical set of function based on user's knowledge of their plant system properties. In the fuzzy logic controller there are consists of several process need to undergo from input parameter to the output parameter which are fuzzification, inference mechanism, rule-based and defuzzification as show in the Figure 2.4. The fuzzification process simply modifies the inputs so that can be interpreted and compared to the rules in the rule base. During fuzzification process also the crisp quantities from input is convert to fuzzy quantities. The rule based is the connective between the input variable and output variable by using IF- THEN rules. For inference mechanism is define as the evaluation which control rule are relevant at the current time and then decide what should the input to the plant should be to generate the desirable output. Finally, the defuzzification process will convert the fuzzy quantities into the crisp quantities.

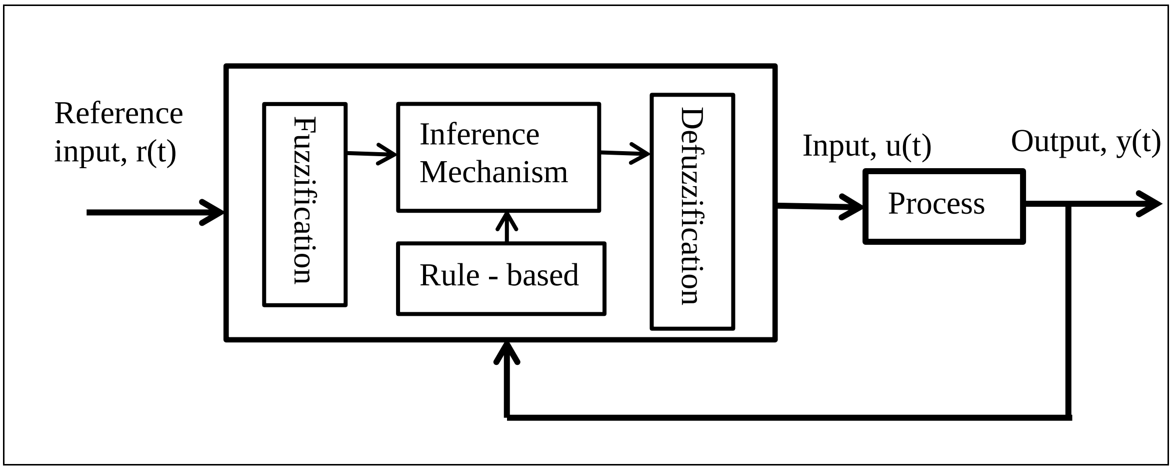


Figure 2.4: The process of fuzzy logic controller.

In the design of fuzzy logic controller, many fuzzy logic controllers have been design in order to improve the output performance of the system. Due to the capability of the fuzzy logic controller in choosing better decision, many researchers have integrated the fuzzy logic controller to the PID controller. This is because the fuzzy controller is able to manipulate the value of the proportional, integrator and derivative gains accordingly to obtain better results.

2.5 Tuning method for PID controller and fuzzy PID controllers

Advance in designing the PID controller has greatly contribute to the increasing the performance of nonlinear system, but the design of fuzzy PID controller has no specific method or procedure to design the fuzzy inference system (FIS) for the PID controller. Therefore, several method or procedure has been proposed and develop by the previous researchers to optimize the system operating performance.

In paper [17], the researcher has developed a procedure which consists of 4 steps to design an advance controller from conventional PID controller to the fuzzy PID controller. First step is tuning the conventional PID controller by using the

Ziegler-Nichols frequency response method or hands tuning method as shown in Table 2.1 and Table 2.2.

Table 2.1: The Ziegler-Nichols rules (frequency response method).[17]

Controller	Kp	Ti	Td
P	0.5Ku	-	-
PI	0.45Ku	Tu/1.2	-
PID	0.6Ku	Tu/2	Tu/8

Table 2.2: The rules of thumb for Hand tuning method.[17]

Gains	Rise time	Overshoot	Settling Time	Steady state error
Increase Kp	Decrease	Increases	Small change	Decrease
Increase Ki	Decrease	Increases	Increases	Great reduce
Increase Kd	Small change	Decrease	Decrease	Small change

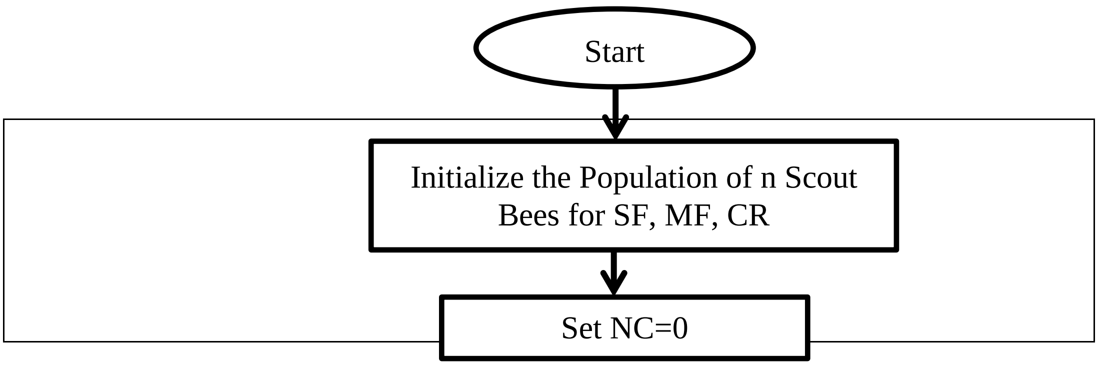
Then in step two, the PID gains are transfer to the fuzzy controller accordingly to the desired performance from conventional PID to fuzzy proportional (FP), proportional and derivative control (FPD), incremental control (FInc) and proportional, integral and derivative control (fuzzy PD+I) [17]. As a result, each of all four designed fuzzy PID controllers shows advantages and disadvantages as Table 2.3. In step three, the linear fuzzy controller is making to the nonlinear fuzzy controller. This process can be done by changing the two input membership function from linear triangle or trapezoidal to bell-shaped or Gaussian shape. At last, the further tuning for nonlinear fuzzy controller also had done by increase the range of course of universe and adjusting the gains factor (GU or GCU) to control the speed and stability of the system.

Table 2.3: Quick reference to controllers.[17]

Controller	Advantage	Disadvantage
FP	Simple	Too simple
FPD	Less overshoot	Noise sensitive, derivative kick
FInc	Removes steady state error, smooth control signal	Slow
FPD+I	All in one	Windup, derivative kick

Besides that, another method of designing the fuzzy PID controller has been proposed in previous research was robust extended Kalman Filter [18]. This method of design is to optimize a Mamdani fuzzy PID controller. The robust extended Kalman filter is used to adjust the controller parameter automatically during the operation process of any system applying the controller to minimize the control error by tuning the shaped of membership function and rules to adapt with the system condition and performance required. Design using this method requires extra knowledge regarding to the Kalman filter and it is complicated to design it.

Another method of Bee Colony Optimization (BCO) algorithm is proposed in paper [19]. This method is mimics the food foraging behavior of swarms of honey bees by using several mechanism such as waggle dance to locate the food sources and to search new ones. This mechanism is become good example to develop new intelligent search algorithms. It is very simple, robust and population based stochastic optimization algorithm. The certain knowledge of BCO algorithm is required in order to tune the parameter of fuzzy gain scheduling PID controller as show in Figure 2.5.



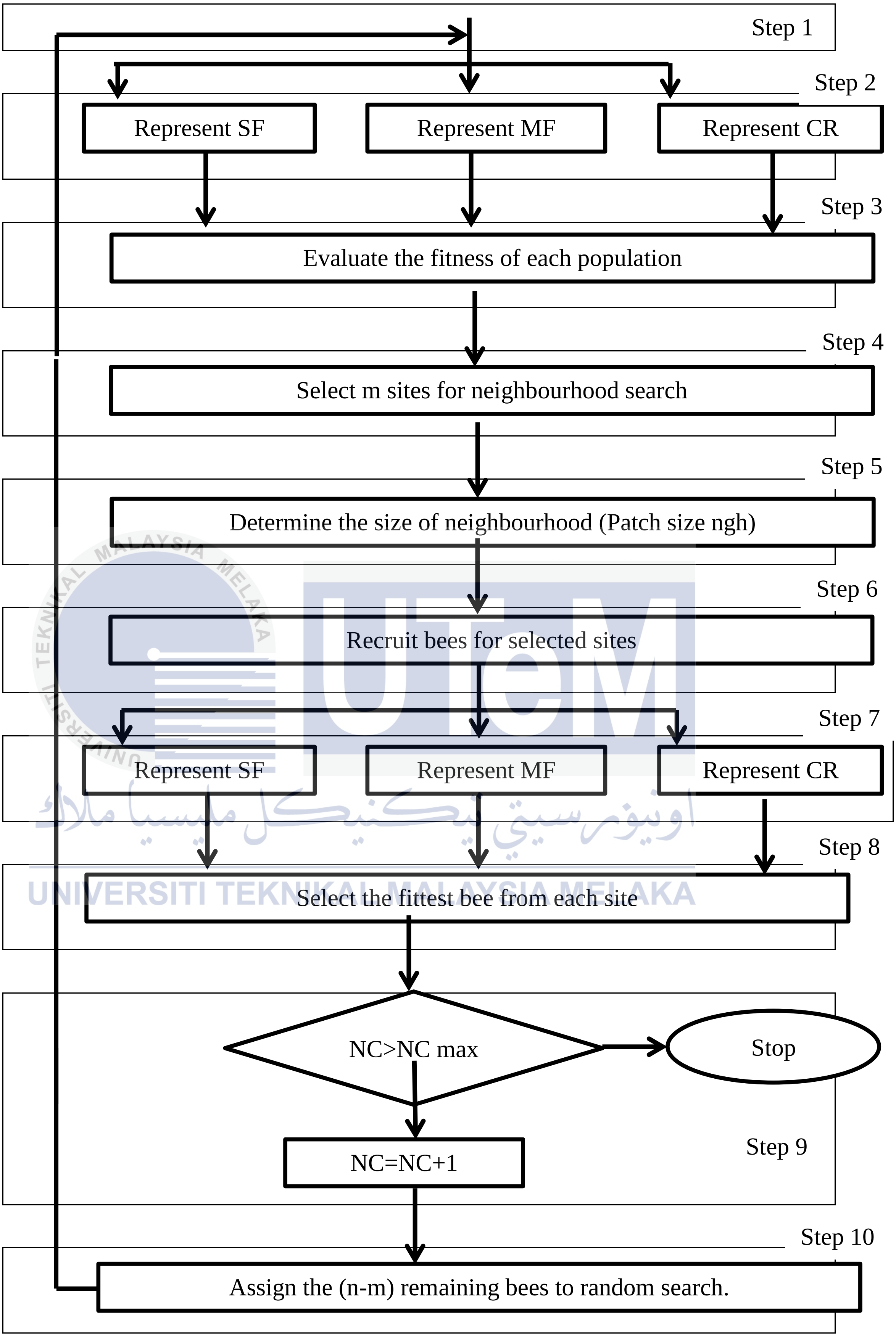


Figure 2.5: Procedure of BCO algorithm for tuning FGS-PID parameters. [19]

CHAPTER 3

METHODOLOGY

3.1 Hardware operating principle

As for hardware setup shown in Figure 3.1, from the host CPU the pulse train or sine wave signal generate from the design block using Matlab/Simulink software. A set of signal is transfer to the Microbox to control the speed and direction of the DC motor. Microbox is representing as a controller and it is use to receive and sending the signal which is suitable for data acquisition purpose.

Besides that, Microbox is also operating as converter and amplifier where the digital signal is converting into analog signal and reverse. The signal is then amplify before sending to the DC motor. DC motor is function as actuator of the ball screw system where the speed and direction of rotation is depends on the amplitude and sign of the voltage signal from host CPU. Then DC motor is connecting to the ball screw mechanism through the coupling of motor shaft and ball screw shaft. The rotation of screw shaft result in displacement of table load which is equal to lead per revolution of the helical raceway (displacement = lead (mm/rev) x angle of rotation (rad)). Then the change of the displacement of the table load is sense by linear encoder which converts the analog displacement into digitize pulse signal. This voltage signal is then feed into the Microbox and the host CPU convert the number of pulse into distance travelled by table load of the ball screw system.

For closed loop system, the compensation of input reference voltage signal with the positioning output response is resulting to error. The Host CPU will continue to send pulse train when there are errors present and stops sending when the error is equal to zero. Additional application is also implemented into the ball screw system such as the limit switch as a protection for the motor driver. Two limit switches are attached between front and end line along the ball screw. When the table load is touching one of the limit switches, the DC motor will stop to operate. With this protection, it can prevent the DC motor from drawing more current from the driver which can cause the driver to explode due to over current.

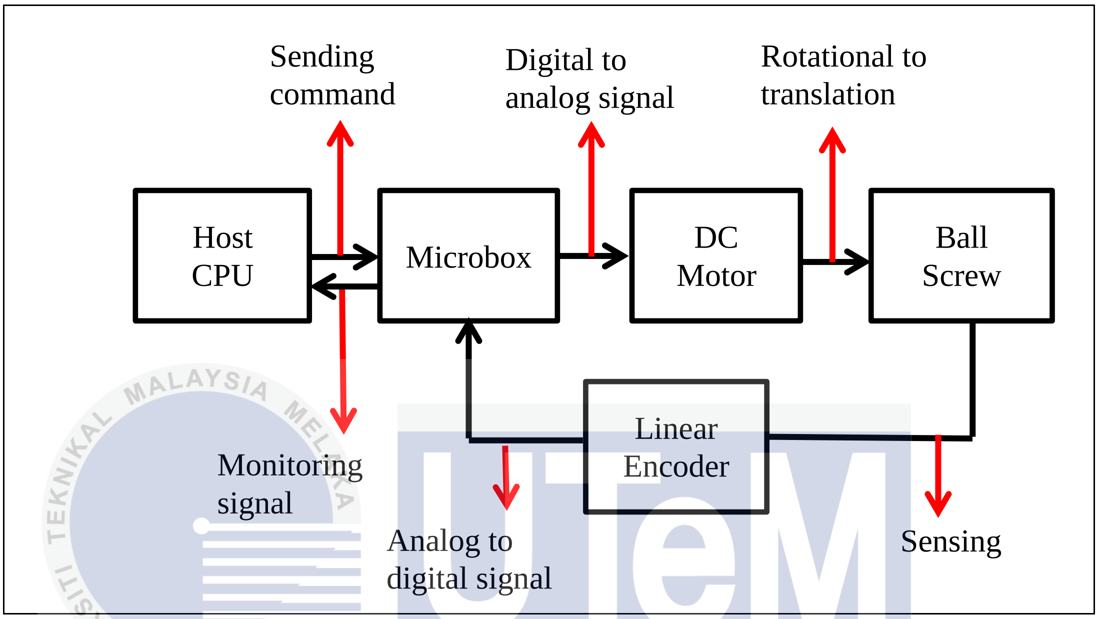


Figure 3.1: Block diagram of hardware setup.

3.2 Research methodology

In this project, there are several experiments are proposed to observe, design and validate the performance of controller and ball screw system itself. The following experiments are:

a) Experiment 1: Experimental setup.
b) Experiment 2: Data acquisition.
c) Experiment 3: Open loop test
d) Experiment 4: Closed loop test.
e) Experiment 5: Design the fuzzy PID controller.
f) Experiment 6: Design a PID controller.
g) Experiment 7: Point to point positioning test.
h) Experiment 8: Variation of load parameter under system with and without controller.

In the first experiment, the data acquisition process is conduct to obtain the output signal from the sensor. The output signal from the linear encoder is number of pulse. In order to validate the resolution of the linear encoder, the number of pulse is record and takes the measurement for every distance travelled. Then the process is repeat for every input voltage of 2V, 3V, 4V and 5V. After that, the average of millimeter per pulse is calculating and compare with the resolution of linear encoder's specification.

Next step is to obtain the plant modeling by conduct an open loop real time test. In this test, the output response of speed and displacement is obtain and record. Then the output response of speed is representing as the output data and the input pulse is representing as input data for the system identification process. The generated transfer function by using the system identification is then test in open loop simulation and compares the speed response of the simulation with the real time output speed response to verify the generated transfer function as the plant modeling. Therefore, another integrator is adding after the transfer function in order to obtain the displacement output response.

Another closed loop test is also conduct to observe the similarity of output response between the real time and simulation system using the generated transfer function. These open loop and closed loop test is test with input pulse signal and input sine wave. Besides that, the purpose of using the input pulse signal is to observe performance of the system in time domain (rise time, overshoot, settling time and steady state error). In closed loop test, the range of error and range of rate of error in both real time and simulation are record to further use for design the fuzzy inference system.

In the designing the Sugeno Takagi fuzzy inference system, there are 2 fuzzy inference system need to design with different rule. First fuzzy inference system is use for auto tuning the gains of Kp and Ki, whereas the second fuzzy inference system is use for auto tuning the Ki gain. The membership function of error and rate of error inputs are using 3 Gaussian shapes and 3 constant values for output membership function. The universe of discourse for 3 membership function of inputs and output are set equally along the range of error and range of rate of error.

After the design of fuzzy inference system, the process is proceed to implement the fuzzy inference system into fuzzy controller. The Kp, Kd and Ki gains are add after the fuzzy controller block. In simulation the Kp, Kd and Ki gains will manually tune to obtain the best output response performances. This method is known as hand tuning method. By using this method, the Kp values initially set from 1 to the certain values to obtain best performances of output response. After the Kp gain was set, the Kd gain is adjust same way as the Kp gain and then adjust the Ki gain. The simulation is execute under different input signals and plots the output response.

After the fuzzy PID controller was designed in simulation, the fuzzy PID controller is then implemented in experimental. Run the experiment with step input and sine wave input and plot the output response. If the output response is not satisfy then tuning the Kp, Kd and Ki gains until the best performance is obtain. Then the output response between the real time and simulation are observe and compare. Any different between simulation and real time output response is discuss.

In the next experiment, point to point positioning test is test in experimental. The input using is step input with different final value. The purpose of using this step input is to test the point to point positioning of the experimental test under closed loop system, system with PID controller and system with fuzzy PID controller. The output responses are plot and compare the output response. The rise time, settling time, overshoot, steady state error and standard deviation in experimental under closed loop, system with PID controller and system with fuzzy PID controller are calculate. The experiment of point to point positioning is repeat at 10 mm, 25 mm and 50 mm.

There are several methods to design the PID controller likes root locus, frequency response and hand tuning method. By using the root locus method, the PD controller is design by using calculation to obtain the best performance of output response. For frequency response method, the Ziegler Nichols in frequency response method is use to obtain the Kp, Kd and Ki gains as shown in Table 2.1 in Chapter 2. In hand tuning method, the Kp and Ki gains are tune to obtain best output performance and the Kd gain is set to 0, the Kd gains can cause unstable when input pulse signal is use to test in simulation with PID controller.

Then the PID controller using the root locus, frequency response (Ziegler Nichols) and hand tuning method is implementing in experimental. Run the experiment using the sine wave input and step input. The output response is plot and compares the output response and steady state error between the closed loop and system with PID controller. Discuss the results of output response of every methods used and choose the best PID controller for the experimental.

Next experiment is to increase the mass of the load to test the system with Fuzzy PID controller, system with PID controller and system without any controller (closed loop system). In experiment the load with weight of 1000g, 2000g and 3000g is test using sine wave input and step input. The output responses are plot and compare between the system with fuzzy PID controller, PID controller and system without any controller. The steady state errors of every system under different weight of load are comparing and discuss.

3.2.1 Design procedure of fuzzy PID controller.

This procedure is design to achieve the first objectives of design a Fuzzy PID controller for the ball screw system driven by DC motor. The steps are as follow:

a. First is to create a Mamdani type of fuzzy inference system for the Kp and Kd gains. In Matlab window type “fuzzy” and enter. In the FIS editor, the type can be change by click the file then click new and Mamdani or Sugeno. Then create 2 inputs by click the edit tab and click the add variables input. Name the 2 inputs to error and rate of error. Name the output to Kp and Kd.

b. Double click the input, in the membership function editor create the Gaussian membership function in both error and rate of error by click edit and remove all membership function and then click add membership function and click the gaussmf with number of 3. As for output Kp and Kd, the membership function will be the 3 triangular. If the Sugeno type of fuzzy inference system is used set the output to 3 constant membership functions. Then name every members function for inputs and output to negative, zero and positive.

c. To set the range of inputs and output membership functions, the inputs error and rate of error is depend on the amplitude of the input is use to run the simulation and experiment. For example, the step input of amplitude 2 is used in closed loop system. Therefore, the range for the error is -2 to 2 and the range for rate of error is -2000 to 2000. This is because the sampling time is set to 0.001, so the amplitude of 2 is divide by 0.001 will get 2000 for the range of rate of error.So set the input error range is -50 to 50 and rate of error range is -50000 to 50000. For output, the range is set to -10 and 10. Set the output range to -50 to 50 in output membership function.

d. After design the membership function, create the rule by double click the middle box in FIS editor. Then, rule editor set the rule according to below:

   i. IF error is negative AND rate of error is negative THEN Kp&Kd is negative.
   ii. IF error is zero AND rate of error is zero THEN Kp&Kd is zero.
   iii. IF error is positive AND rate of error is positive THEN Kp&Kd is positive.

e. After the rule is set, then export the fuzzy inference system to workspace by click the file in FIS editor and click the export to workspace.

f. Create another Sugeno Takagi fuzzy inference system for output of Ki by following the step from (a) to (e), but set the rule as follow:

   i. IF error is negative AND rate of error is positive THEN Ki is negative.

   ii. IF error is zero AND rate of error is zero THEN Ki is zero.

   iii. IF error is positive AND rate of error is negative THEN Ki is positive.

g. After finish design the fuzzy inference system, the fuzzy logic controller block is add into experimental before the Kp, Kd and Ki gains as shown in Figure 3.2.

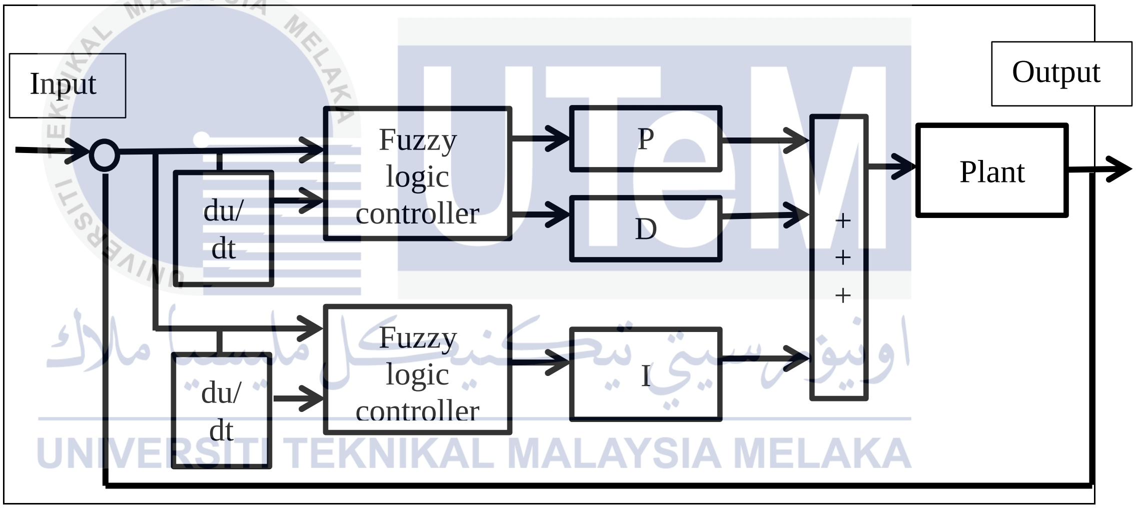


Figure 3.2: Block diagram of fuzzy PID controller.

3.2.2 Design procedure for point to point test.

This procedure is design to achieve the second objectives of examine the effectiveness of the proposed controller in PTP (point to point) positioning performance.

a. Set the point to point distance to 10mm, 25mm and 50mm by using step input. The amplitude is set to 10, 25 and 50 at step time of 1s and total time is 16s.

b. Run the experiment for 10 times in closed loop, system with PID controller and system with fuzzy PID controller. Plot the displacement output responses together with the error of the system.

c. Calculate the overshoot, rise time, settling time, error and standard deviation. Tabulate each calculated parameter in a table, compare the results and discuss.

3.2.3 Design procedure of system with fuzzy PID controller under variation mass.

This procedure is design to achieve the third objectives of to validate the robustness of the Fuzzy PID controller under variation of load mass in the comparison to the conventional PID controller.

a. Prepare the load with weight of 1000g, 2000g and 3000g. Set the distance need to travel to 50mm and set the total time to 15s.

b. There are two input need to test which are the step input and sine wave input. Set the parameter of each input as follow:
   i. Set the step input with amplitude of 50 and step time to 1s.
   ii. Set the sine wave input with amplitude of 50 and frequency of 3 rad/s.

d. The experiment is repeat 10 times in closed loop, system with PID controller and system with Fuzzy PID controller. Plot the displacement output responses together with the error of the system.

e. Calculate the overshoot, rise time, settling time, error and standard deviation. Tabulate each calculated parameter in a table, compare the results and discuss.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Experimental setup

The experimental plant shown in Figure 4.1 was set up according to designed Solidwork plant model. Additional limit switches were add to protect the driver from current overflow to DC motor when the table load is stuck at the end of ball screw mechanism. This limit switch is non-contactless therefore it may affect a little bit on the results when the table load is start or end at the limit switch.

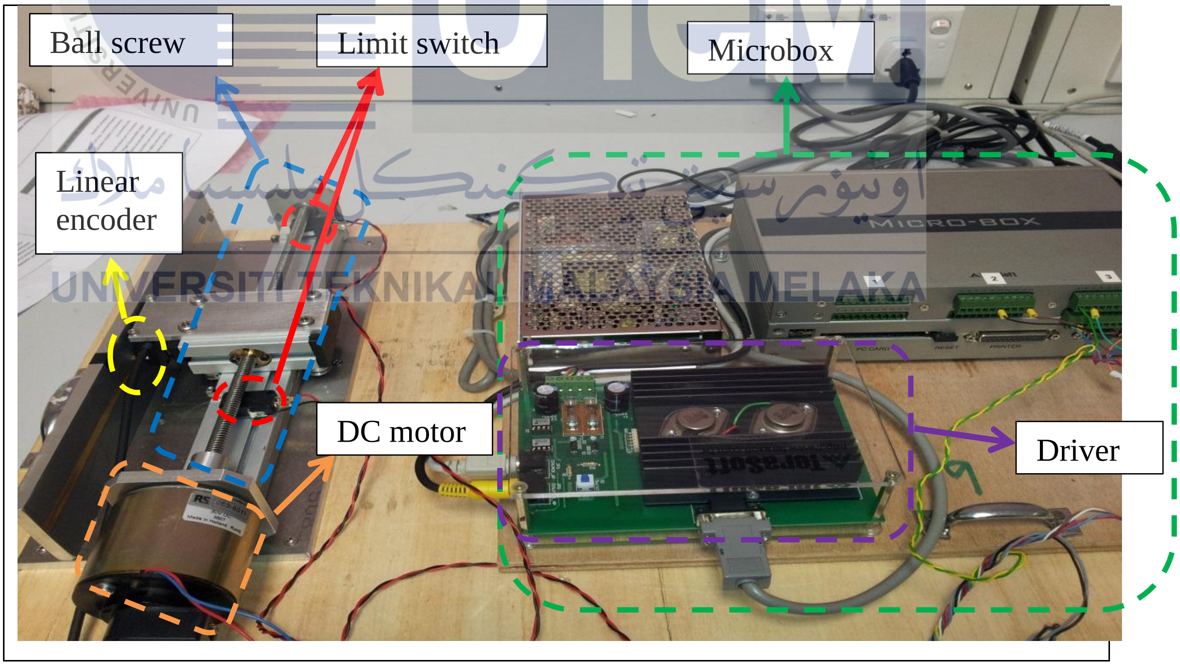


Figure 4.1: Experimental setup for ball screw system with Microbox.

There are two interfacing between the ball screw system and Microbox. One is the interface between the motor to the driver and another interface is between the linear encoder and Microbox. The clockwise rotation and anticlockwise rotation of DC motor is depend on the connection of DC motor to driver which is positive to supply voltage and negative to ground for clockwise and positive to ground and negative to supply voltage for anticlockwise. The change in polarity of voltage supply to the DC motor is depend on the command signal from host PC to the Microbox and Microbox convert this command signal from digital to analog signal. Then the driver amplify the analog signal before go to DC motor. The pin connected between the Microbox to driver is 13 and 19 on the connector 2 (digital to analog) as shown in Figure 4.2 and Table 4.2.

For interfacing between the linear encoder to the Microbox, there are 4 connections between linear encoder to Microbox connector 3 (encoder) which are incremental signal channel A to pin 1, incremental signal channel B to pin 2, voltage supply to pin 15 and ground to pin 19 as shown in Table 4.3. Through this connection, the linear encoder sends the number of pulse signal to Microbox and Microbox counts the number of pulse (digital signal) send to the host PC. This number can be representing as analog signal in the host PC.

Figure 4.2: Microbox connectors.

Table 4.2: Micro-Box 2000/2000C Connector 2

PIN NO.	PIN name	PIN NO.	PIN name
1	AD0	2	AD1
3	AD2	4	AD3
5	AD4	6	AD5
7	AD6	8	AD7
9	ADGND	10	ADGND
11	DA0	12	DA1
13	DA2	14	DA3
15	NA	16	NA
17	NA	18	NA
19	GND	20	GND

Table 4.3: Micro-Box 2000/2000C Connector 3

PIN NO.	PIN name	PIN NO.	PIN name
1	Encoder0 phase A	2	Encoder0 phase B
3	Encoder0 INDEX	4	Encoder1 phase A
5	Encoder1 phase B	6	Encoder1 INDEX
7	Encoder2 phase A	8	Encoder2 phase B
9	Encoder2 INDEX	10	Encoder3 phase A
11	Encoder3 phase B	12	Encoder3 INDEX
13	NA	14	NA
15	+5V	16	+5V
17	+5V	18	+5V
19	GND	20	GND

4.2 Data acquisition

This experiment was done to verify the resolution of linear encoder and to obtain the gain value for conversion of number of pulse into distance in millimeter. From the Table 4.4, the pulse to displacement ratio is approximate to -200 pulses/mm. Therefore the gain for conversion of pulse to displacement is -0.005mm/pulse. Therefore, every increment of input amplitude from 2 to 3, 3 to 4 and 4 to 5 shows an incremental of displacement and pulse is approximate to 25mm and -5000 pulses. The negative sign shows directions of linear encoder oppose the direction of table load. As a result, to neutralize the negative sign the negative gain of -0.005mm/pulse instead of positive gain was added.

There are two channels for linear encoder to operate which are channel A and channel B. Both of these channels are operating in the same ways which is sense the optical tape and generate the pulse but by using two channels together the direction of system move can be identified either forward or reverse. The principle is when the system is moving in forward direction, the generated pulse in channel A will lead the generated pulse in channel B. Same to the reverse, the pulse generated in channel A will lag the pulse generated in channel B. Therefore, the linear encoders also capable to sense the direction move instead of distance move only.

Table 4.4: Data acquisition from the open loop system.

Voltage, V	Displacement, mm	Pulse	Ratio
2	20	-4066	-199.27
	22.5	-4501	
	23	-4544	
	22	-4322	
	24	-4786	
(Average)	22.3	-4443.8	
3	52	-10230	-196.99
	51	-10050	
	49	-9687	
	52	-10270	
	52.5	-10290	
(Average)	51.3	-10105.4	
4	80	-15970	-198.86
	80	-15950	
	80.5	-16000	
	81	-16020	
	81	-16100	
(Average)	80.5	-16008	
5	106	-21070	-198.36
	106.5	-21100	
	105.5	-20940	
	105.5	-20890	
	106	-21030	
(Average)	105.9	-21006	

4.3 Open loop and closed loop test

The open loop test was done to observe the characteristics of the system. Based on the Figure 4.3 to Figure 4.11, the output response of displacement is increasing when the amplitude of input pulse is increasing. The longer the pulse width is, the longer the displacement to increase proportionally before the amplitude of input pulse drop to negative sign. When the amplitude is in negative sign the displacement is begin to decrease proportionally. For output response of speed, the increase of amplitude of the input pulse will results in greater speed. The speed will remain constant along the pulse width and begin to drop to negative constant when the input pulse is in negative sign.

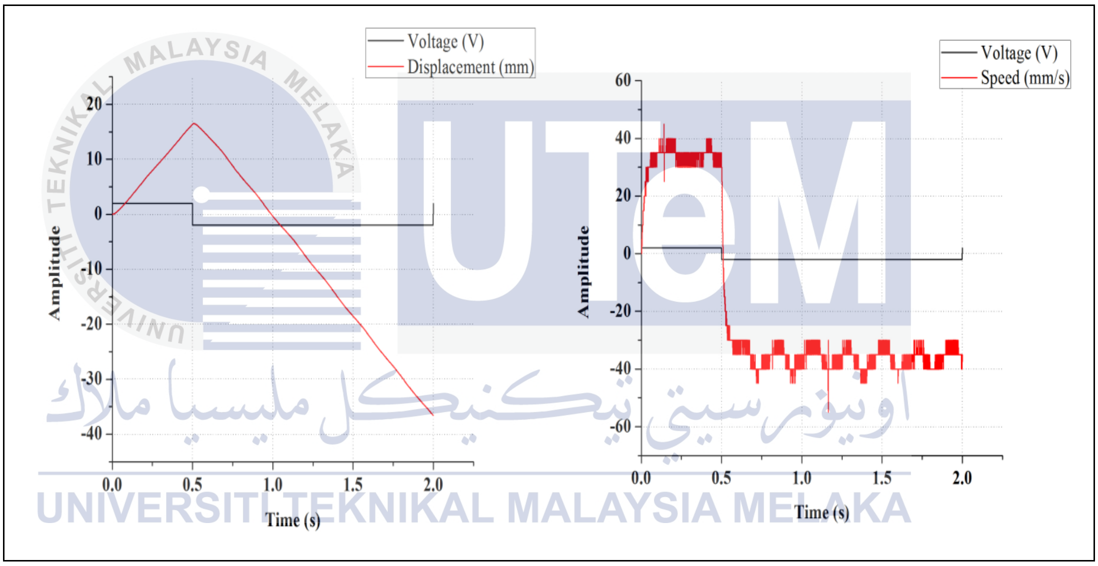


Figure 4.3: Displacement and speed output response at input pulse of amplitude 2 and pulse width of 0.5s.

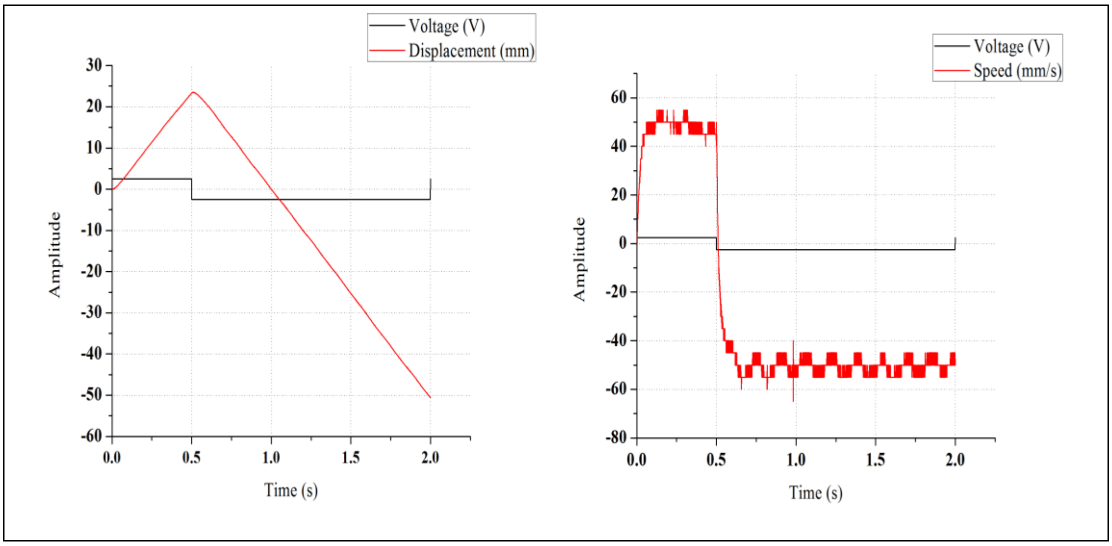


Figure 4.4: Displacement and speed output response at input pulse of amplitude 2.5 and pulse width of 0.5s.

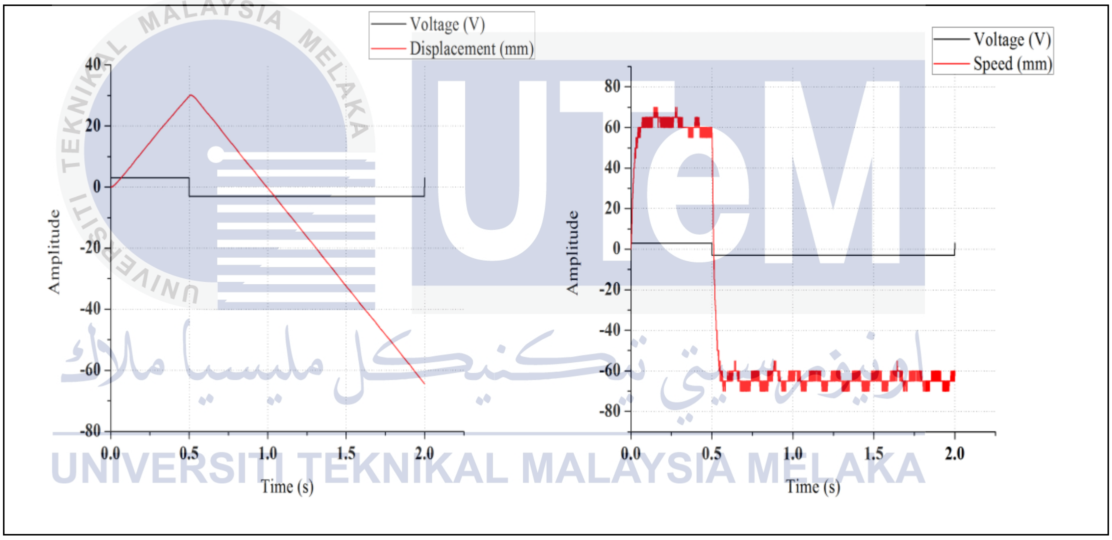


Figure 4.5: Displacement and speed output response at input pulse of amplitude 3 and pulse width of 0.5s.

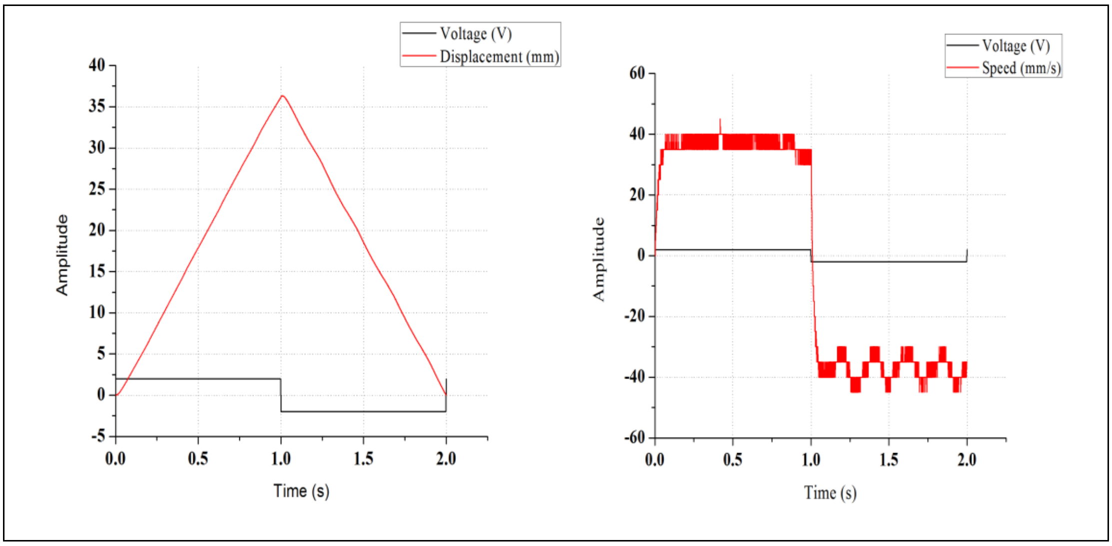


Figure 4.6: Displacement and speed output response at input pulse of amplitude 2 and pulse width of 1s.

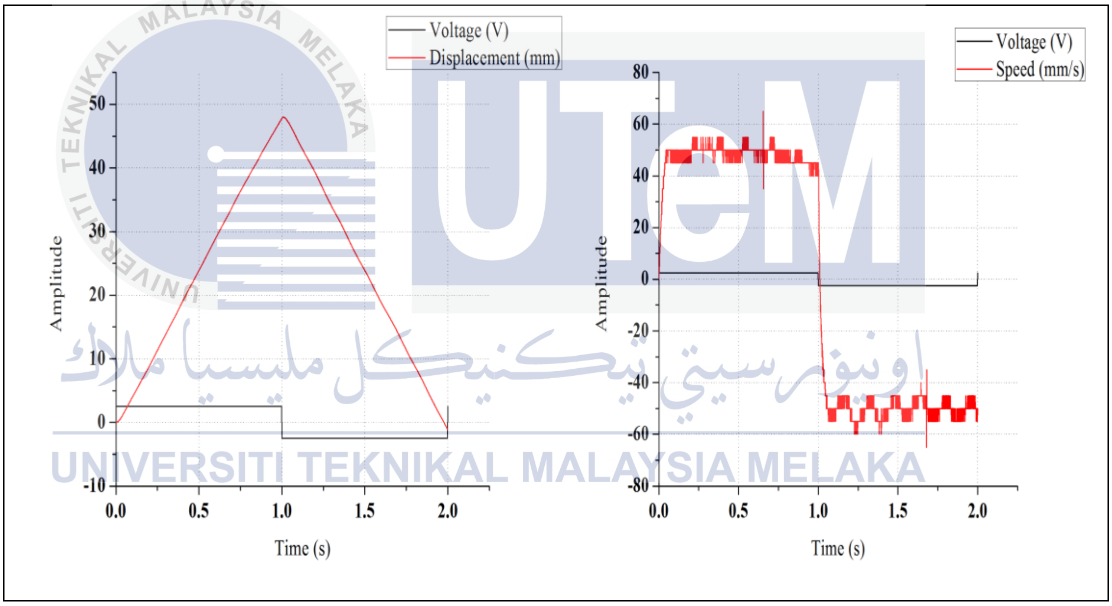


Figure 4.7: Displacement and speed output response at input pulse of amplitude 2.5 and pulse width of 1s.

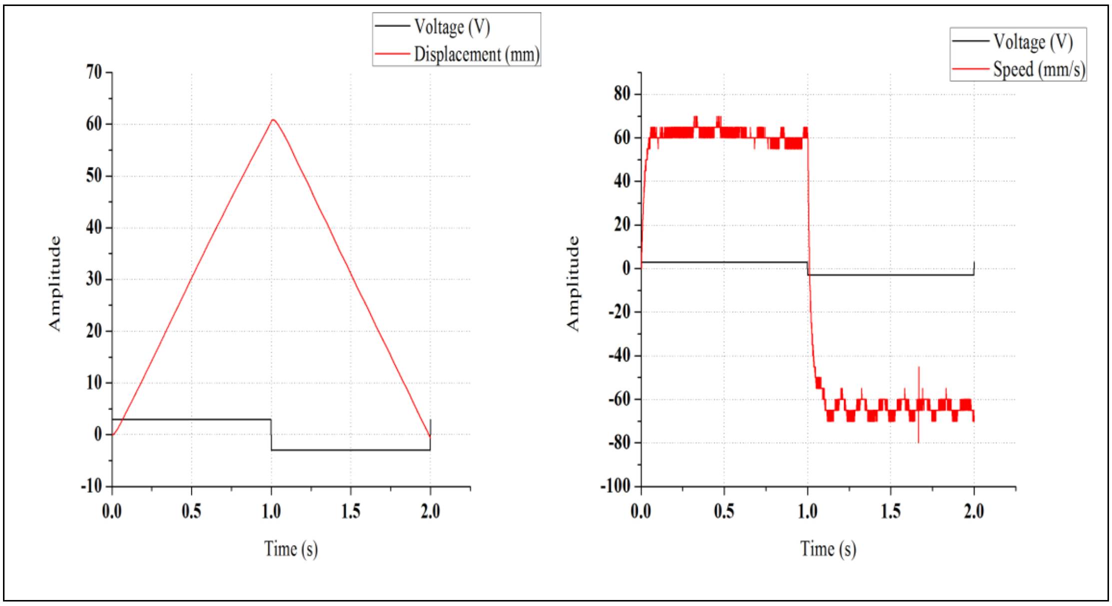


Figure 4.8: Displacement and speed output response at input pulse of amplitude 3 and pulse width of 1s.

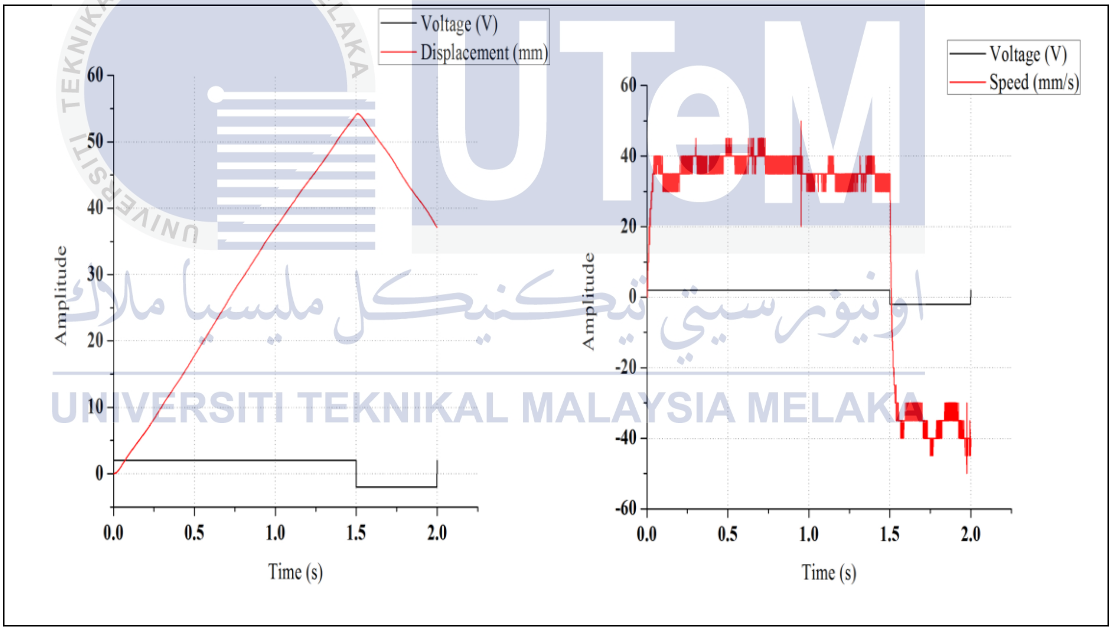


Figure 4.9: Displacement and speed output response at input pulse of amplitude 2 and pulse width of 1.5s.

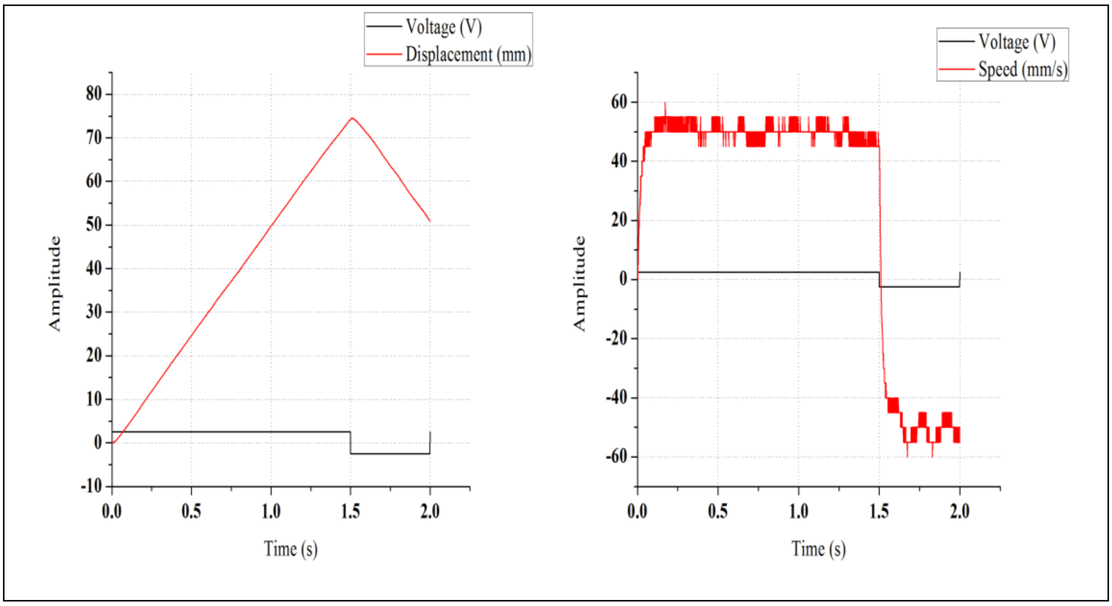


Figure 4.10: Displacement and speed output response at input pulse of amplitude 2.5 and pulse width of 1.5s.

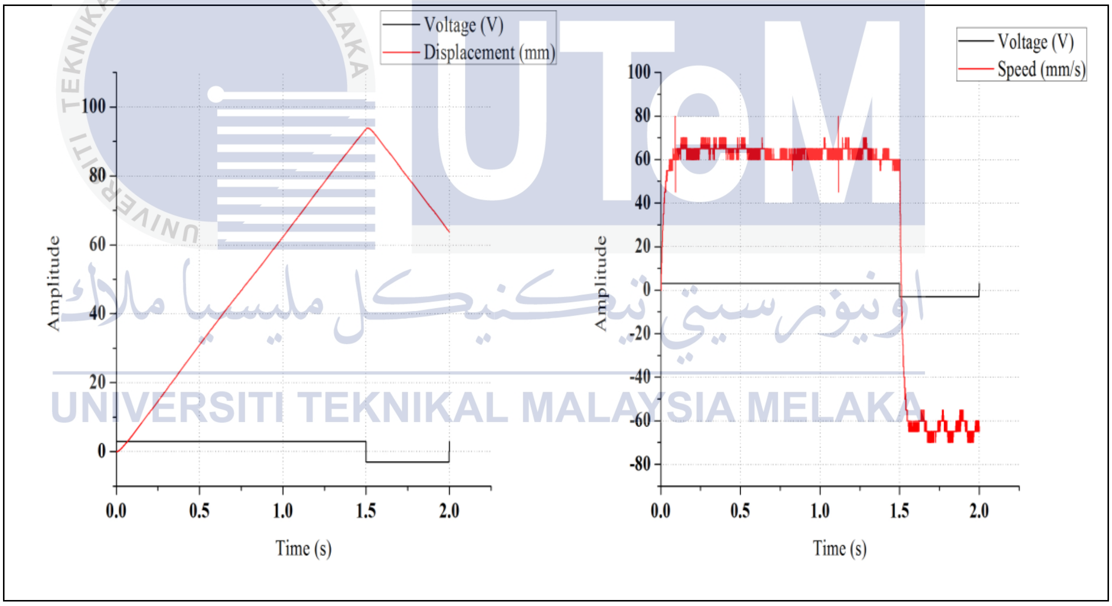


Figure 4.11: Displacement and speed output response at input pulse of amplitude 3 and pulse width of 1.5s.

From the Figure 4.12 to Figure 4.23 shows the output displacement in sine wave using the input sine wave at amplitude of 2, 2.5 and 3 with frequency of 1 rad/s, 3 rad/s, 10 rad/s and 30 rad/s. Based on the observation the greater the frequency of the input sine wave, the lower the amplitude of the output displacement. Besides that, the greater the frequencies of the input sine wave, the output displacement tend to be stable within 10 cycles. The increase of amplitude of the input sine wave, the output displacement shows small change in amplitude of output displacement.

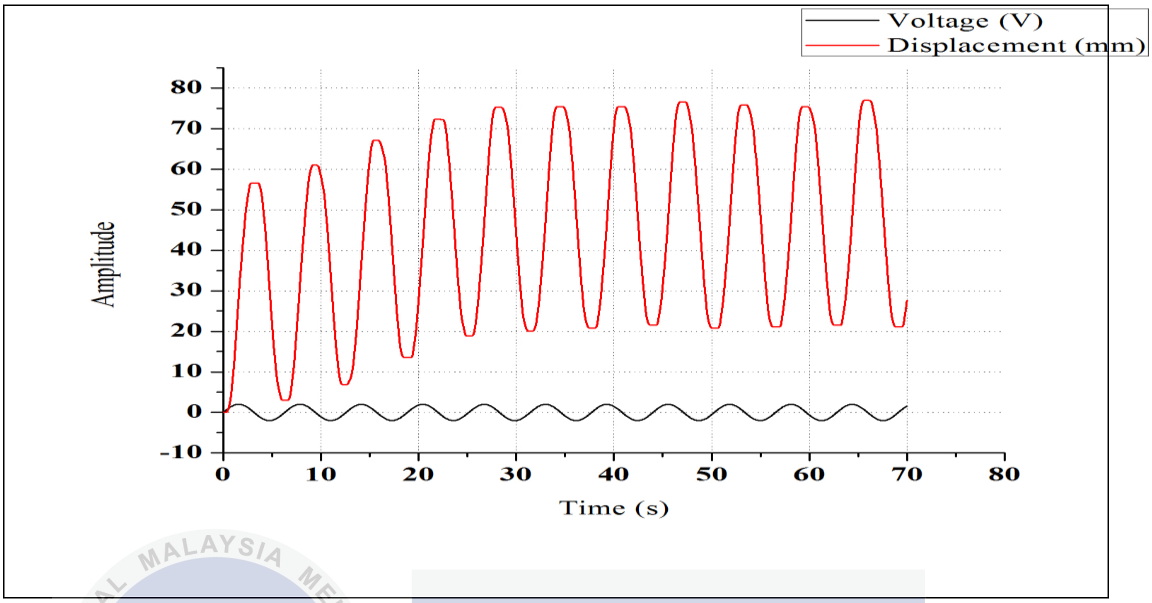


Figure 4.12: Displacement output response at sine wave input of amplitude 2 and frequency of 1 rad/s.

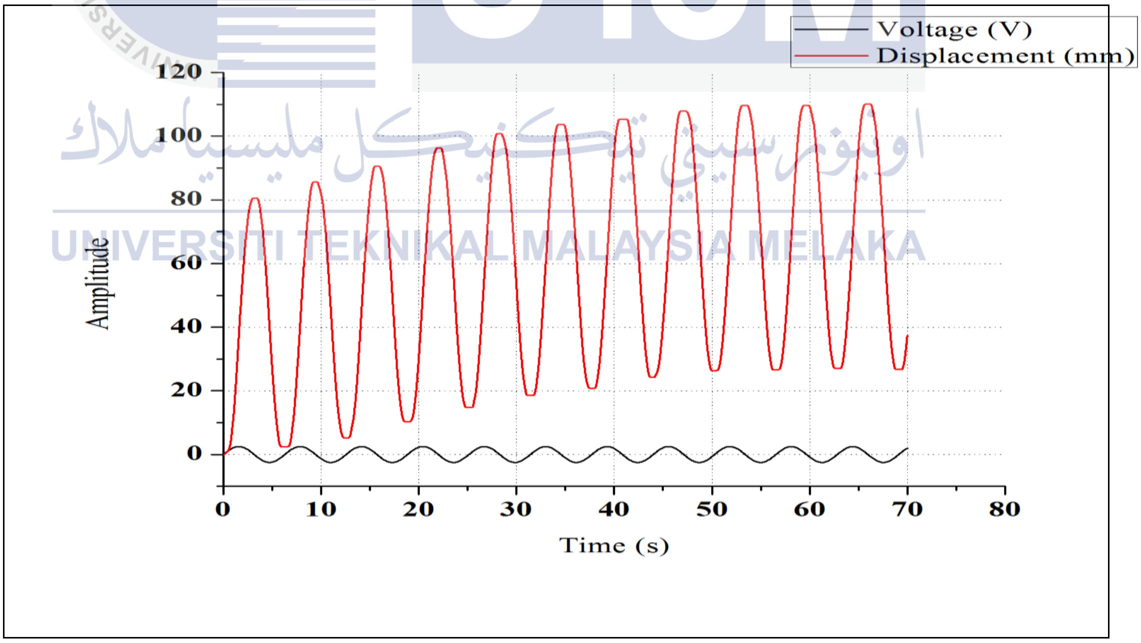


Figure 4.13: Displacement output response at sine wave input of amplitude 2.5 and frequency of 1 rad/s.

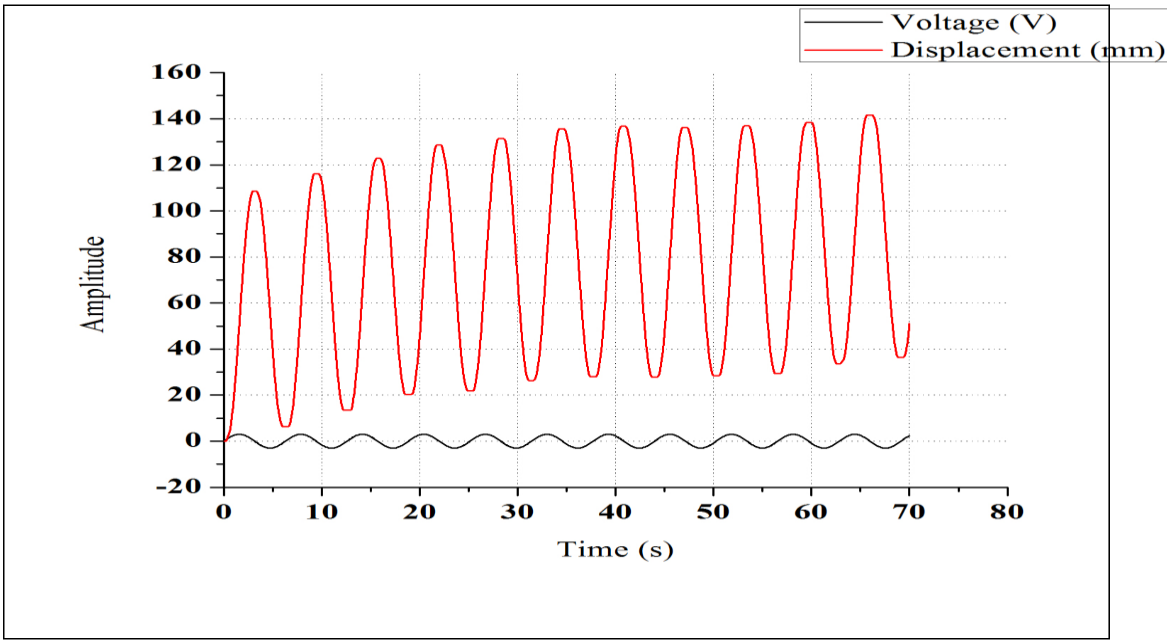


Figure 4.14: Displacement output response at sine wave input of amplitude 3 and frequency of 1 rad/s.

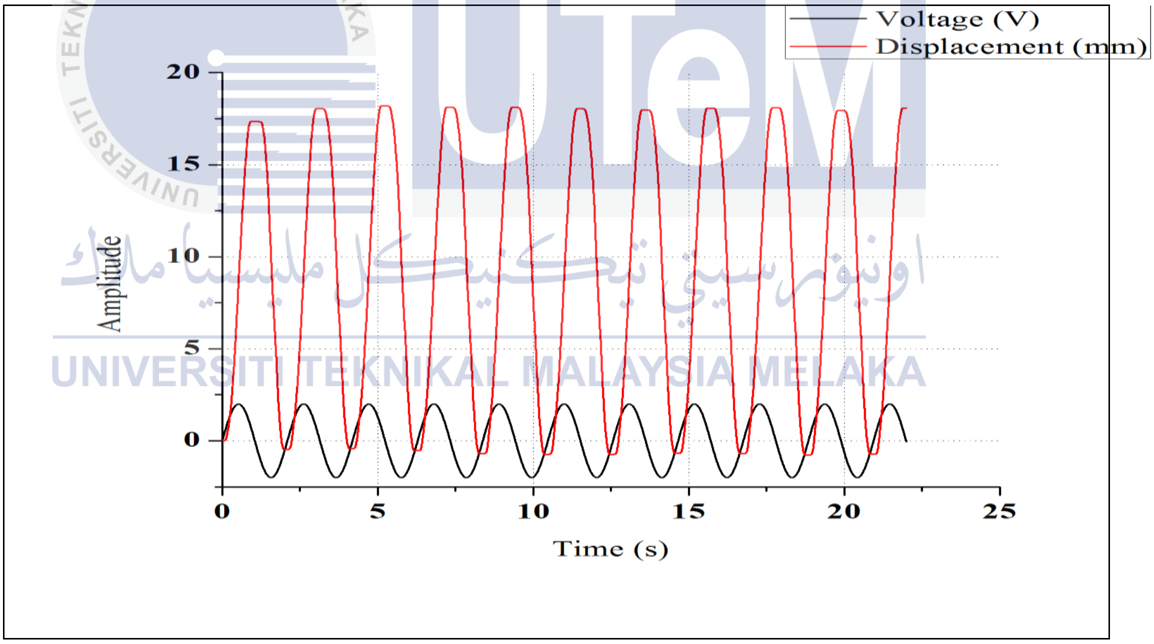


Figure 4.15: Displacement output response at sine wave input of amplitude 2 and frequency of 3 rad/s.

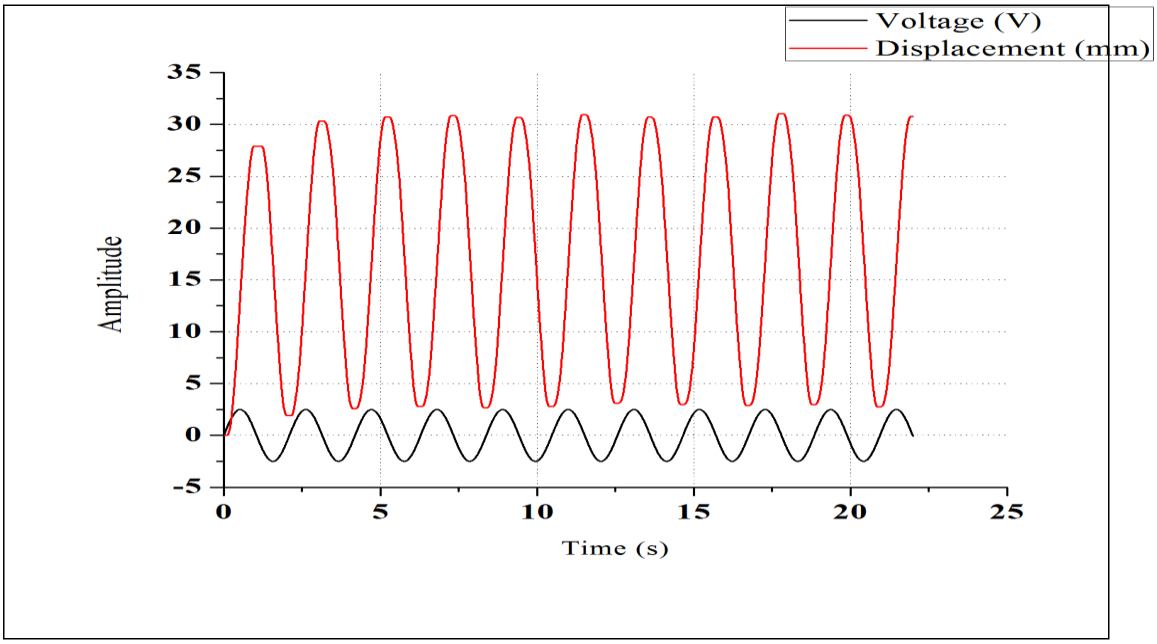


Figure 4.16: Displacement output response at sine wave input of amplitude 2.5 and frequency of 3 rad/s.

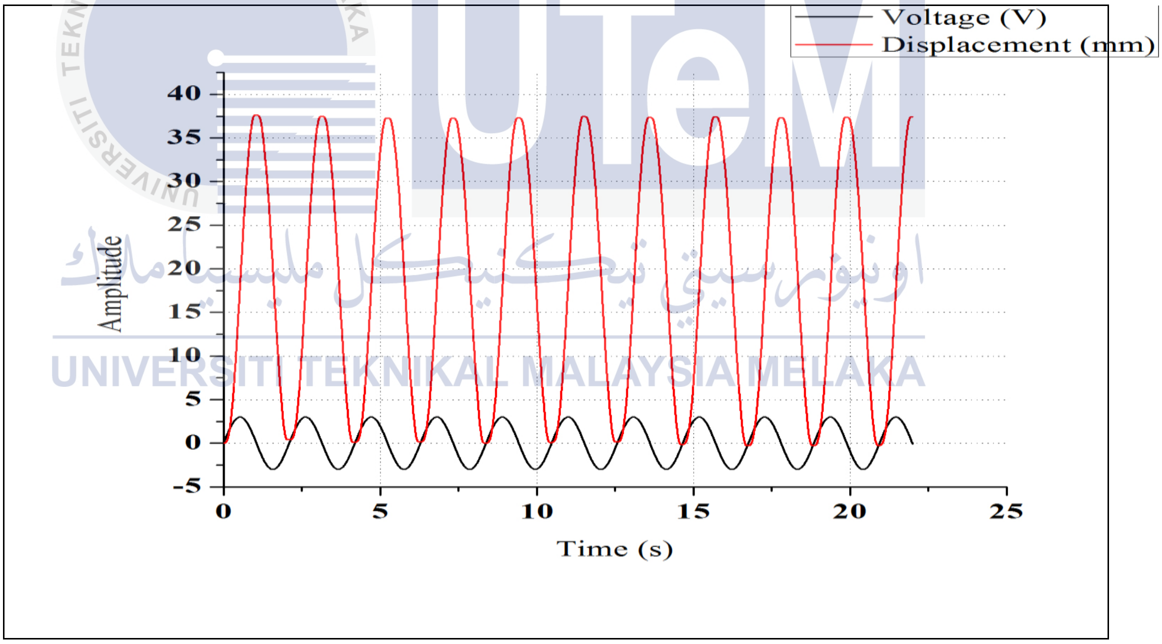


Figure 4.17: Displacement output response at sine wave input of amplitude 3 and frequency of 3 rad/s.

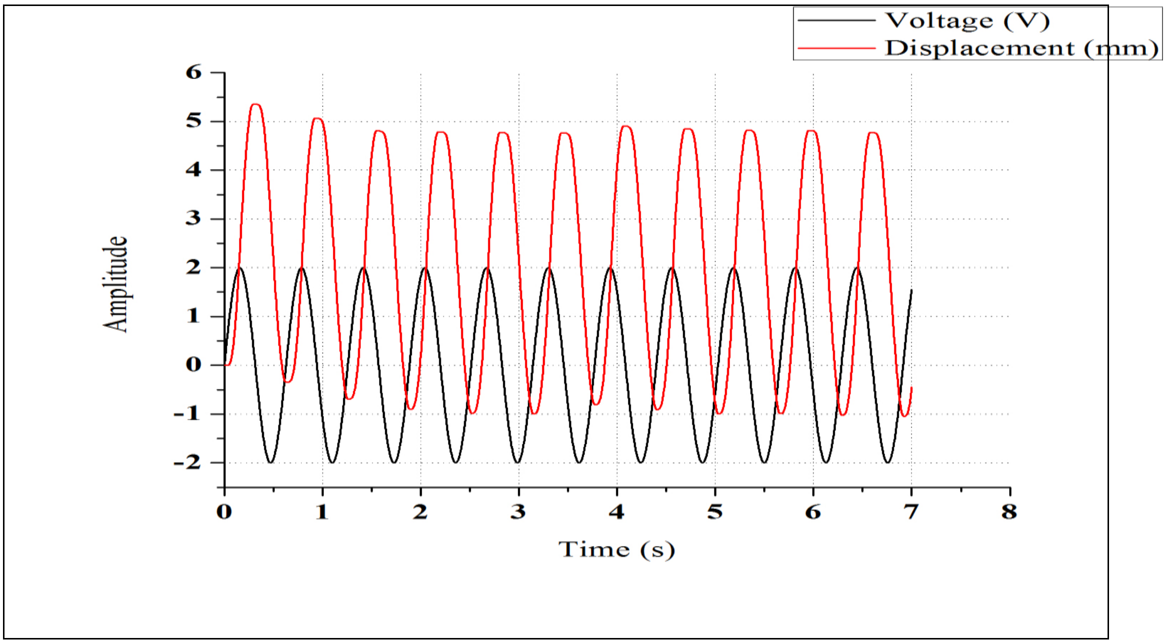


Figure 4.18: Displacement output response at sine wave input of amplitude 2 and frequency of 10 rad/s.

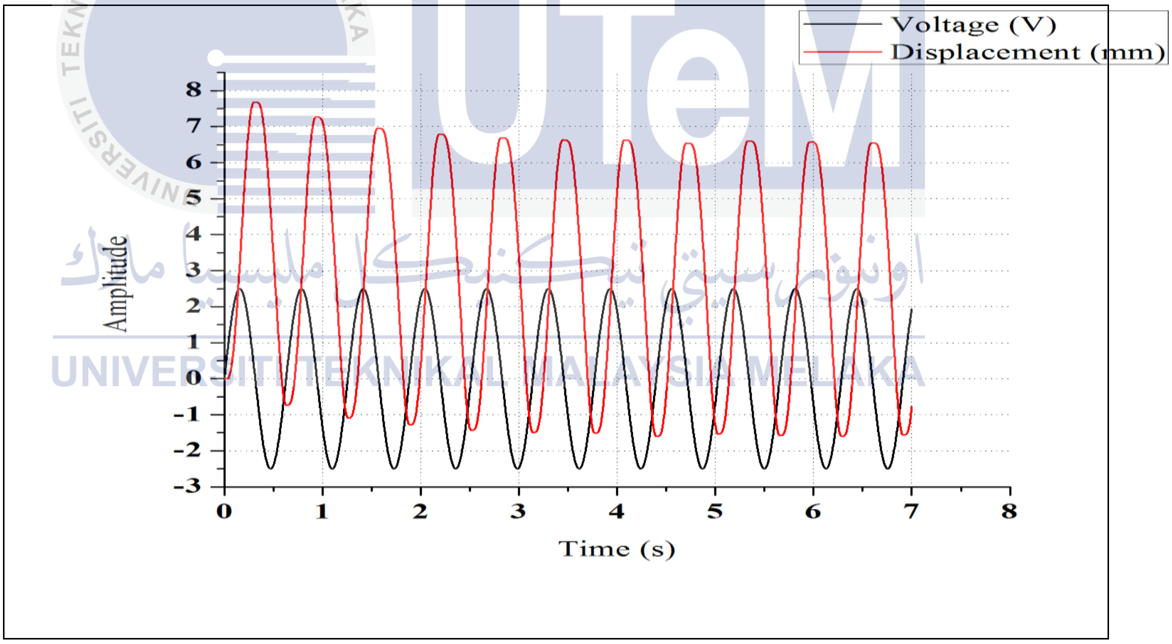


Figure 4.19: Displacement output response at sine wave input of amplitude 2.5 and frequency of 10 rad/s.

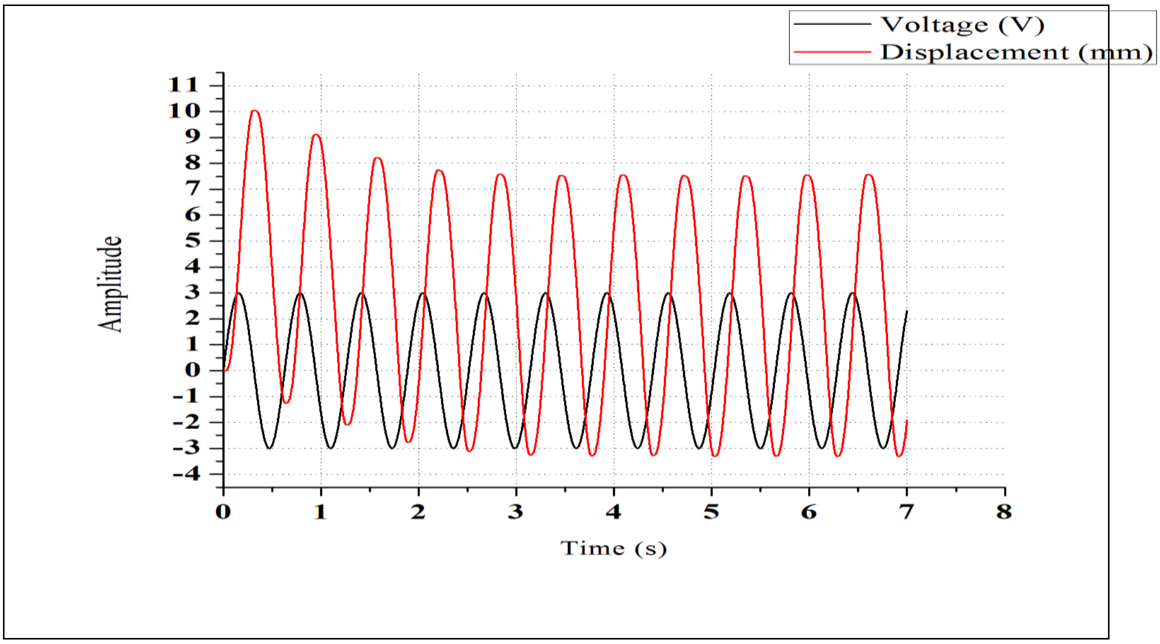


Figure 4.20: Displacement output response at sine wave input of amplitude 3 and frequency of 10 rad/s.

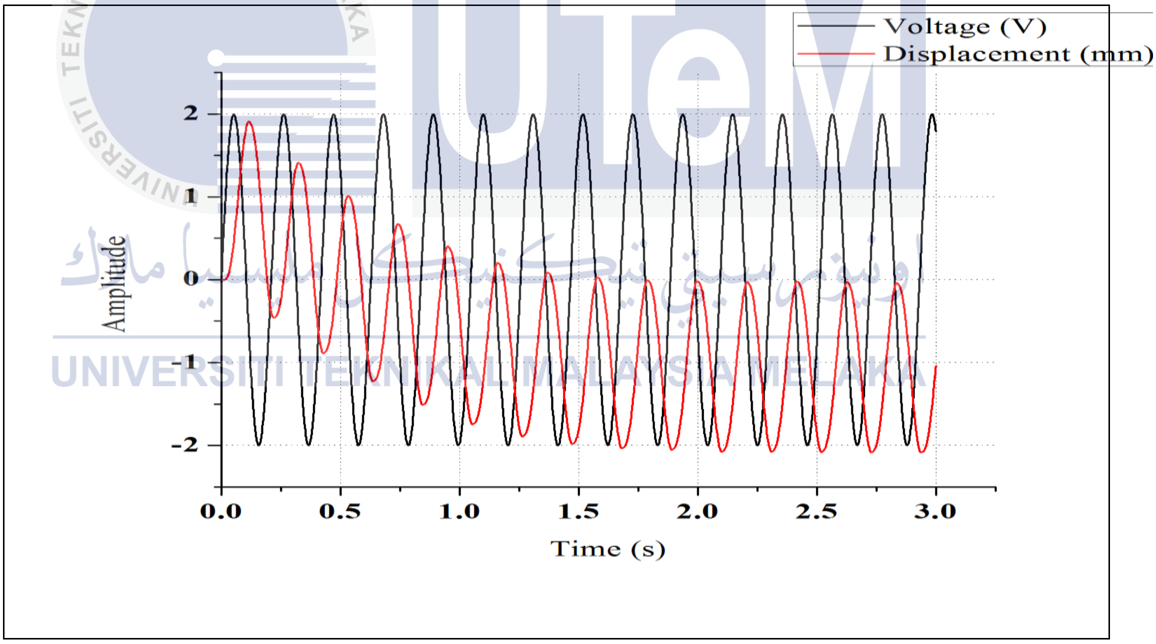


Figure 4.21: Displacement output response at sine wave input of amplitude 2 and frequency of 30 rad/s.

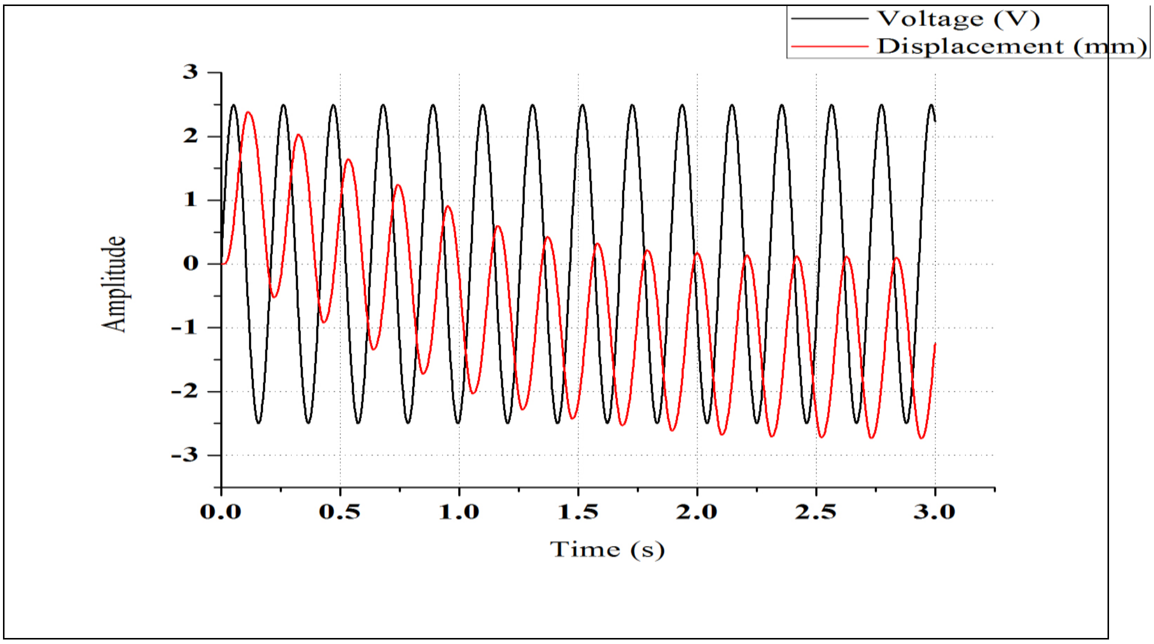


Figure 4.22: Displacement output response at sine wave input of amplitude 2.5 and frequency of 30 rad/s.

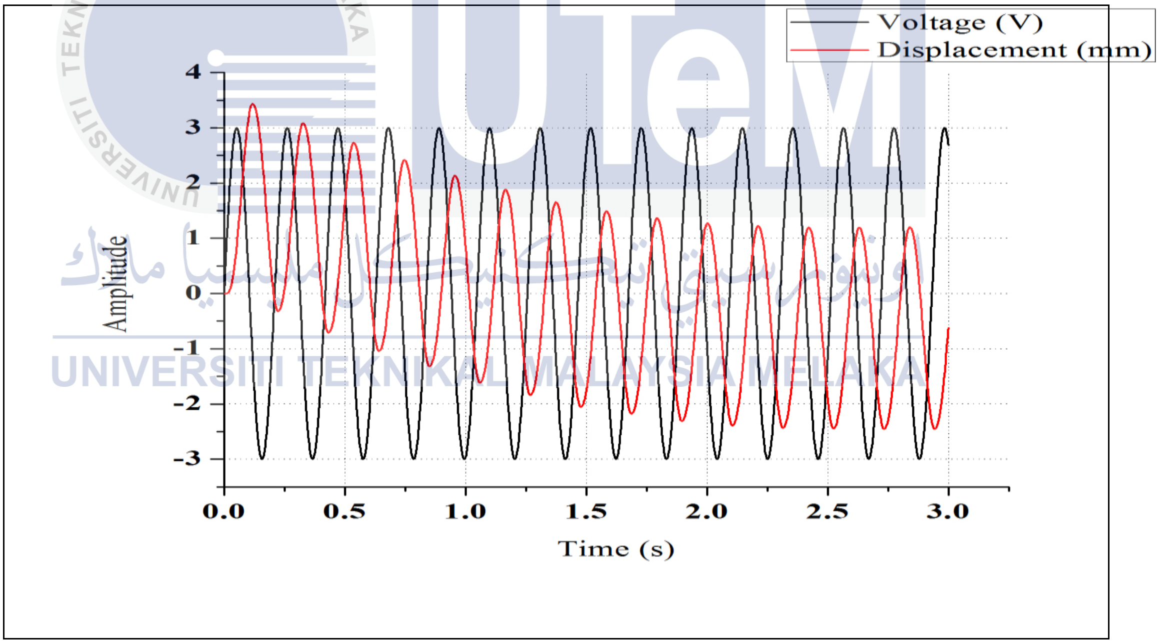


Figure 4.23: Displacement output response at sine wave input of amplitude 3 and frequency of 30 rad/s.

By using the speed plot as output and input pulse voltage as input from the Figure 4.8, the transfer function of open loop system was generated by using system identification as shown below:

$$G(s) = \frac{1406s+95480}{s^2+206s+5334} \qquad \text{Eq} \quad 4.2$$

The equation 4.2 shows the open loop transfer function of the speed model. From the equation given the transfer function can give displacement output response by adding the integrator at output of transfer function block. By compare the mathematical modeling of eq. 2.2.11 with the generated transfer function eq 4.2, its shows are almost same as the mathematical modeling. By compare the transfer function above, both of the transfer functions shows 3rd order system with one integrator to obtain output in displacement. The different part is on numerator, the numerator of generated transfer function is 1st order system. and zero order system for numerators of mathematical modeling.

From the Figure 4.24 to Figure 4.26, the closed loop is test with using the step input at different amplitude of 1, 5 and 10. The error is greater when the amplitude is low and begins to decrease to negative when the amplitude of step input is increasing. The rise time and settling time are increase when the amplitude of step input is increase. The overshoot is zero at any amplitude of step input.

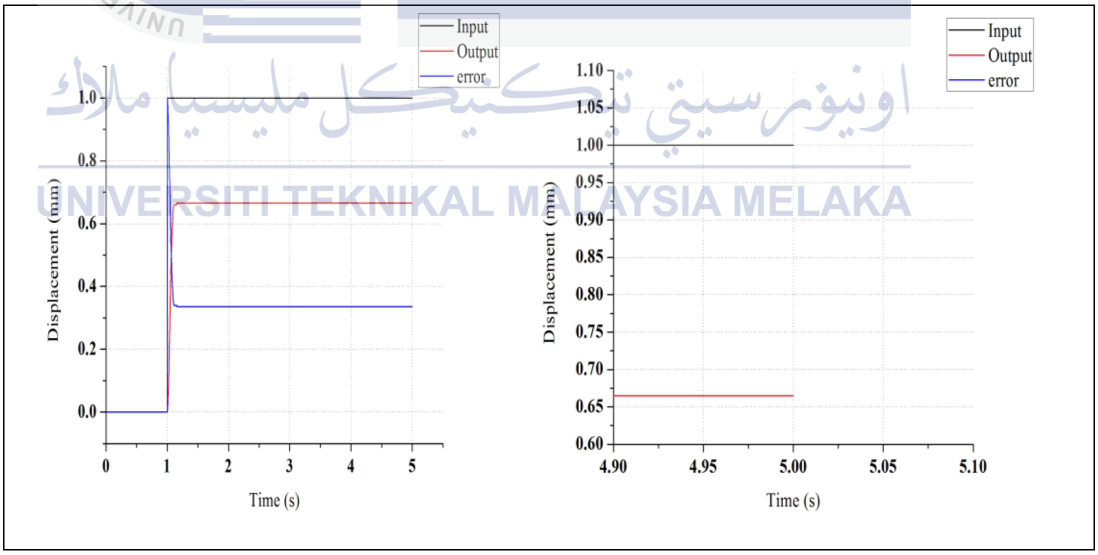


Figure 4.24: The displacement and error output responses for closed loop system at input of 1mm.

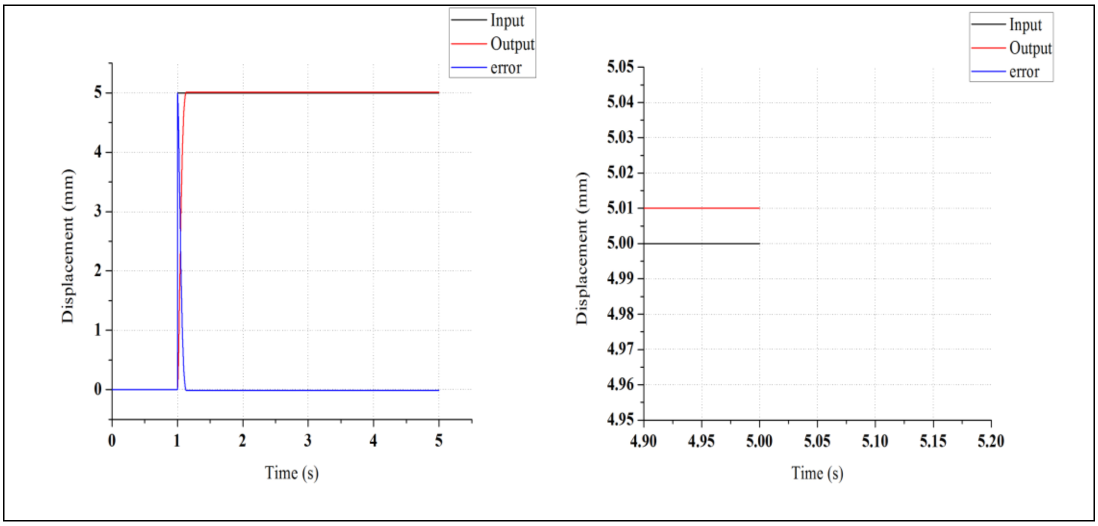


Figure 4.25: The displacement and error output responses for closed loop system at input of 5mm.

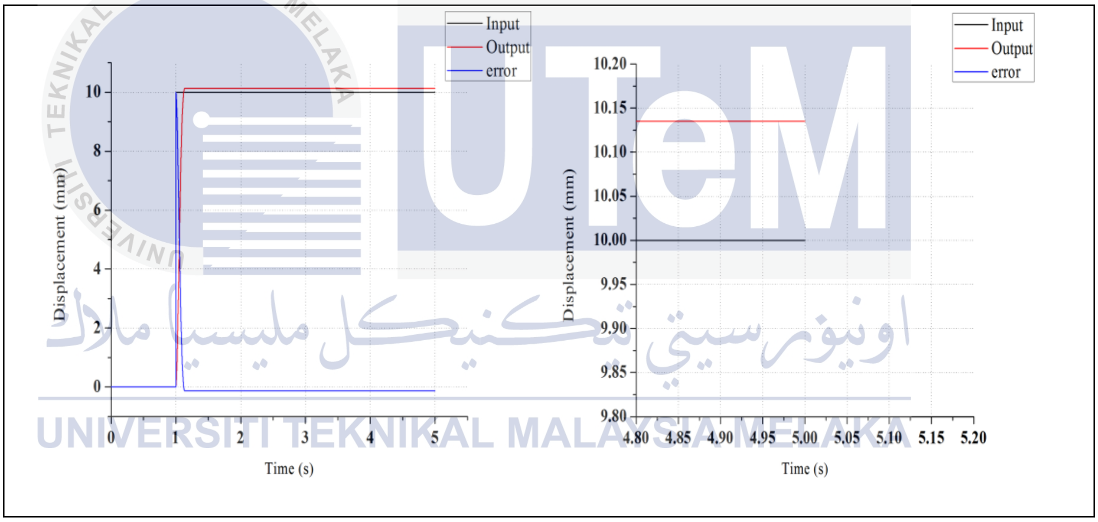


Figure 4.26: The displacement and error output responses for closed loop system at input of 10mm.

Table 4.5: Performance of the closed loop uncompensated system

Input (mm)	Rise time (s)	Settling time (s)	Overshoot	Steady state error (mm)
1	0.066	1.1023	0	0.335
5	0.0745	1.1145	0	-0.010
10	0.0768	1.1175	0	-0.135

Figure 4.27 to Figure 4.33 shows the displacement and error output response in closed loop system using the sine wave as input signal. The amplitude of the input is set to 10 and the frequency is vary to 0.1 rad/s, 0.3 rad/s, 1 rad/s, 3 rad/s, 10 rad/s, and 100 rad/s to observe the characteristic of the system. The average error of output responses show inconsistent. The standard deviation of the closed loop show decreasing at frequency of 0.1 rad/s to 1 rad/s and increase gradually from 1 rad/s to 100 rad/s as shown in Table 4.6.

Based on the Table 4.7, the frequency response of closed loop system at input of 10 , shows the gains are almost around 0.9 which mean at input of 10 with the change in frequency from 0.1 rad/s to 10 rad/s shows the output displacement is follow the input displacement accurately and then the output displacement begins to not follow the input displacement at higher frequency of 30 rad/s to 100 rad/s. As for the phase, the phase at frequency of 30 and 100 rad/s shows output displacement is lead the input displacement compared to other lagging phase at frequency of 0.1 rad/s to 10 rad/s.

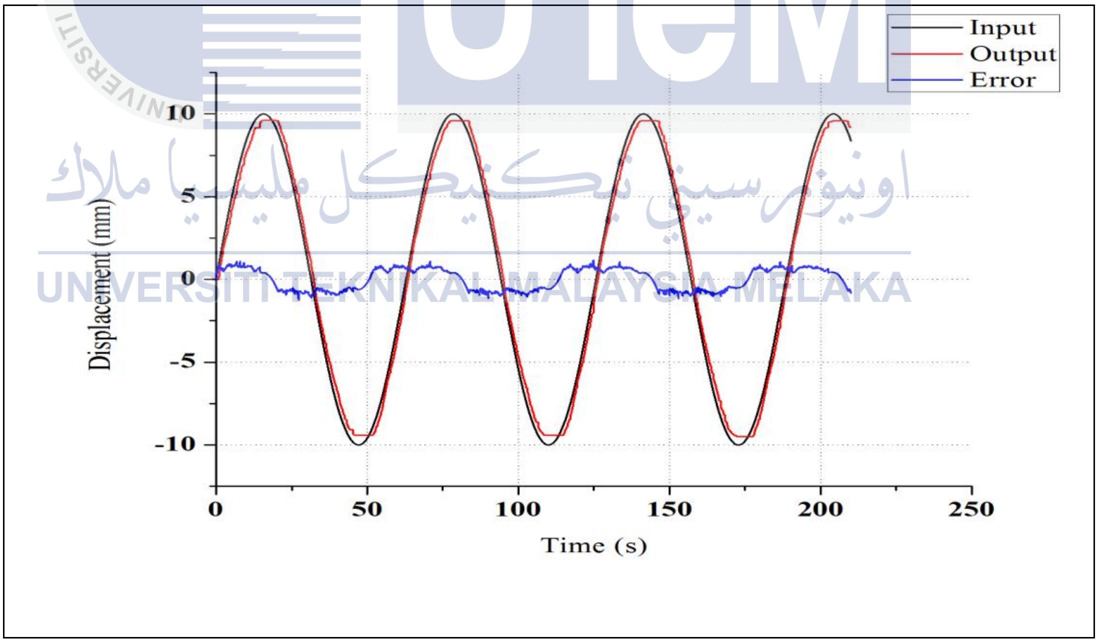


Figure 4.27: The displacement and error output response for closed loop system at input sine wave of amplitude 10 and frequency 0.1 rad/s.

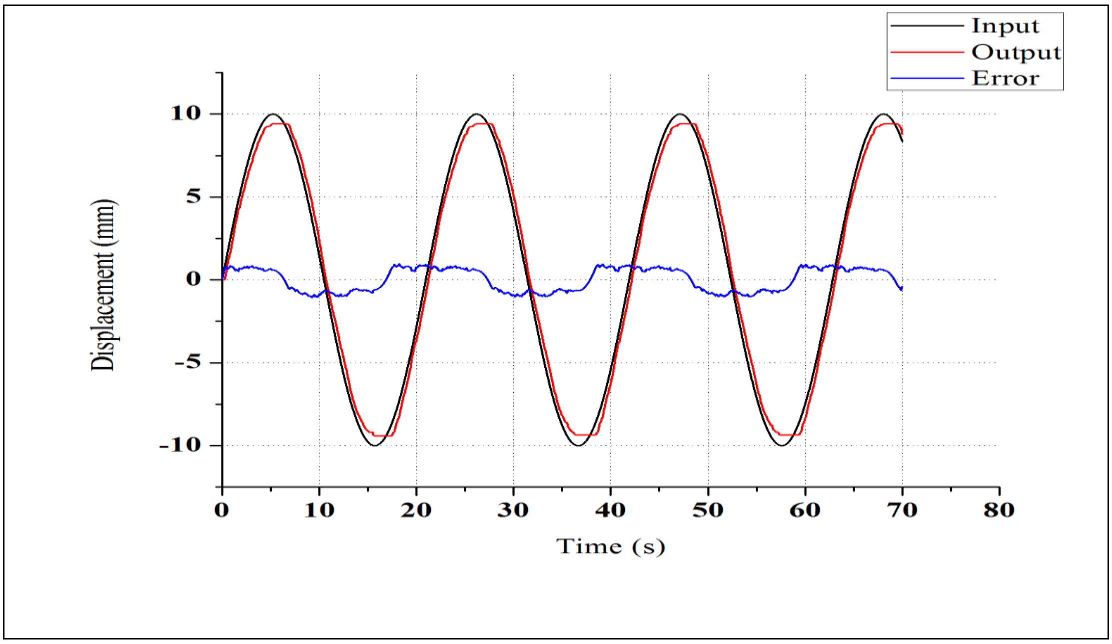


Figure 4.28: The displacement and error output response for closed loop system at input sine wave of amplitude 10 and frequency 0.3 rad/s.

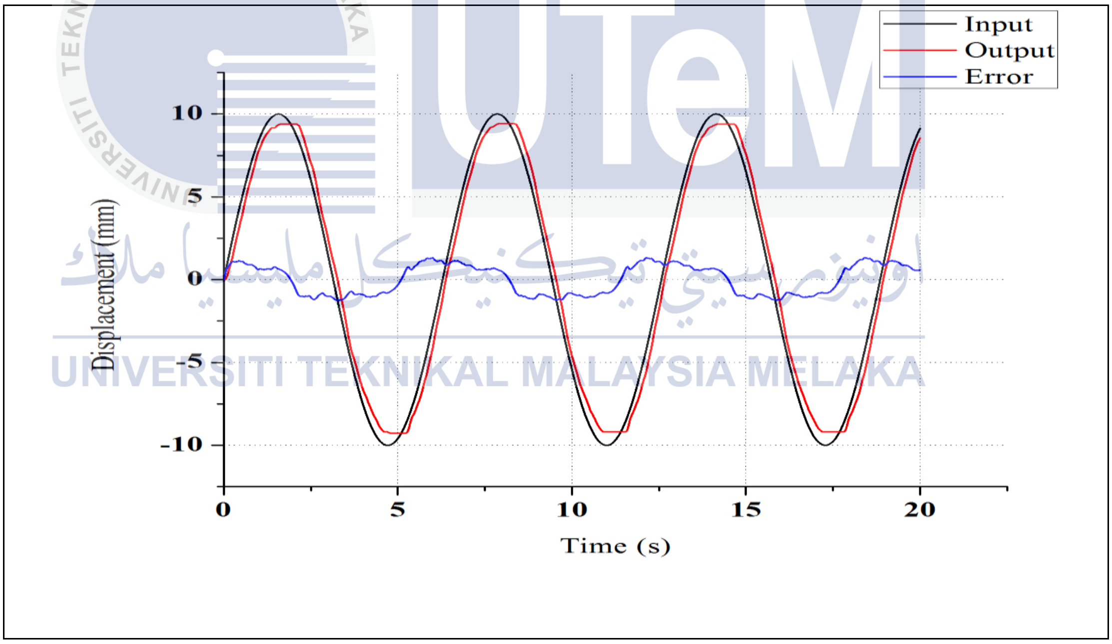


Figure 4.29: The displacement and error output response for closed loop system at input sine wave of amplitude 10 and frequency 1 rad/s.

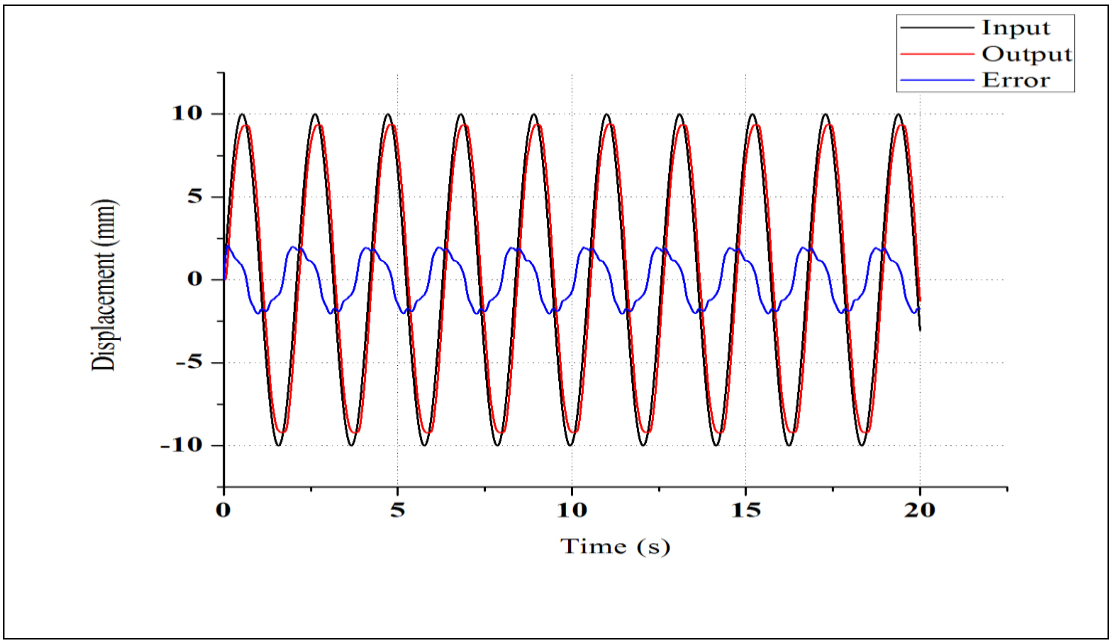


Figure 4.30: The displacement and error output response for closed loop system at input sine wave of amplitude 10 and frequency 3 rad/s.

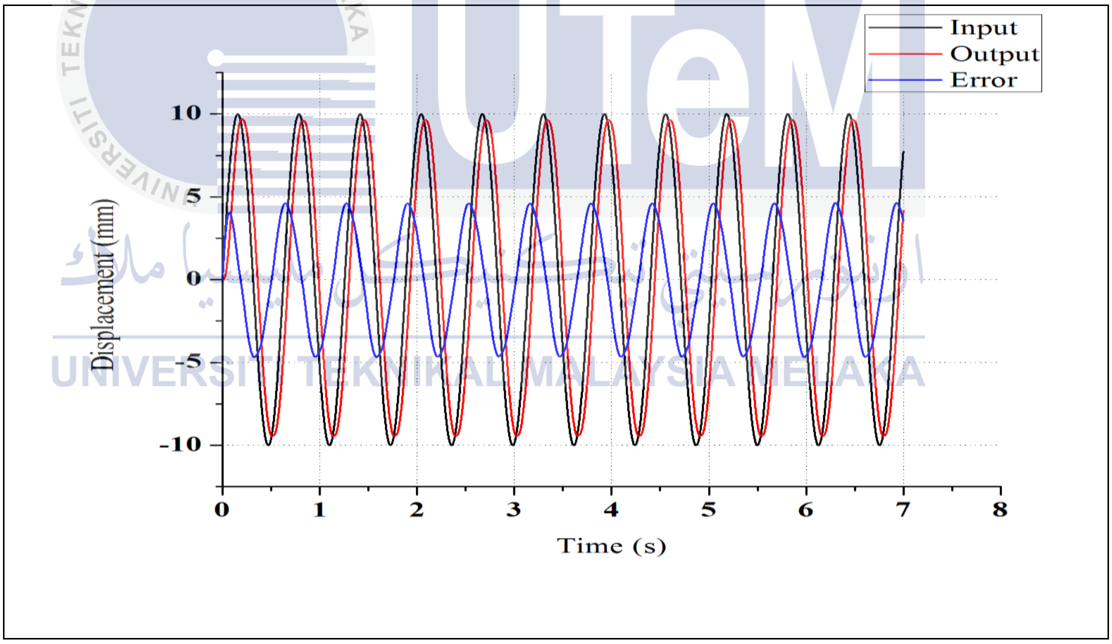


Figure 4.31: The displacement and error output response for closed loop system at input sine wave of amplitude 10 and frequency 10 rad/s.

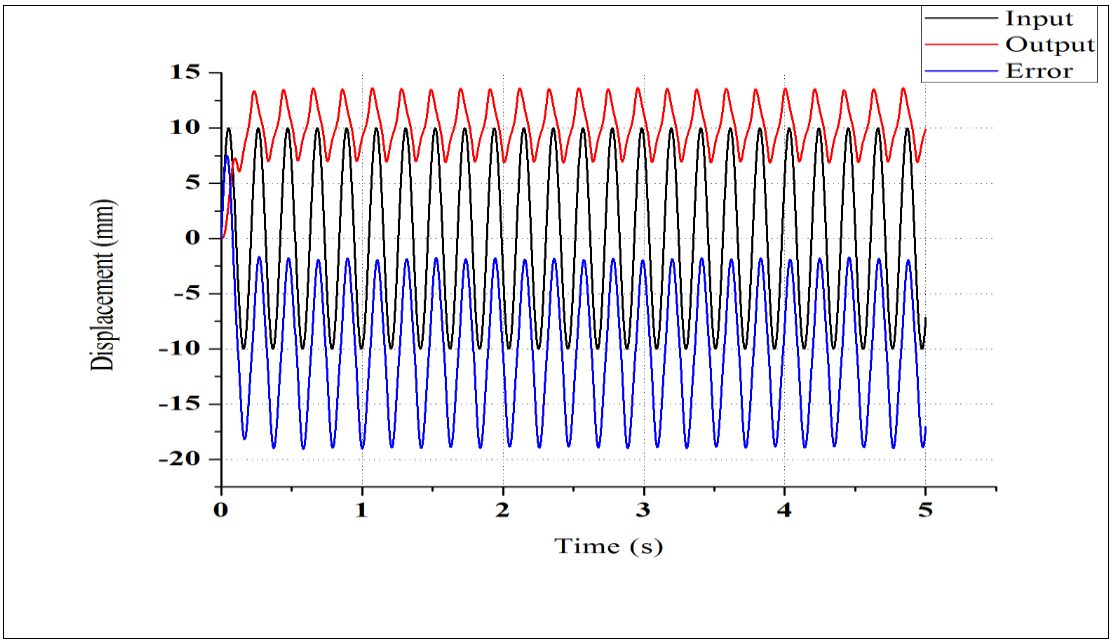


Figure 4.32: The displacement and error output response for closed loop system at input sine wave of amplitude 10 and frequency 30 rad/s.

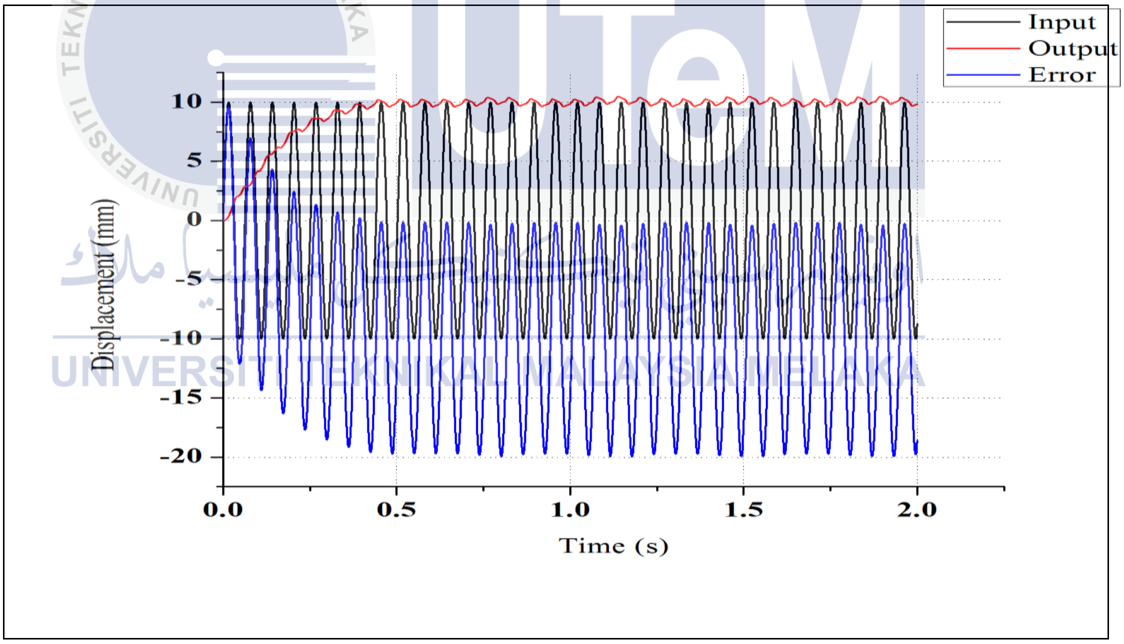


Figure 4.33: The displacement and error output response for closed loop system at input sine wave of amplitude 10 and frequency 100 rad/s.

Table 4.6: Error and standard deviation of the closed loop uncompensated system.

Frequency (rad/s)	Average error (mm)	Standard deviation (mm)
0.1	0.0144	0.6569
0.3	0.0360	0.7002
1	0.0063	0.9005
3	0.0199	1.4424
10	-0.0283	3.2178
30	-10.0573	6.0504
100	-9.2562	7.2616

Table 4.7: The frequency response of closed loop system.

Frequency (rad/s)	Period (s)	Gain	Gain (dB)	Phase
0.1	62.8	0.9508	-0.4382	-4.7
0.3	20.94	0.939	-0.5467	-5
1	6.28	0.931	-0.6210	-6.02
3	2.09	0.9275	-0.6537	-11.71
10	0.63	0.9533	-0.4154	-25.71
30	0.21	0.3313	-9.6	7.632
100	0.06	0.0325	-29.76	244.2

4.4 Design of fuzzy PID controller and conventional PID controller

By using the step as input signal with amplitude of 50, the output response for system with fuzzy PID controller shows better performance when the gain factors Kp, Kd and Ki are tuned to 25, 2.6 and 13.5.

Several of tuning method is used in this experiment especially the Ziegler Nicholas in frequency response method, root locus method and hand tuning method. But most of the tuning method cannot be used and unpractical in experimental test. Therefore, the last ways to tuned the PID controller is by using hand tuning method. There will be three sets of Kp, Ki and Kd gains are used to obtain better performance in transient response and steady state error which are (Kp1=20, Kd1=0.4 and Ki1=90), (Kp2=10, Kd2=0.03 and Ki2=100) and (Kp3=6.5, Kd3=0.4 and Ki3=30).

4.5 Point to point positioning test

From the Figure 4.34 to Figure 4.42, the output response of displacement shows different output performance at different amplitude of inputs and set of PID gains. There are 3 set of PID gains that tuned for each of inputs' amplitude. The Table 4.8 shows the positioning output response of 3 set of PID gain at different amplitude of inputs. The positioning output response of PID controller clearly show that the PID controller is only able to generate better positioning output response at certain amplitude of inputs with certain set of PID gains. Therefore point to point positioning, PID controller is able to generate better performance but less adaptability.

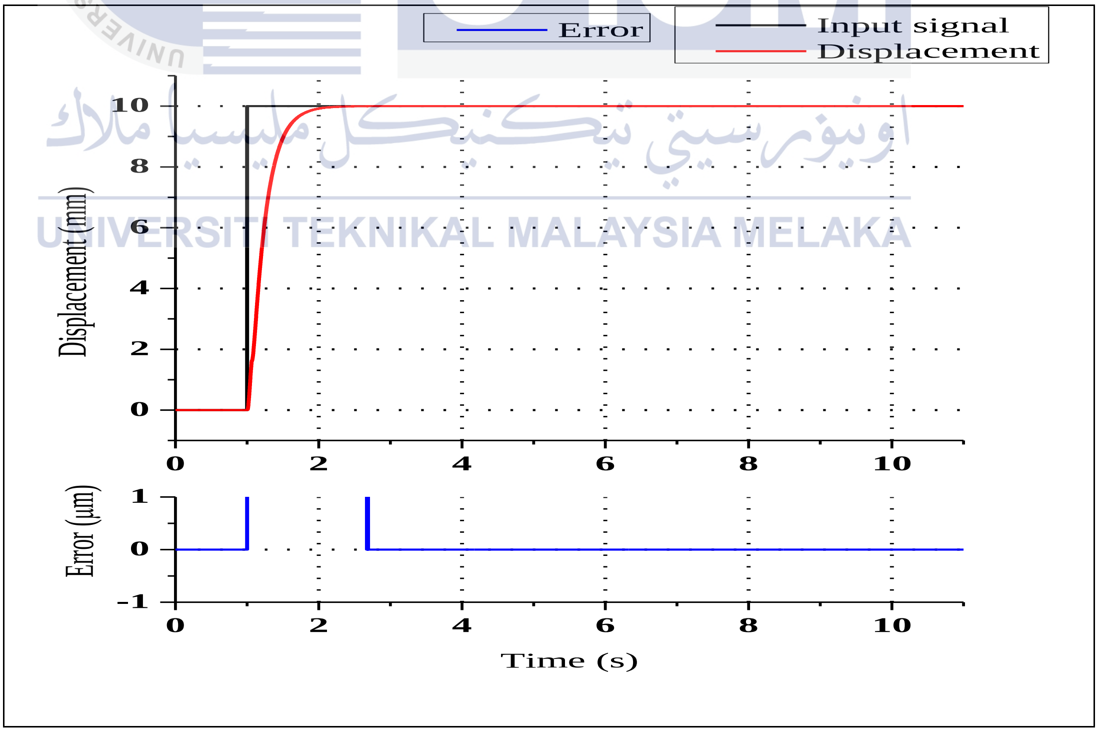


Figure 4.34: The displacement and error output response for system with PID controller at step input of amplitude 10 when (Kp1=20, Kd1=0.4 and Ki1=90).

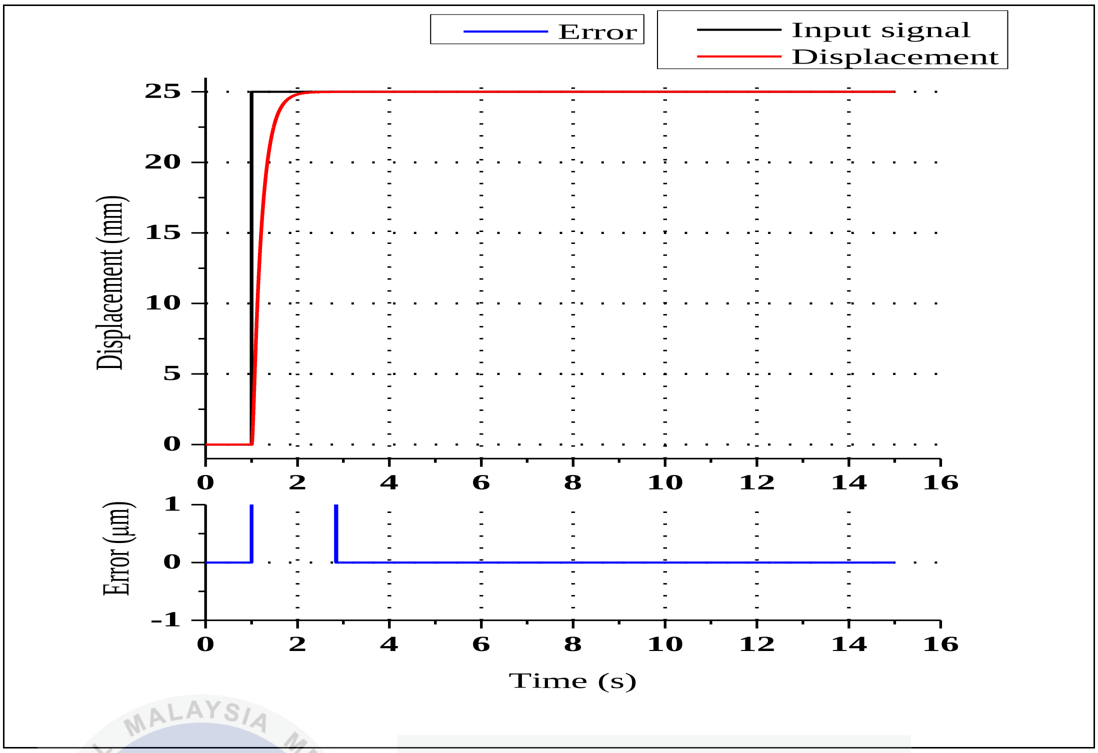


Figure 4.35: The displacement and error output response for system with PID controller at step input of amplitude 25 when (Kp1=20, Kd1=0.4 and Ki1=90).

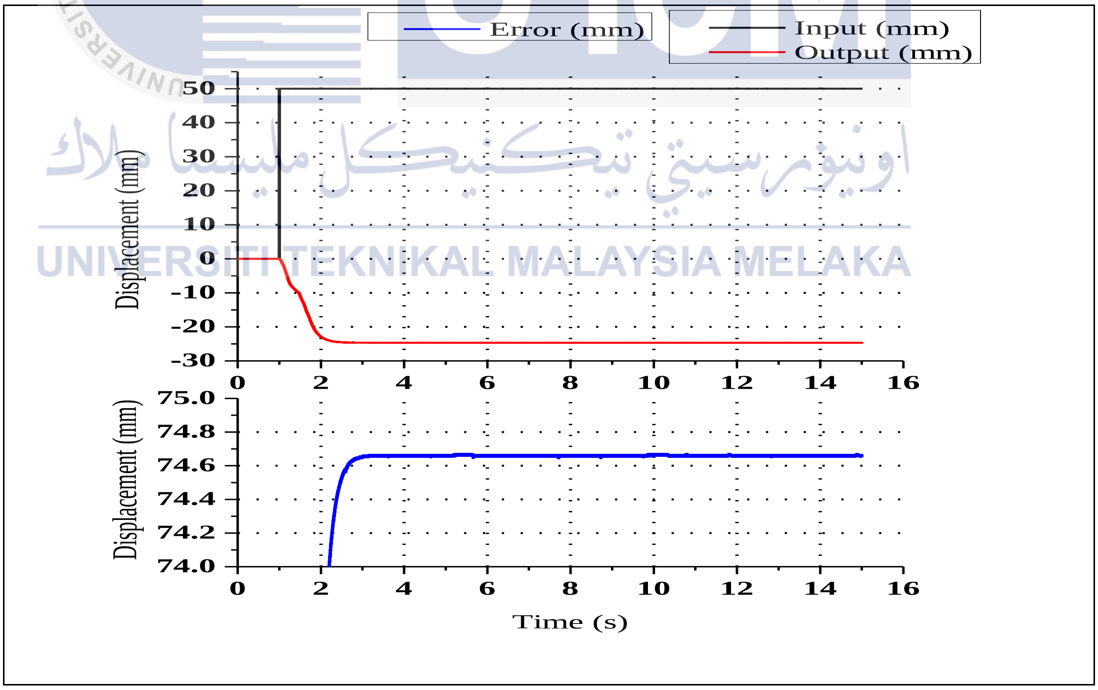


Figure 4.36: The displacement and error output response for system with PID controller at step input of amplitude 50 when (Kp1=20, Kd1=0.4 and Ki1=90).

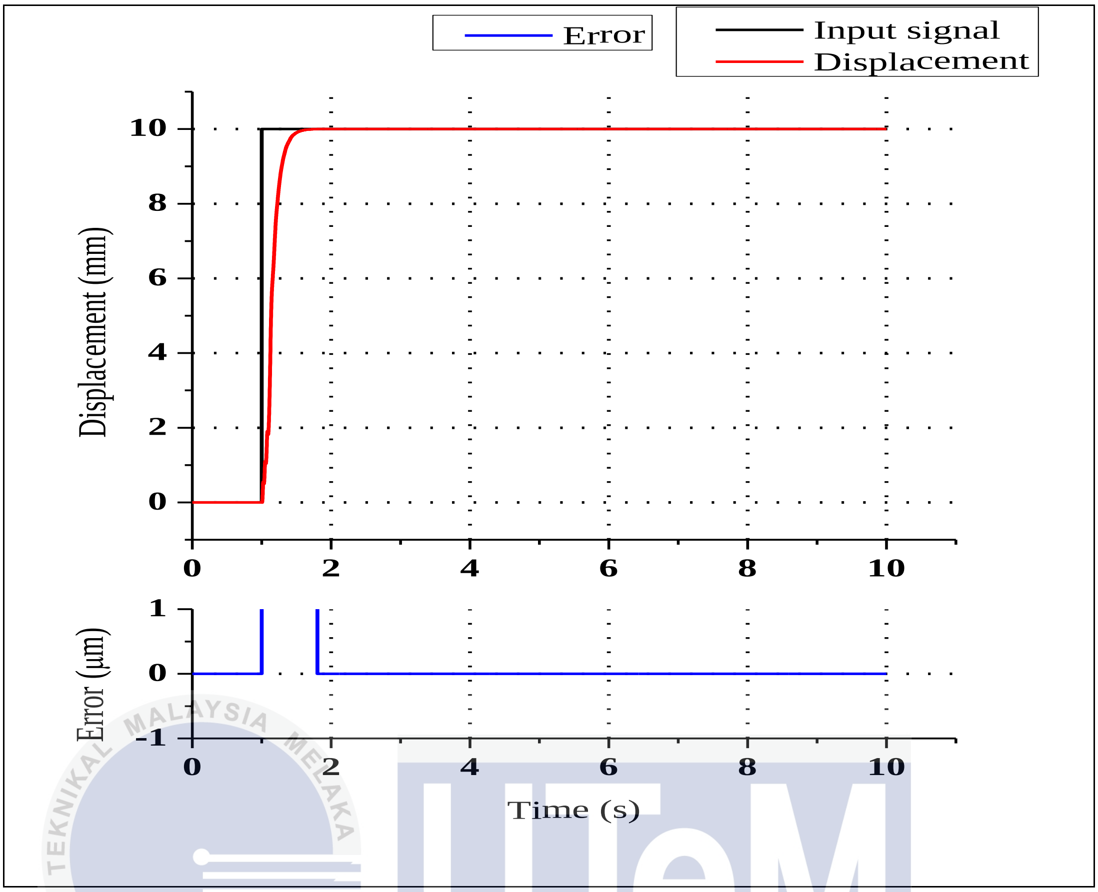


Figure 4.37: The displacement and error output response for system with PID controller at step input of amplitude 10 when (Kp2=10, Kd2=0.03 and Ki2=100).

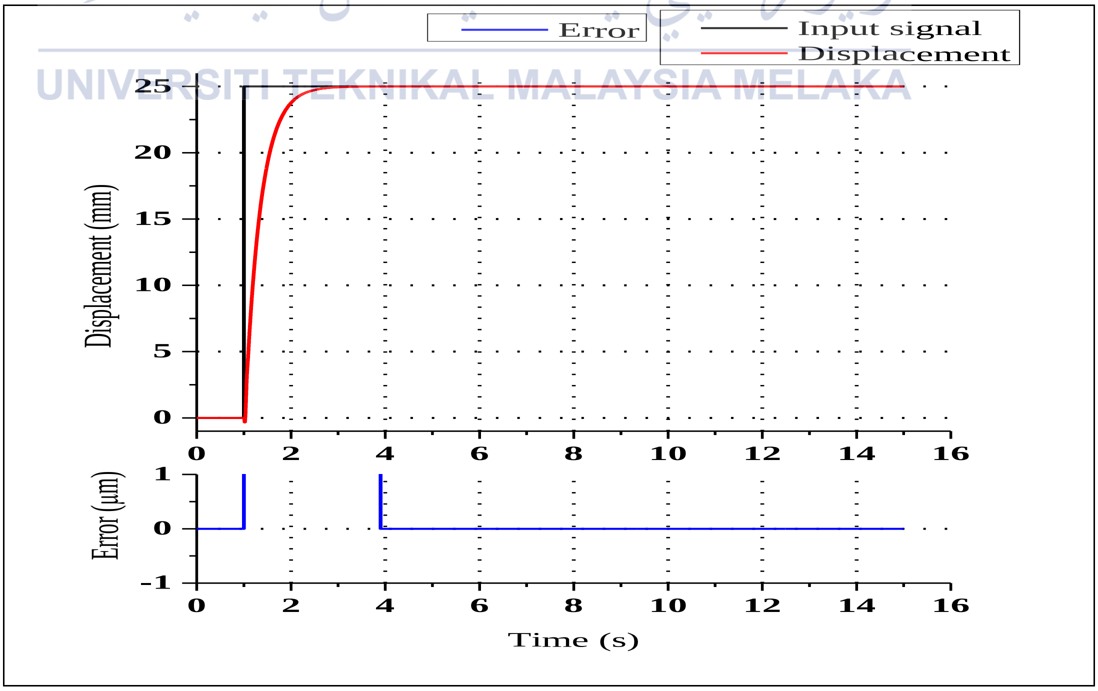


Figure 4.38: The displacement and error output response for system with PID controller at step input of amplitude 25 when (Kp2=10, Kd2=0.03 and Ki2=100).

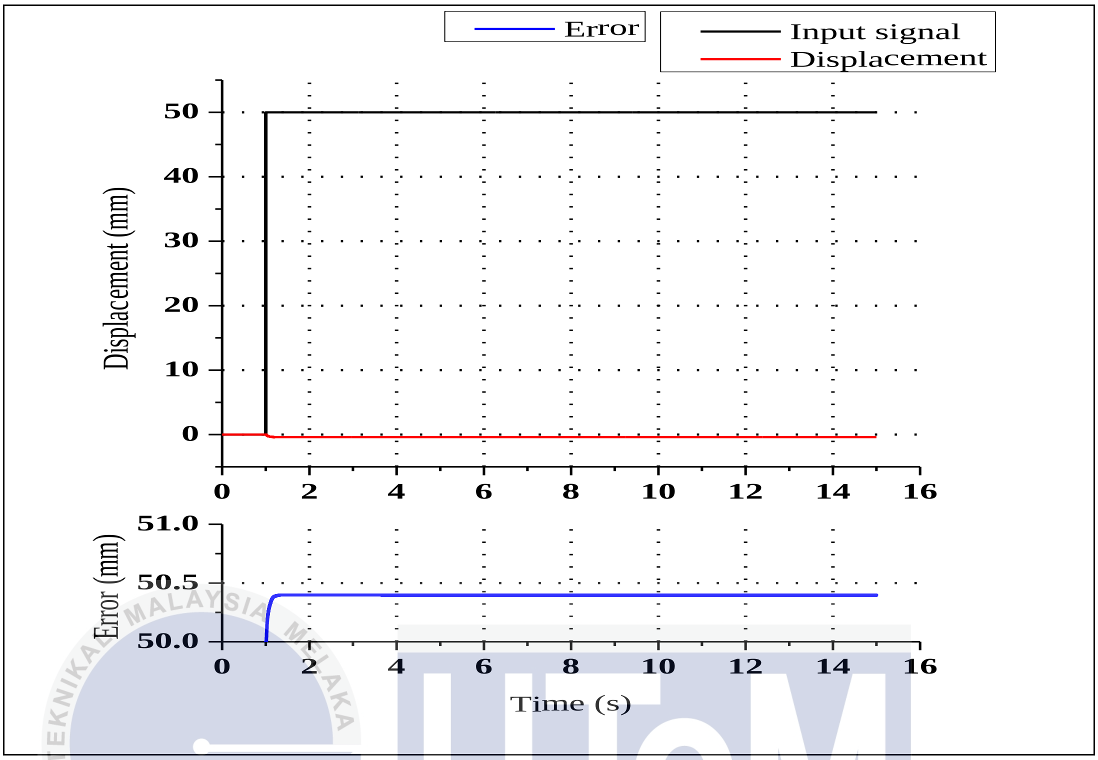


Figure 4.39: The displacement and error output response for system with PID controller at step input of amplitude 50 when (Kp2=10, Kd2=0.03 and Ki2=100).

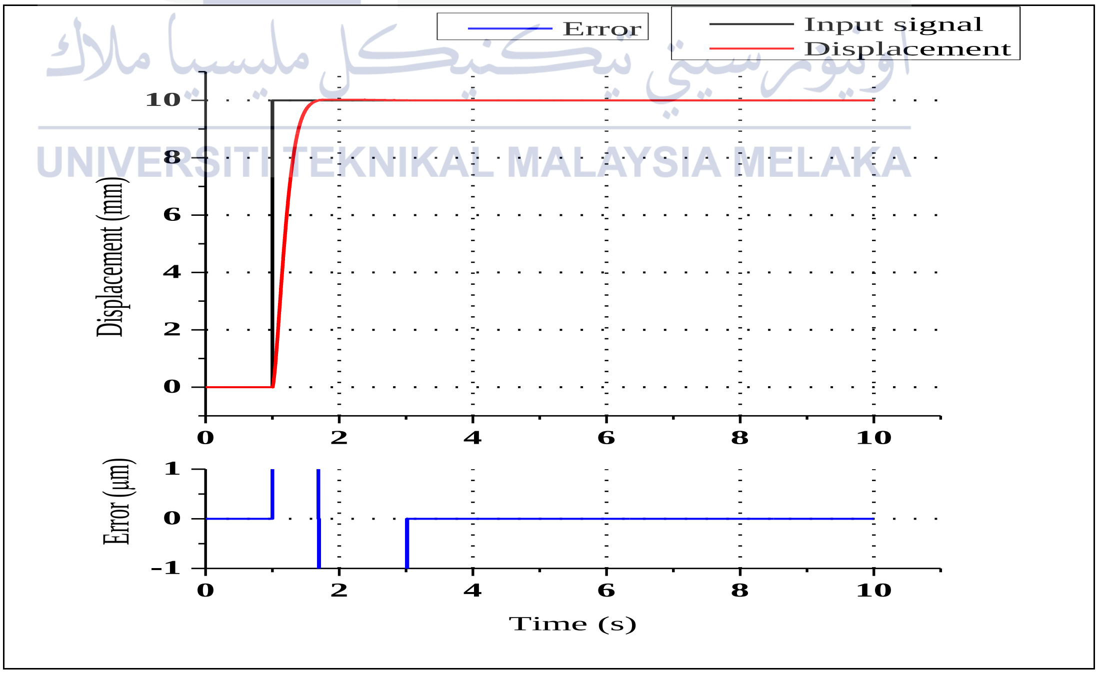


Figure 4.40: The displacement and error output response for system with PID controller at step input of amplitude 10 when (Kp3=6.5, Kd3=0.4 and Ki3=30).

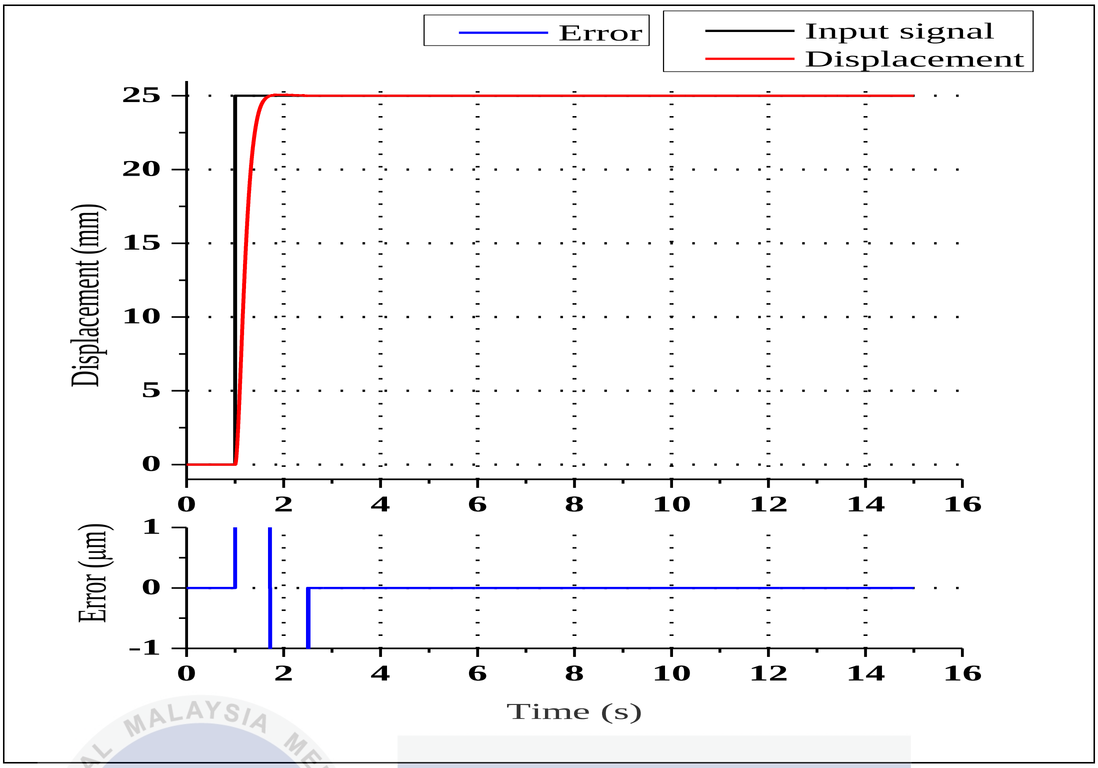


Figure 4.41: The displacement and error output response for system with PID controller at step input of amplitude 25 when (Kp3=6.5, Kd3=0.4 and Ki3=30).

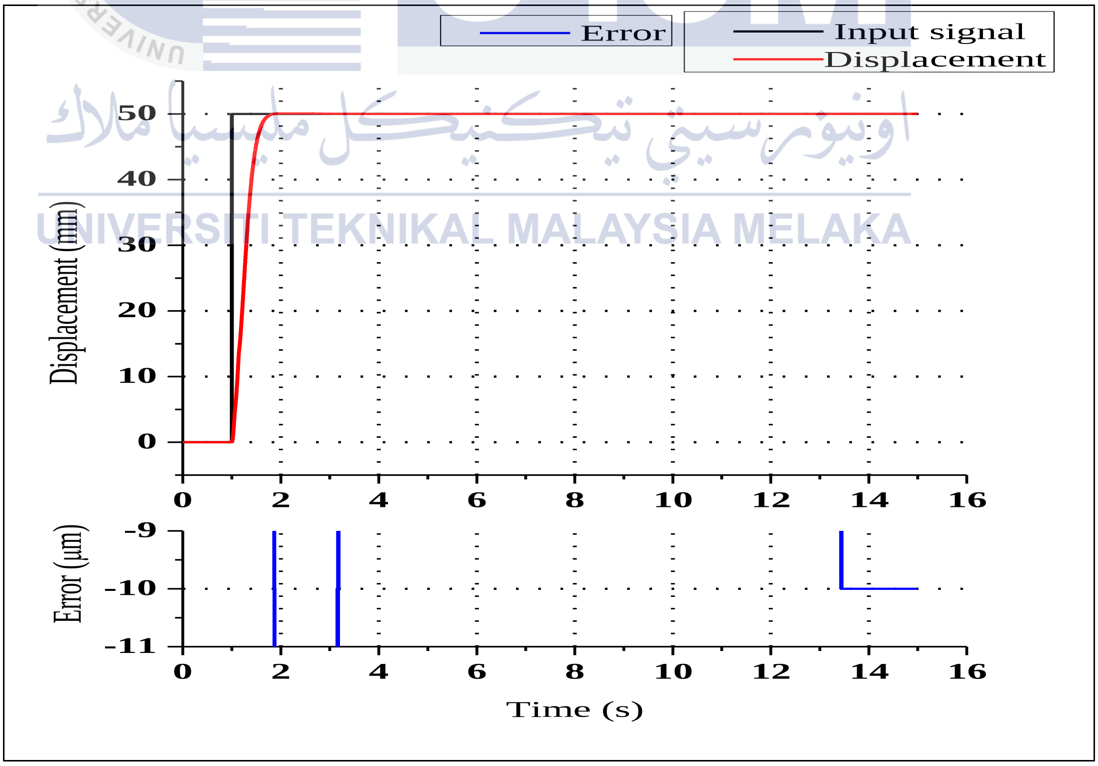


Figure 4.42: The displacement and error output response for system with PID controller at step input of amplitude 50 when (Kp3=6.5, Kd3=0.4 and Ki3=30).

Table 4.8: Output performances at different amplitude of input and PID gains for system with PID controller.

PID gains	Performance	Amplitude of step inputs		
		10	25	50
B	Error, (mm)	0	0	5.0395×10
	Overshoot, (%)	0	0	0
	Settling time, (s)	1.433	2.291	0
	Rise time, (s)	2.42×10^{-1}	7.201×10^{-1}	0
C	Error, (mm)	0	0	7.4665×10
	Overshoot, (%)	0	0	0
	Settling time, (s)	1.824	1.799	0
	Rise time, (s)	4.639×10^{-1}	4.378×10^{-1}	0
D	Error, (mm)	0	0	1×10^{-2}
	Overshoot, (%)	2.5×10^{-1}	2.6×10^{-1}	1.1×10^{-1}
	Settling time, (s)	1.54	1.558	1.6555
	Rise time, (s)	3.392×10^{-1}	3.432×10^{-1}	4.256×10^{-1}

Lets B= (Kp1=10, Kd1=0.03 and Ki1=100), C= (Kp2=20, Kd2=0.4 and Ki2=90), D=(Kp3=6.5, Kd3=0.4 and Ki3=30).

Based on the Table 4.9, the output performance is a bit lower for fuzzy PID controller compare with PID controller. The settling time and rise time is more significantly telling that the performance to reach in steady state condition is quite slow if compare to PID controller as shown in Figure 4.3 to Figure 4.5.

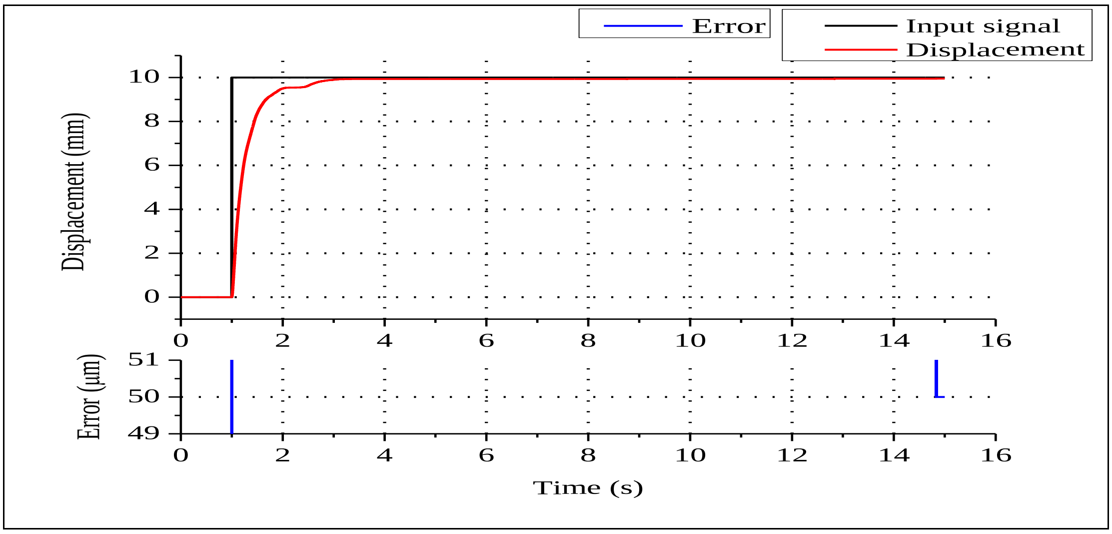


Figure 4.43: The displacement and error output response for system with fuzzy PID controller at step input of amplitude 10 when (Kp=25, Kd=2.6 and Ki =13.5).

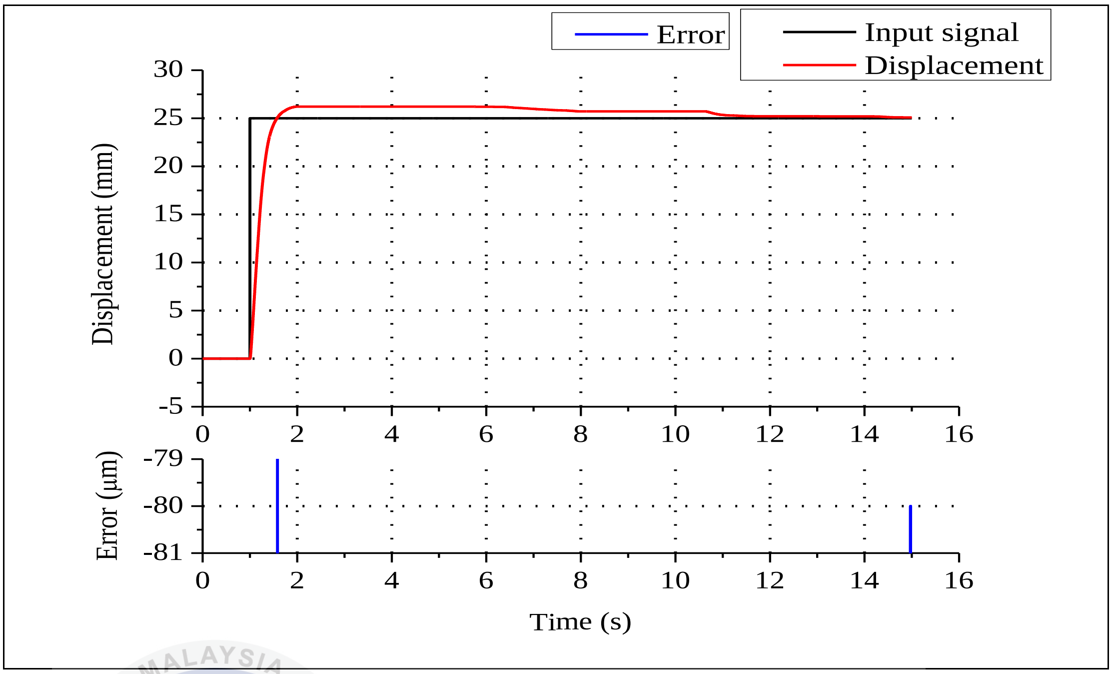


Figure 4.44: The displacement and error output response for system with fuzzy PID controller at step input of amplitude 25 when (Kp=25, Kd=2.6 and Ki =13.5).

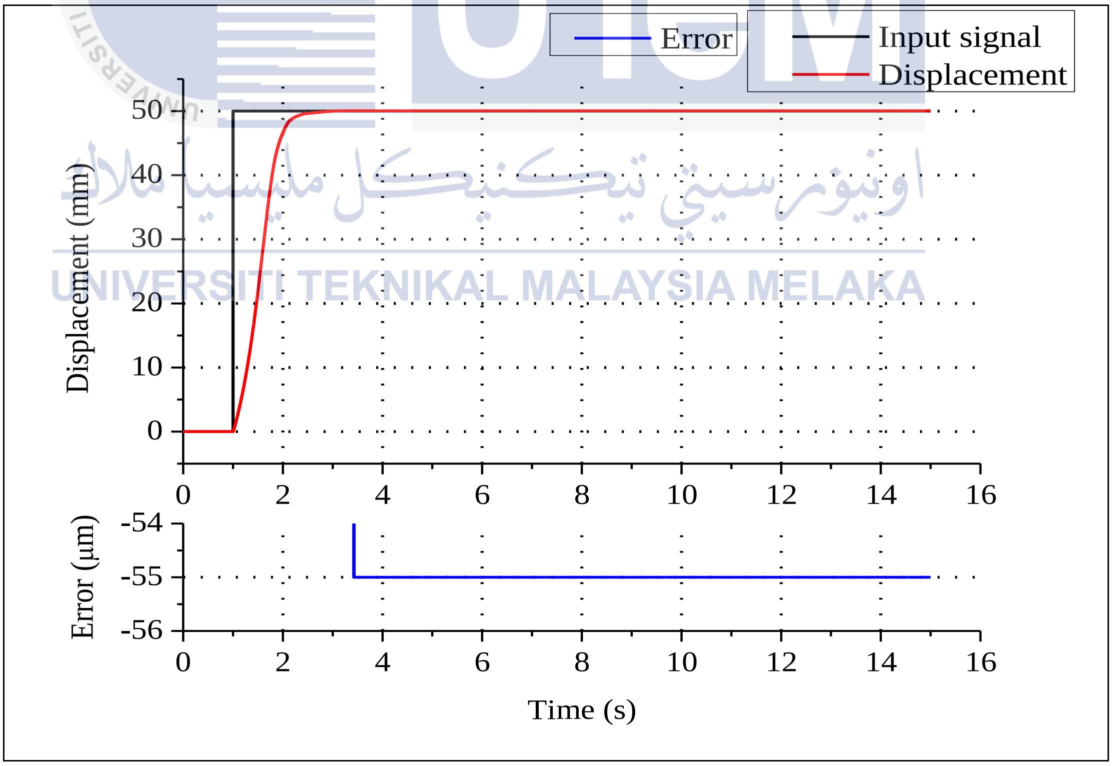


Figure 4.45: The displacement and error output response for system with fuzzy PID controller at step input of amplitude 50 when (Kp=25, Kd=2.6 and Ki =13.5).

Table 4.9: Output performances at different amplitude of input with PID gains factor for system with fuzzy PID controller.

Fuzzy PID gain factors	Performances	Amplitude of step inputs		
		10	25	50
A	Error, (mm)	5×10^{-2}	4×10^{-2}	5.5×10^{-2}
	Overshoot, (%)	0	5.18	0
	Settling time, (s)	2.632	1.523	2.2418
	Rise time, (s)	6.16×10^{-1}	3.507×10^{-1}	7.614×10^{-1}

Let A= (Kp=25, Kd=2.6 and Ki =13.5).

4.6 Load weight variation test

From the Table 4.10, the performance of PID controller under variation of weight with step input of 50 is much better than the performance of fuzzy PID controller. The steady state error, rise time and settling of PID controller is less than the fuzzy PID controller, but fuzzy PID controller shows zero overshoot compare to the overshoot of PID controller. The increase of weight from 1000g to 3000g in both PID controller and fuzzy PID controller do not shows much effect on the controller performances as shown in Figure 4.46 to Figure 4.51. The results of steady state error and transient response show inconsistent change in both PID controller and fuzzy PID controller rather that decrease in performances.

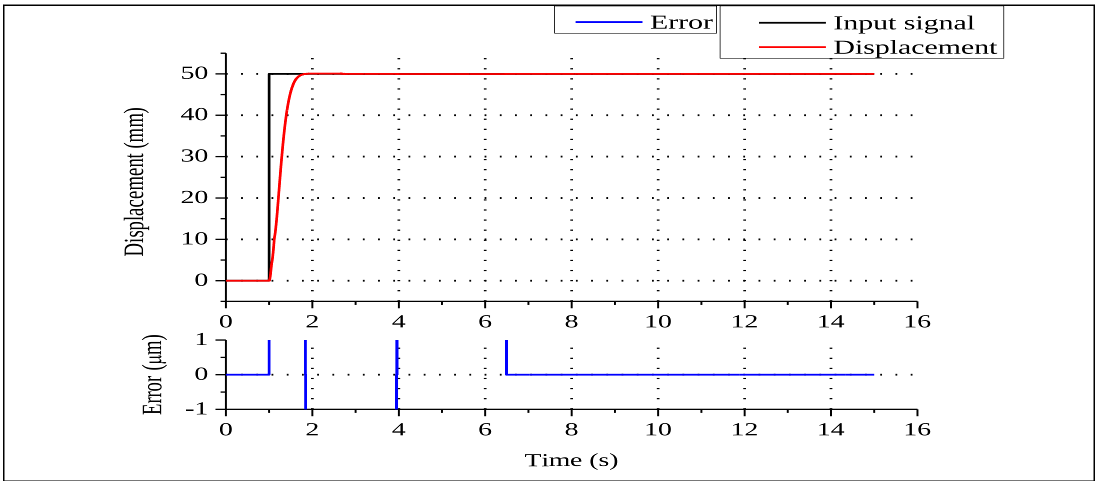


Figure 4.46: The displacement and error output response for system with PID controller at step input of amplitude 50 when the weight of load is increase to 1000g.

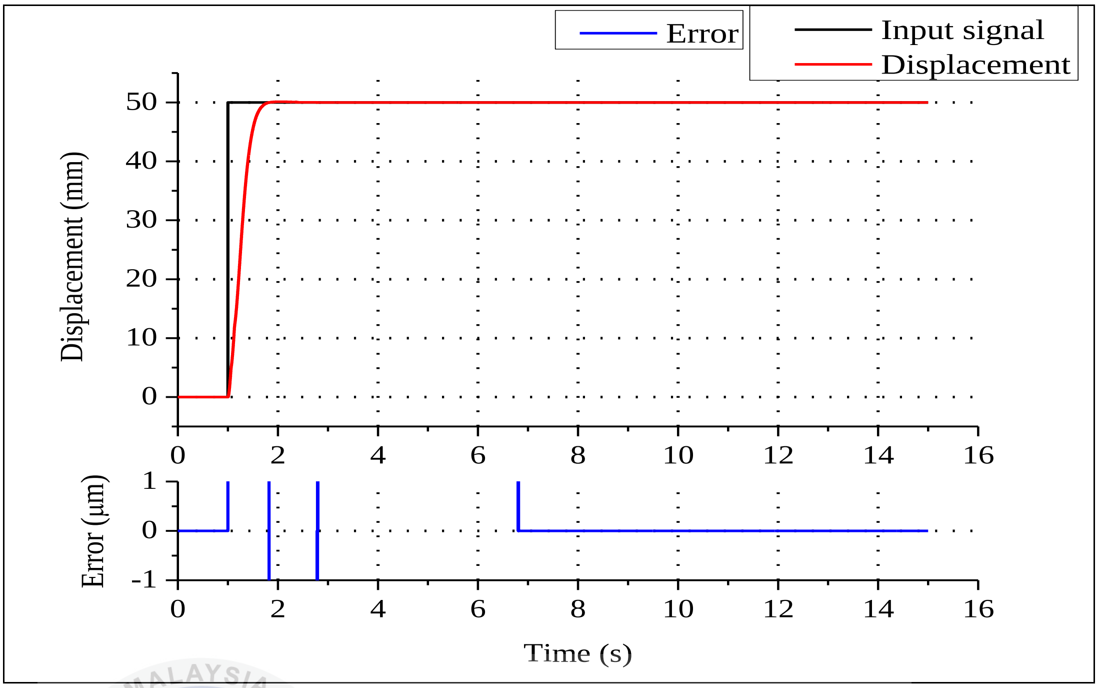


Figure 4.47: The displacement and error output response for system with PID controller at step input of amplitude 50 when the weight of load is increase to 2000g.

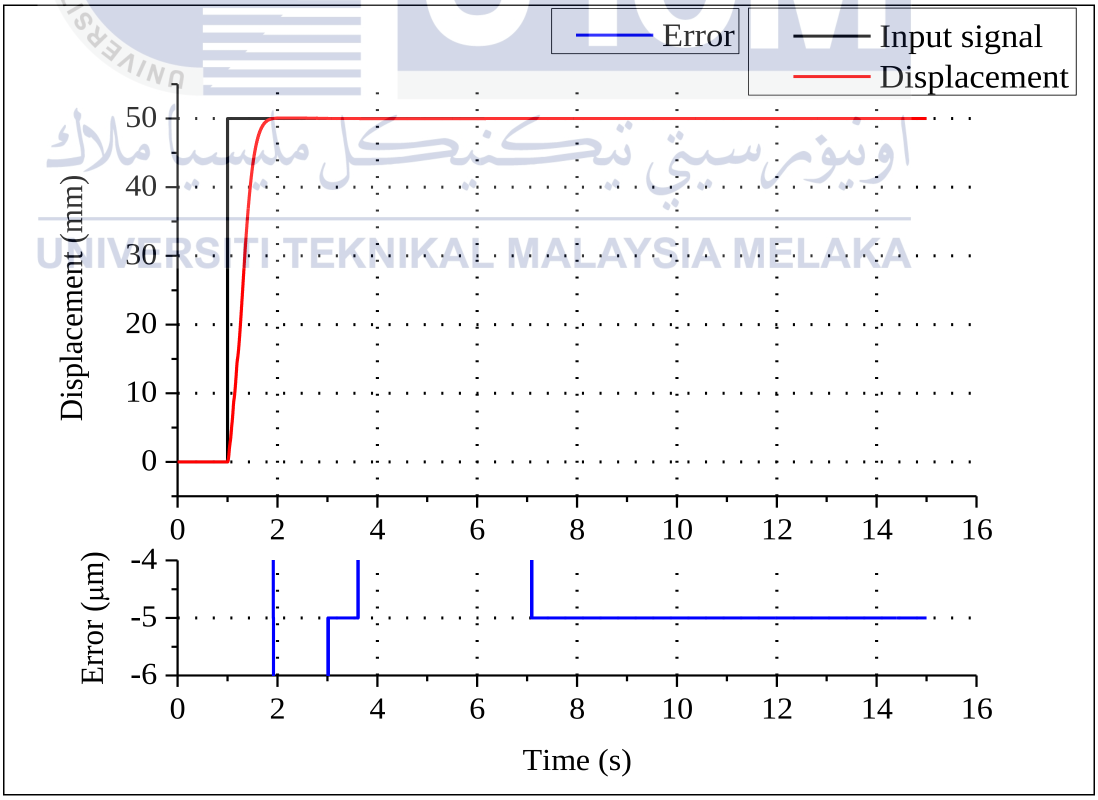


Figure 4.48: The displacement and error output response for system with PID controller at step input of amplitude 50 when the weight of load is increase to 3000g.

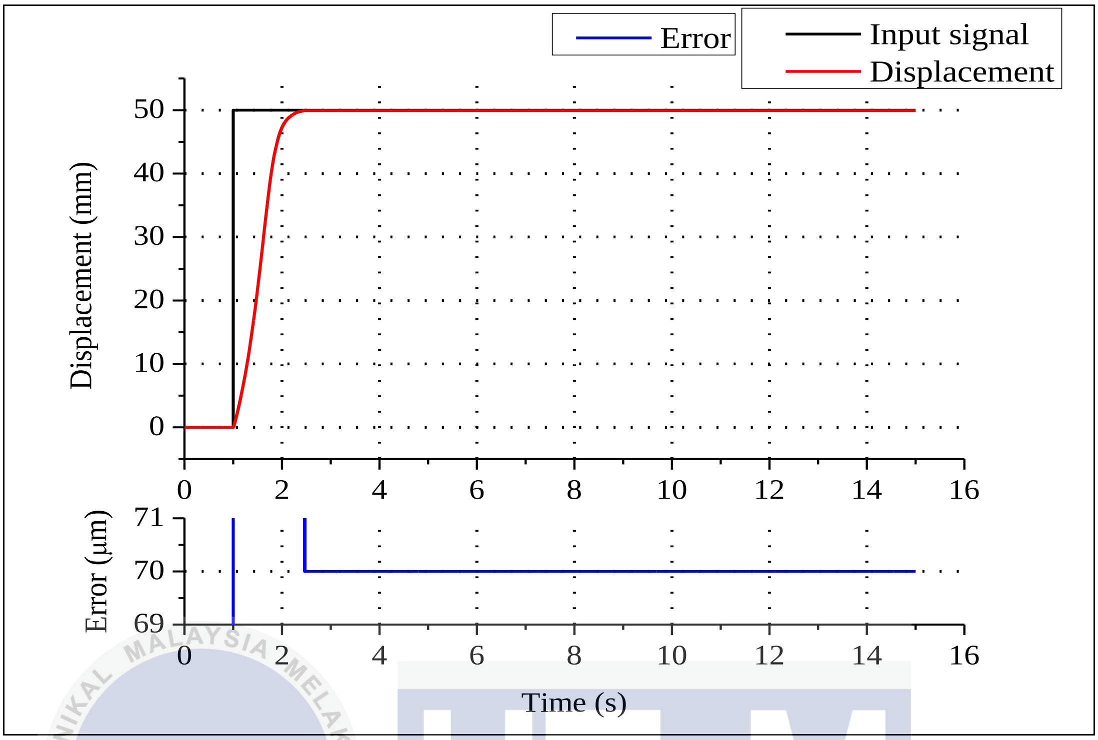


Figure 4.49: The displacement and error output response for system with Fuzzy PID controller at step input of amplitude 50 when the weight of load is increase to 1000g.

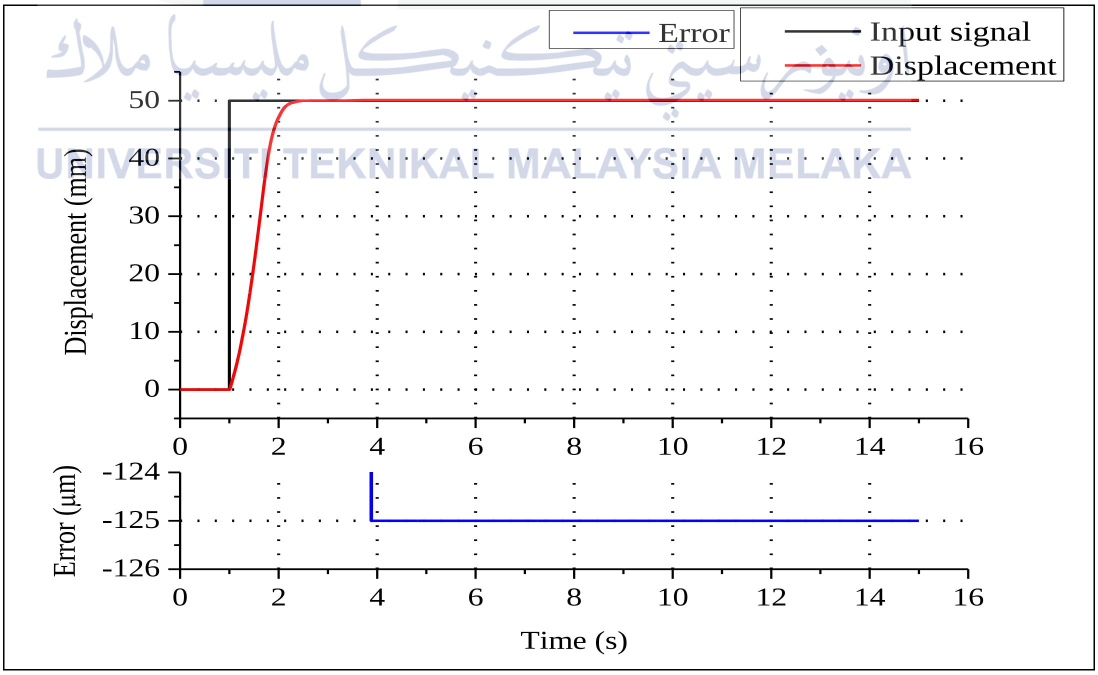


Figure 4.50: The displacement and error output response for system with Fuzzy PID controller at step input of amplitude 50 when the weight of load is increase to 2000g.

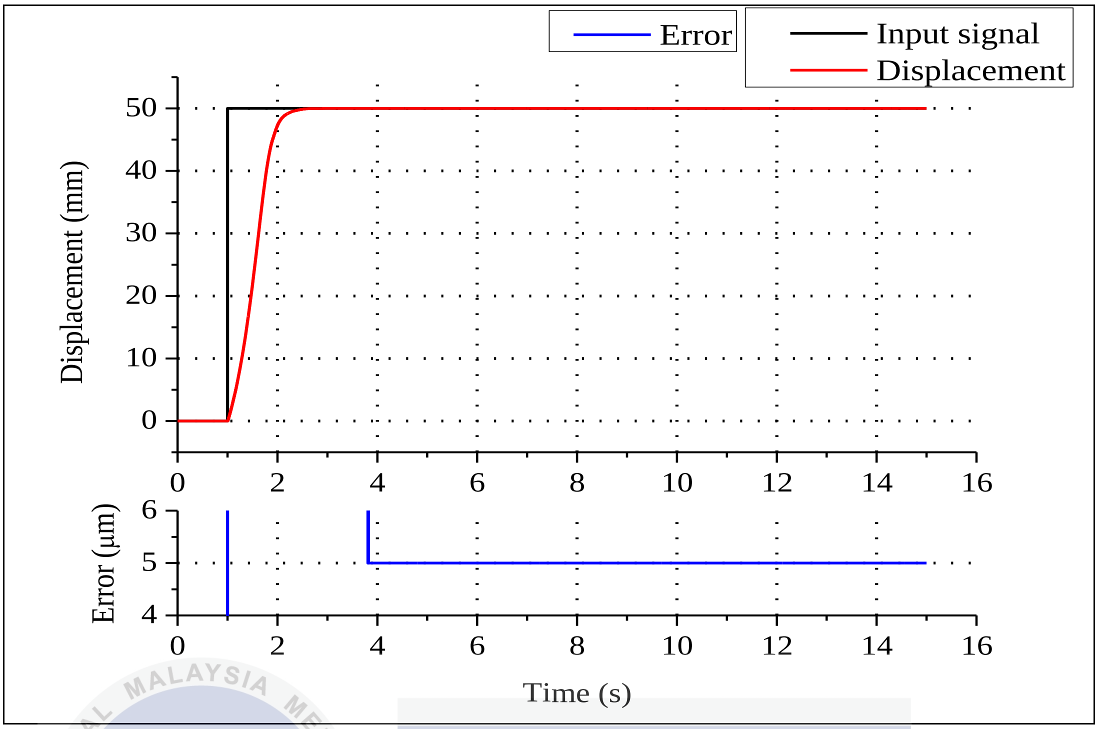


Figure 4.51: The displacement and error output response for system with Fuzzy PID controller at step input of amplitude 50 when the weight of load is increase to 3000g.

Table 4.10: The displacement output response when the step input is at amplitude of 50.

Controllers	Performances	Load weight		
		1000g	2000g	3000g
Fuzzy PID controller at gains of set A	Error, (mm)	7.5×10^{-2}	1.25×10^{-1}	5×10^{-3}
	Overshoot, (%)	0	0	0
	Settling time, (s)	2.1957	2.156	2.166
	Rise time, (s)	7.481×10^{-1}	7.432×10^{-1}	7.376×10^{-1}
PID controller at gains of set D	Error, (mm)	0	0	5×10^{-3}
	Overshoot, (%)	1.6×10^{-1}	2.4×10^{-1}	1.2×10^{-1}
	Settling time,(s)	1.644	1.651	1.708
	Rise time, (s)	4.109×10^{-1}	4.223×10^{-1}	4.605×10^{-1}

Lets A= (Kp=25, Kd=2.6 and Ki =13.5), D=(Kp3=6.5, Kd3=0.4 and Ki3=30).

The error occur in PID controller is much higher due the friction occur in the ball screw system itself when the ball screw in moving in higher speed as shown in Figure 4.52 to Figure 4.54. For the fuzzy PID controller, the lagging or delay occur when start to move as shown in Figure 4.55 to Figure 4.57. Based on the Table 4.11, the results show the maximum peak error when different weight of load when input sine wave was used. By doing the repeatability for 10 times, the results of average errors and standard deviation shows in Table 4.12. In Table 4.12, the average of error of Fuzzy PID controller is almost the same at different of load weight but bigger change of average of error when PID controller is used. By comparing the standard deviation between fuzzy PID controller and PID controller, the values is in fuzzy PID controller in lower than the PID controller. Therefore, the fuzzy PID controller shows higher adaptability compare to PID controller since change in displacement output response is very small when fuzzy PID controller is used.

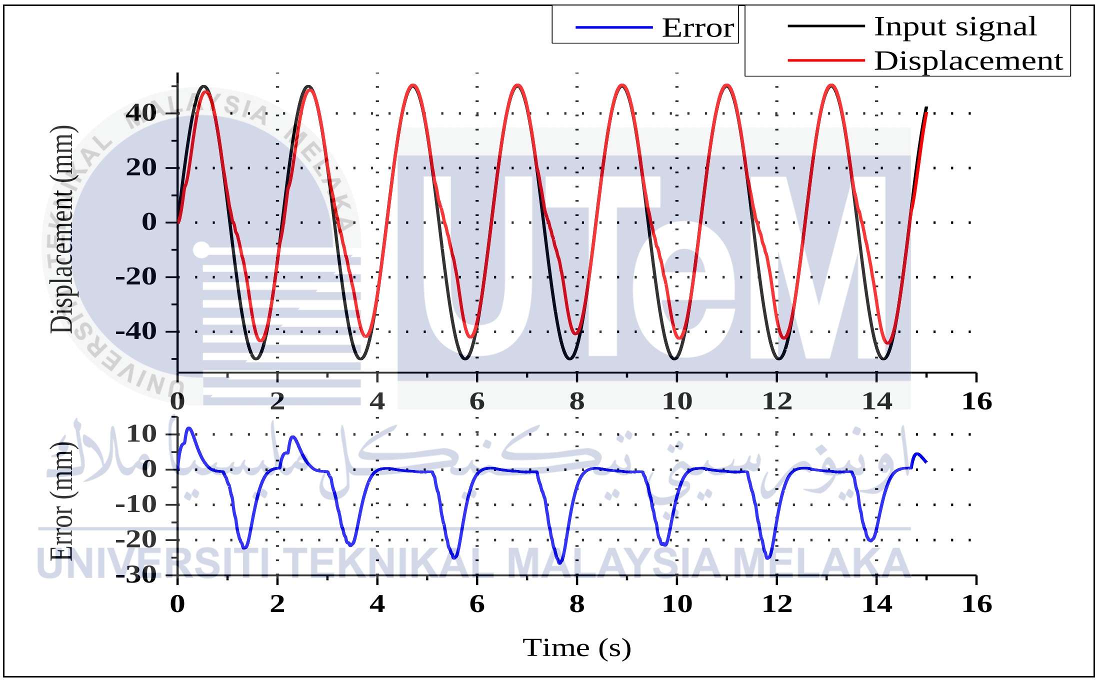


Figure 4.52: The displacement and error output response for system with PID controller at sine wave input of amplitude 50 when the weight of load is increase to 1000g.

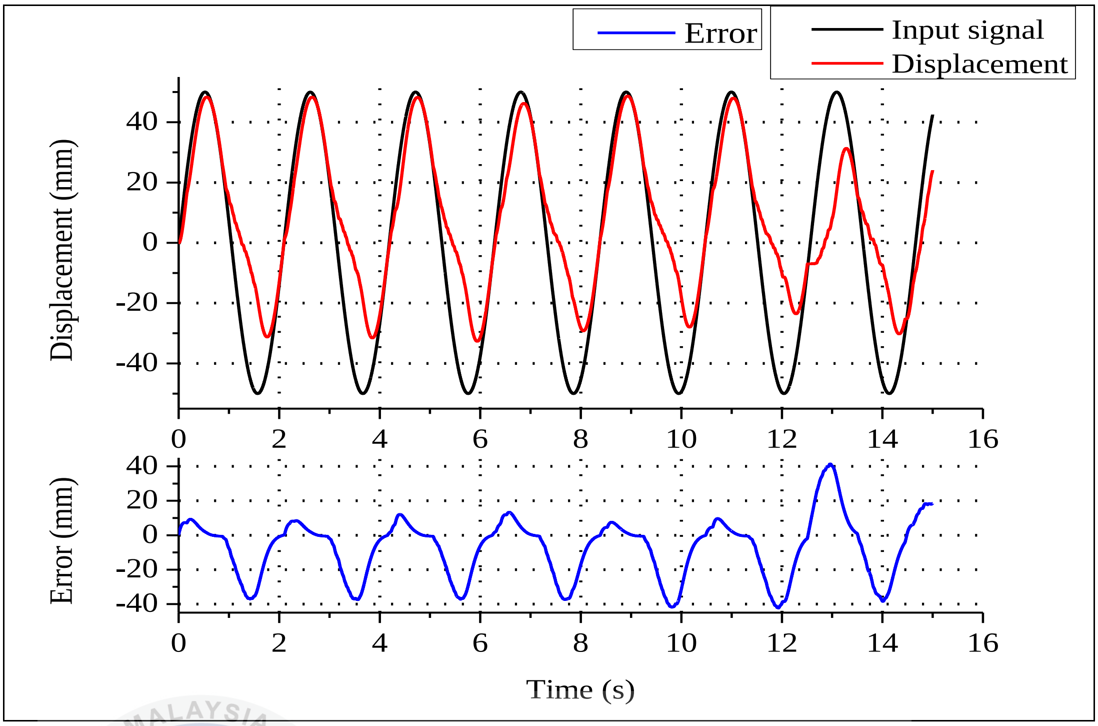


Figure 4.53: The displacement and error output response for system with PID controller at sine wave input of amplitude 50 when the weight of load is increase to 2000g.

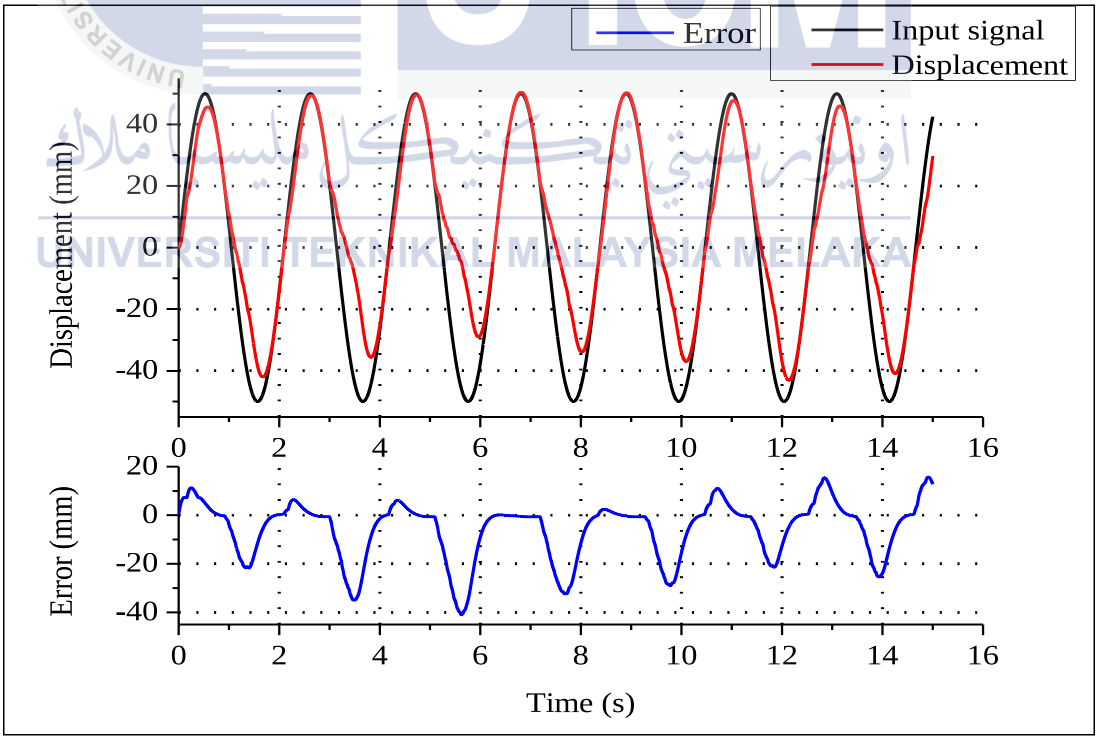


Figure 4.54: The displacement and error output response for system with PID controller at sine wave input of amplitude 50 when the weight of load is increase to 3000g.

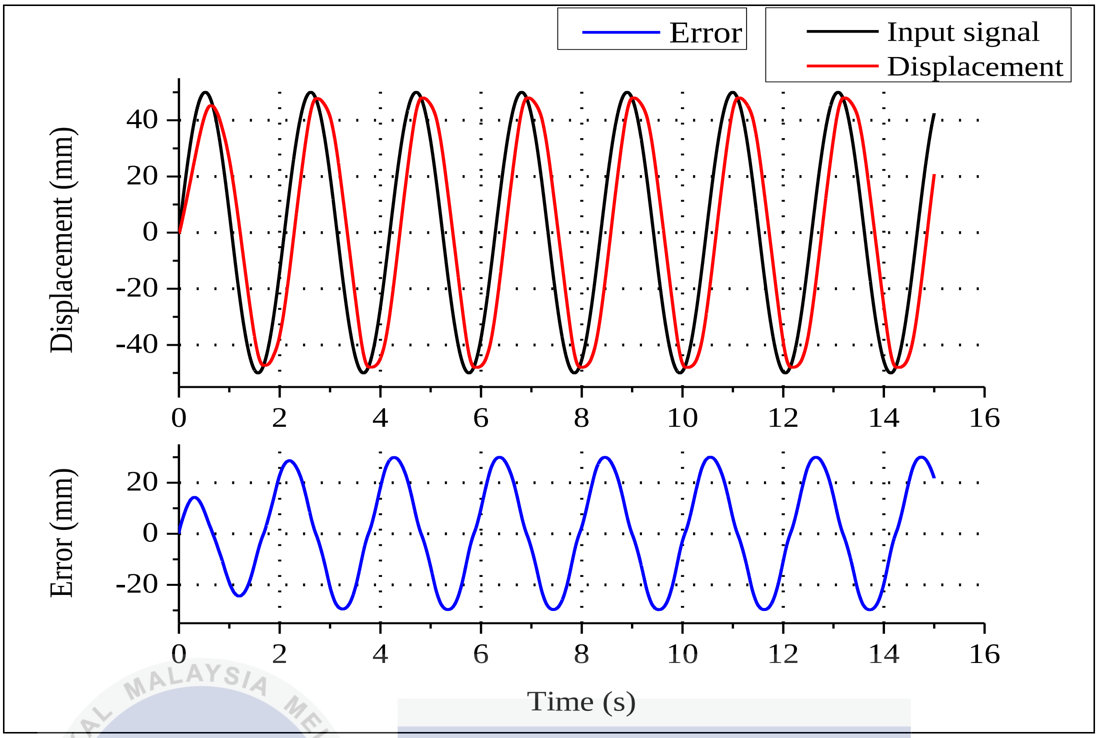


Figure 4.55: The displacement and error output response for system with Fuzzy PID controller at sine wave input of amplitude 50 when the weight of load is increase to 1000g.

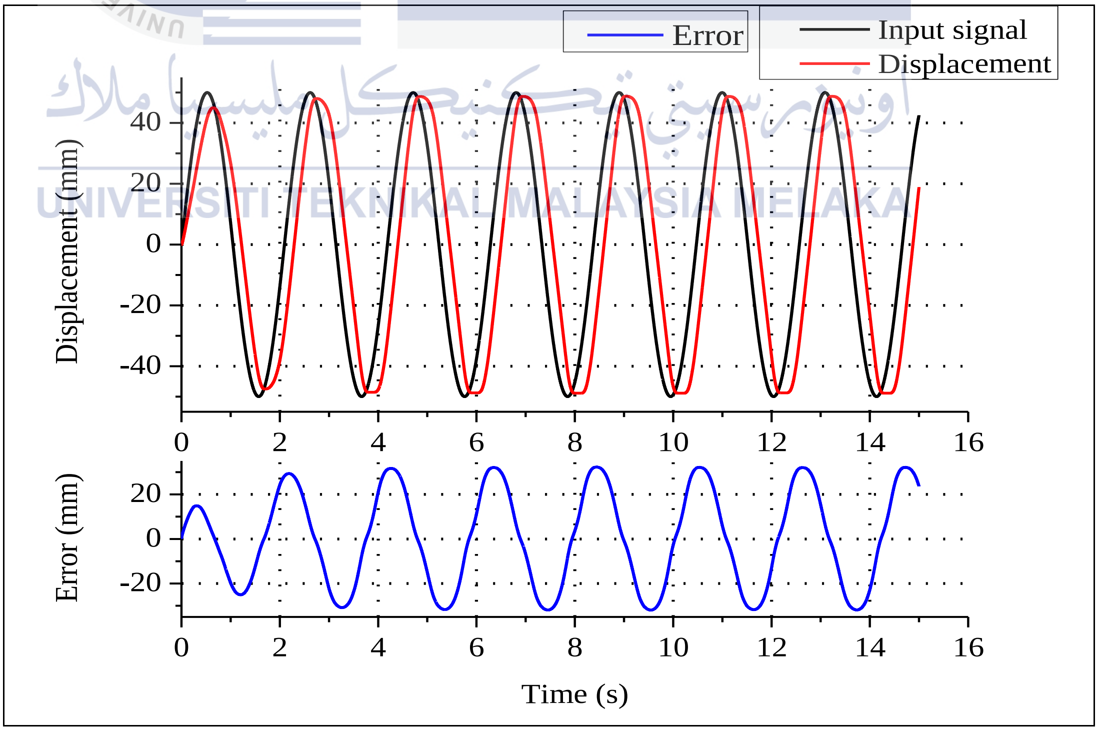


Figure 4.56: The displacement and error output response for system with Fuzzy PID controller at sine wave input of amplitude 50 when the weight of load is increase to 2000g.

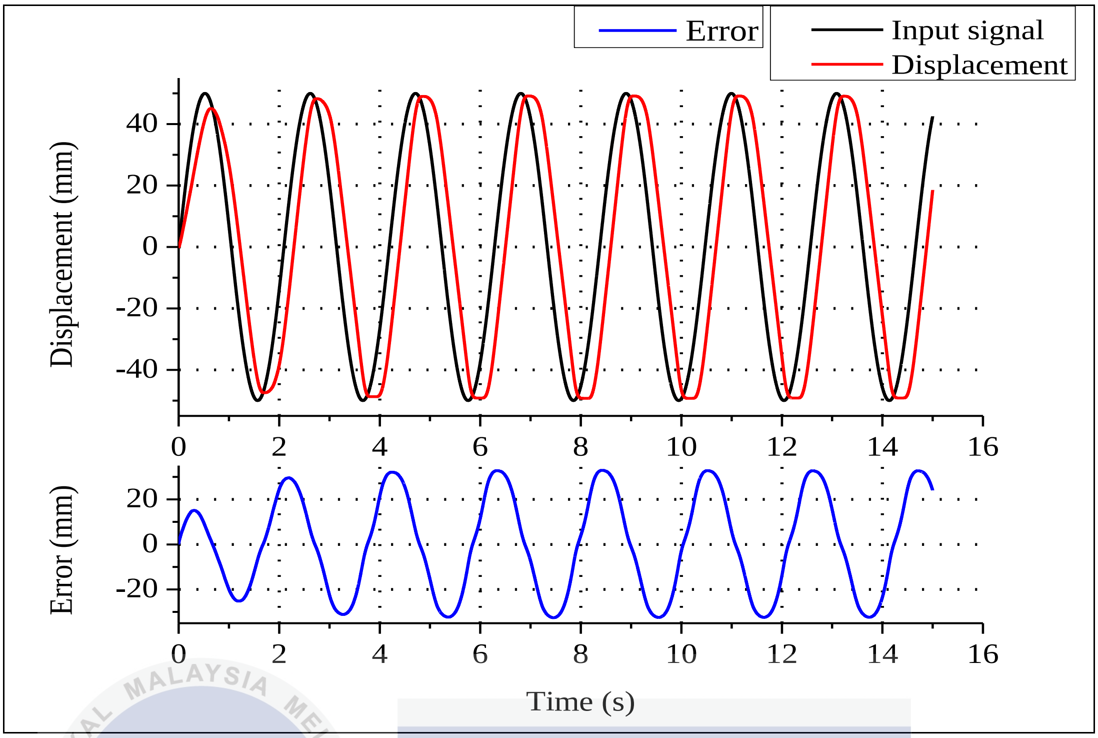


Figure 4.57: The displacement and error output response for system with Fuzzy PID controller at sine wave input of amplitude 50 when the weight of load is increase to 3000g.

Table 4.11: The displacement output response when the sine wave input at amplitude of 50 and frequency of 3 rad/s.

Load weight	Fuzzy PID controller	PID controller
	Maximum peak error, (mm)	Maximum peak error, (mm)
1000g	3.00113×10	2.66276×10
2000g	3.22545×10	4.23058×10
3000g	3.29224×10	4.2589×10

Table 4.12: The average error and standard deviation of 10 repeatability of variation of load weight in tracking experiment.

Load weight	Fuzzy PID controller		PID controller	
	Average of error, (mm)	Standard deviation	Average of error, (mm)	Standard deviation
1000g	3.08298×10	4.021×10^{-1}	2.91522×10	5.5707
2000g	3.29279×10	3.906×10^{-1}	4.11514×10	3.3077
3000g	3.28707×10	3.274×10^{-1}	4.26473×10	9.7404

CHAPTER 5

CONCLUSION AND RECOMMENDATION

As a conclusion, after the experiment was done by compare the PID controller with fuzzy PID controller under variation of load weight and point to point positioning experiments, the proposed controller shown following characteristic:

a. Fuzzy PID controller capable to operate in different input values, compare to PID controller. PID controller need to readjust the PID gains so that the system in operate in stability range compare to fuzzy PID controller which has larger stability range. Therefore, fuzzy PID controller higher adaptability in different amplitude of inputs compare to PID controller.

b. The performance of fuzzy PID controller is lower than PID controller, since the results obtain from the experiment shows that the fuzzy PID controller is taking longer time to reach steady state condition. Besides that, the error of fuzzy PID controller is higher than the PID controller due less precise of fuzzy logic controller itself. Therefore, the fuzzy PID controller is operate in smooth and slow to reach the set point, whereas the PID controller is operate in very fast, lower error and very unstable.

c. The experiment of the variation of load weight shows the fuzzy PID controller capable to maintain the positioning output response at different load weight values compare to PID controller which shows higher change in average error and higher standard deviation.

Therefore, fuzzy PID controller has high adaptability to the variation of input value and weight of load. In this project, the fuzzy PID controller is only test with variation of load mass in point to point and tracking experiments and point to point positioning experiment. Therefore the output response of positioning still may unable to compensate completely the position error that cause by the present on mechanical flexibility together with friction of ball screw mechanism or lacks of complete theory in designing the fuzzy PID controller. It is recommended adding some advance method of Kalman filter and Bee Colony Optimization to optimize the fuzzy logic control in order to obtain higher transient performance and adaptability of ball screw system.

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APPENDIX

Experiment 1: Setup the experimental hardware

i. Design the plant model using Solidwork software as shown in Figure 3.3

ii. Set up the hardware by following the dimension of designed plant model.

iii. Connect the DC motor, linear encoder and limit switch to the Microbox as shown in Figure A1.

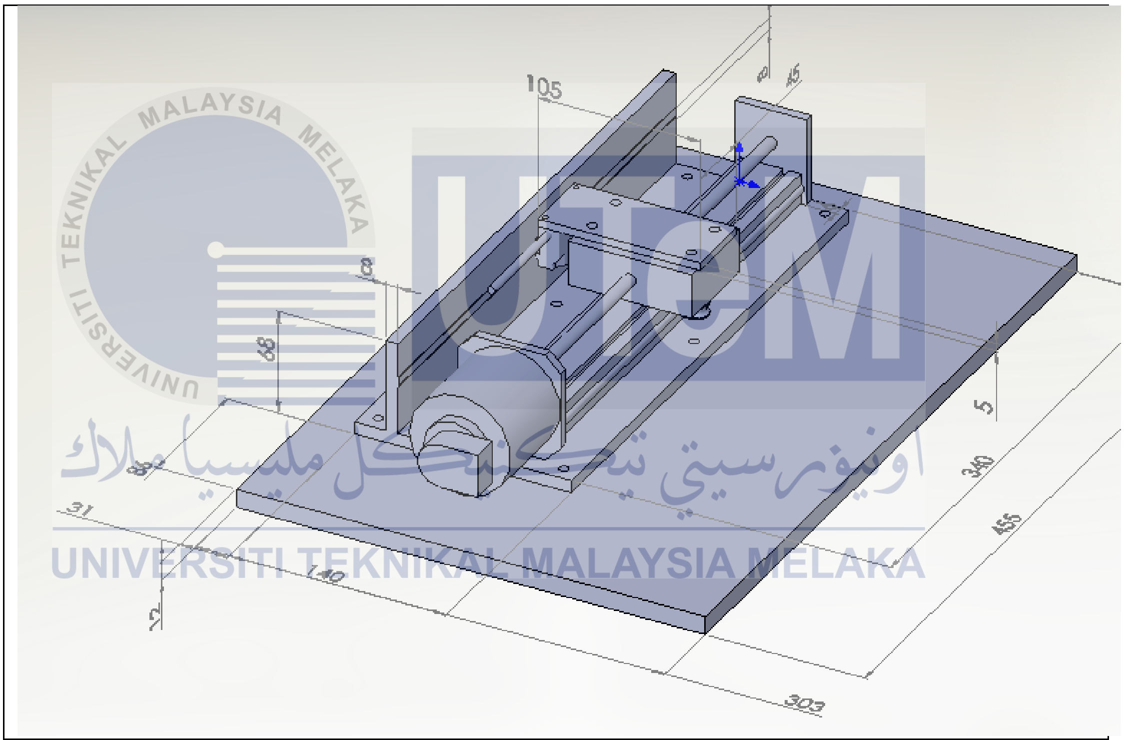

Figure A1: Ball screw system model.

Experiment 2: Data acquisition.

i. Design the open loop system as shown in Figure A2.

ii. Set input pulse generator as below:

a. Amplitude = 2, 3, 4 and 5

b. Period = 2s

c. Pulse width = 50%

d. Phase delay = 1s

e. Time = 2s

iii. Run the experiment and record the number of pulse and distance travel by table load.

iv. Repeat the experiment 5 times at different amplitude of input pulse generator.

v. Calculate the displacement to pulse ratio and descried the changes of every increment of input amplitude.

vi. Design a gain to convert the pulse number into displacement.

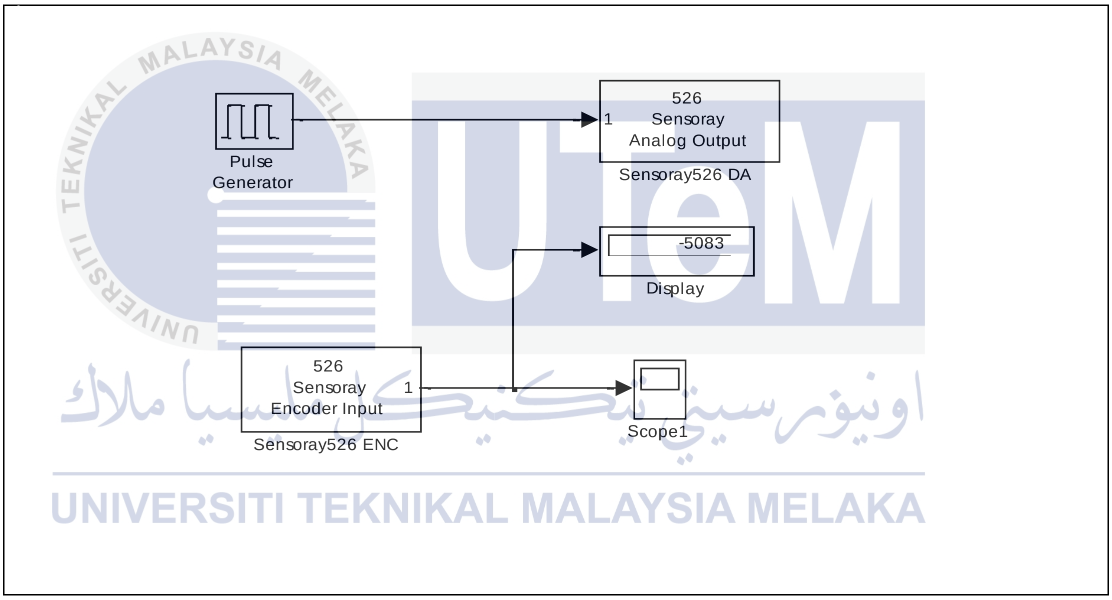

Figure A2: Data acquisition from the experimental open loop.

Experiment 3: Open loop test

i. Design the open loop system with the gain from previous experiment as shown in Figure A3.

ii. Set the input pulse generator as below:

a. Amplitude = 2, 2.5, 3

b. Period = 2s

c. Pulse width = 25%, 50%, 75%

d. Phase delay = 0s

e. Time = 5s

iii. Run the experiment and plot the output responses of the plant.

iv. Change the input signal to sine wave and set the parameter as below:

a. Amplitude = 2, 2.5, 3

b. Frequency = 1 rad/s, 3rad/s, 10 rad/s and 30 rad/s

c. Phase = 0

d. Sample time = 0

e. Time = depend on the cycles

v. Run the experiment and plot the output responses of the plant.

vi. Using the system identification to generate the transfer function using the pulse signal as input and displacement signal as output in step 6 as shown in Figure A4.

vii. Record and plot the step response of the generated transfer function.

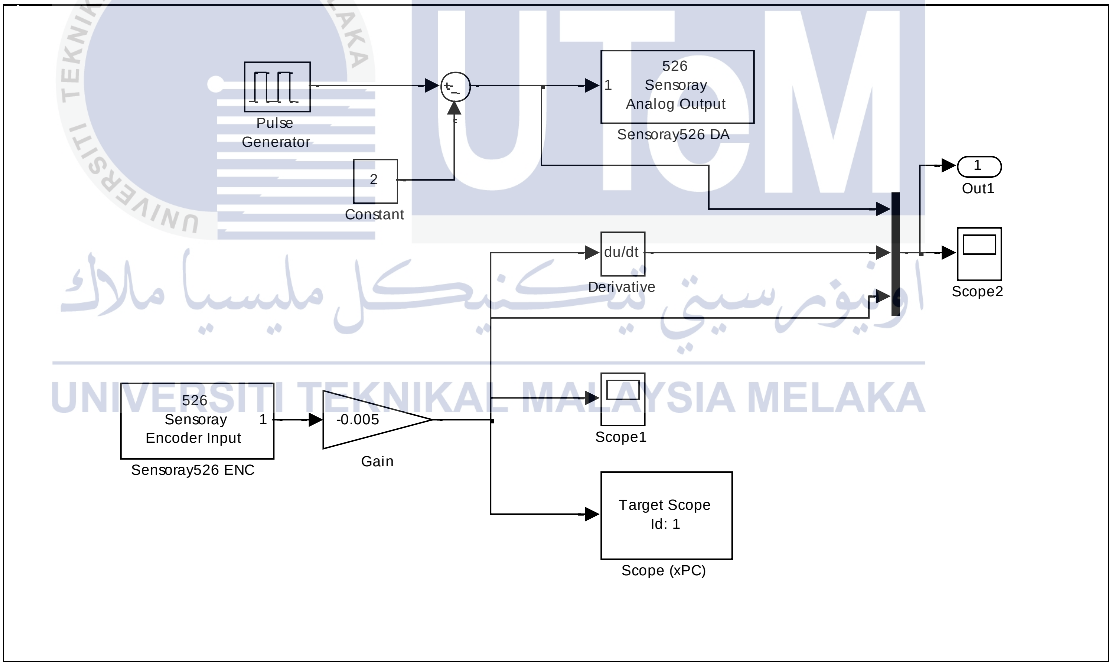

Figure A3: Open loop system.

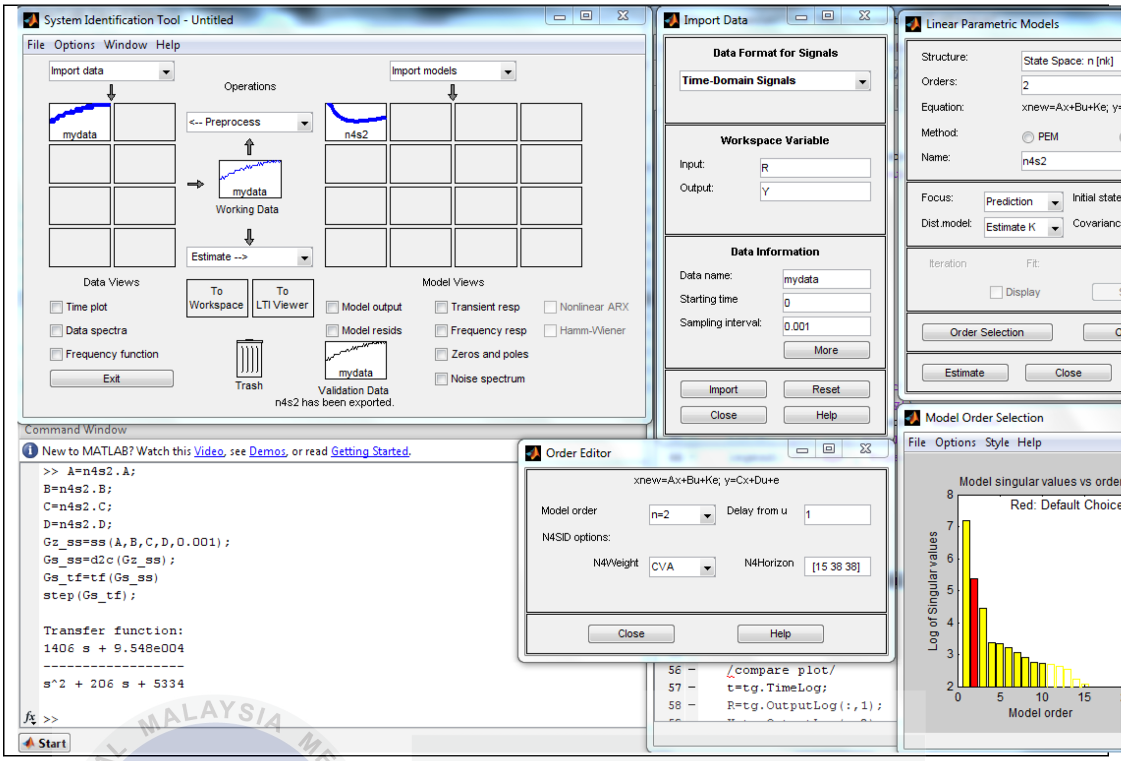

Figure A4: Generate the transfer function using system identification.

Experiment 4: Closed loop test

i. Add another unity feedback to create the closed loop system for both experimental and simulation as shown in Figure A5.

ii. Set the step input as following:

a. Step time = 1

b. Initial value = 0

c. Final value =1, 5, 10

iii. Set the sine wave input as following:

a. Amplitude = 1, 10, 50

b. Frequency = 0.1 rad/s, 0.3 rad/s,1 rad/s, 3rad/s, 10 rad/s, 30 rad/s and 100 rad/s

c. Phase = 0

d. Sample time = 0

e. Time = depend on the cycles

iv. Compare and analyze the output response from closed loop system.

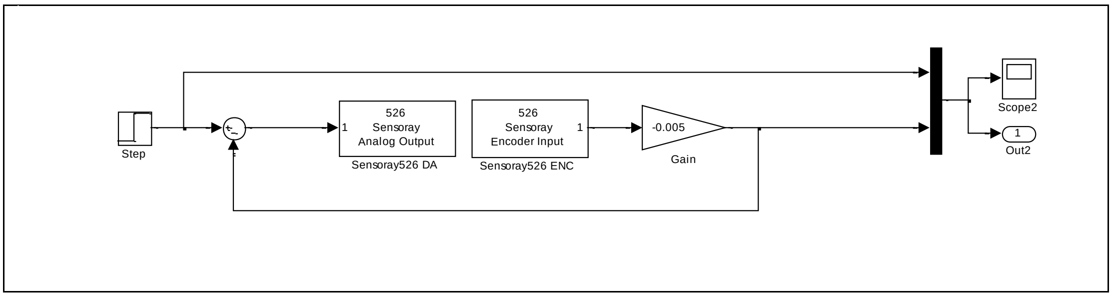

Figure A5: Closed loop tests for experiment.

Experiment 5: Design the fuzzy PID controller

i. Set the range of error and rate of error which can be obtain from the closed loop system.

ii. Design Mamdani and Sugeno Takagi types of fuzzy inference system which has been discuss in design procedure of fuzzy PID controller.

iii. The inputs range or universe discourse for both fuzzy inference systems is set as the range of error and rate of error obtain in step 2.

iv. Set 3 Gaussian membership functions for input and 3 triangular membership function for output for both fuzzy inference systems.

v. Set the range of output membership function is from -10 to 10 for both fuzzy inference systems as shown in Figure A6.

vi. Add a fuzzy logic controller block from fuzzy logic toolbox into the experiment and add the proportional gain, derivative gain and integration gain after the fuzzy logic controller as shown in Figure A7.

vii. The proportional gain, derivative gain and integration gain is adjust manually to obtain the small overshoot and small steady state error as possible by adjust manually the proportional gain and other gains are set to 0. After the proportional gain, Kp was set to desire output, the derivative gain, Kd is adjust as Kp and then adjust the integration gain Ki.

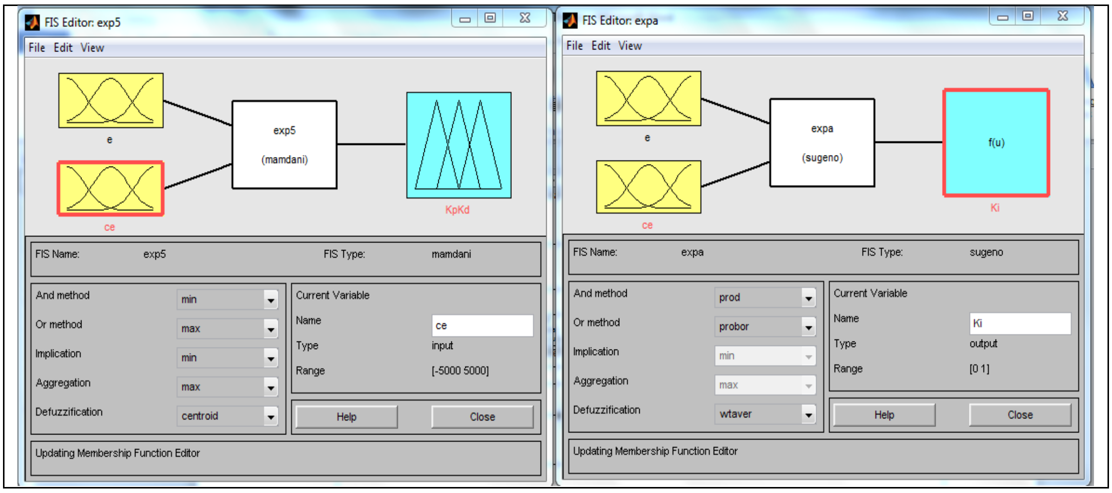

Figure A6: Fuzzy inference system design.

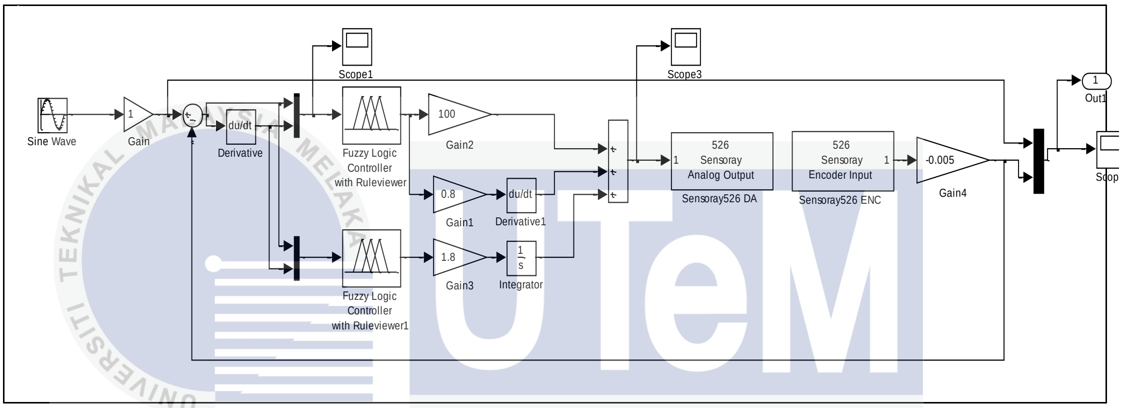

Figure A7: Fuzzy PID controller in real time system.

Experiment 6: Design a PID controller.

i. Design the PID controller by using hand tuning method to tune the Kp, Kd and Ki gains values until obtain the best performance for every input signals as shown in Figure A8.

ii. Using the designed PID controller for both methods, run experiment and plot the output responses.

iii. Compare the output response between the closed loop system and PID controller.

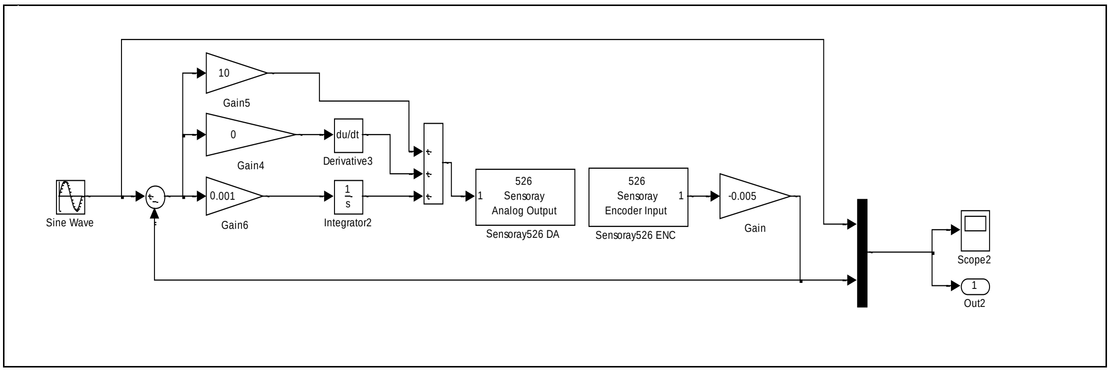

Figure A8: System with PID controller in experiment.

Experiment 7: Point to point positioning test

i. The point to point experiment is set to different distances at 1 mm, 10 mm and 50 mm.

ii. Examine the amplitude of input signal relative to experimental displacement by taking the measurement.

iii. Set the step input as below:

   a. Step input

   Step time = 1

   Initial value = 0

   Final value = 1, 10, 50

iv. Run the experiment in closed loop system, system with PID controller and system with Fuzzy PID controller according to the input setting and calculate the error of displacement between position of table load and set point position.

v. Compare the results of error between closed loop and fuzzy PID controller in real time system.

Experiment 8: Variation of load parameter under system with and without controller.

i. Add the load of 1000g, 2000g and 3000g onto the table load to increase the weight as shown in Figure A9.

ii. Run the experiment repeatly at different weight of load and plot the output response of the closed loop system, system under PID and fuzzy PID controllers.

iii. Analyse the output response and compare the error obtained from the results.

iv. Compare and discuss the simulation and real time system output response.

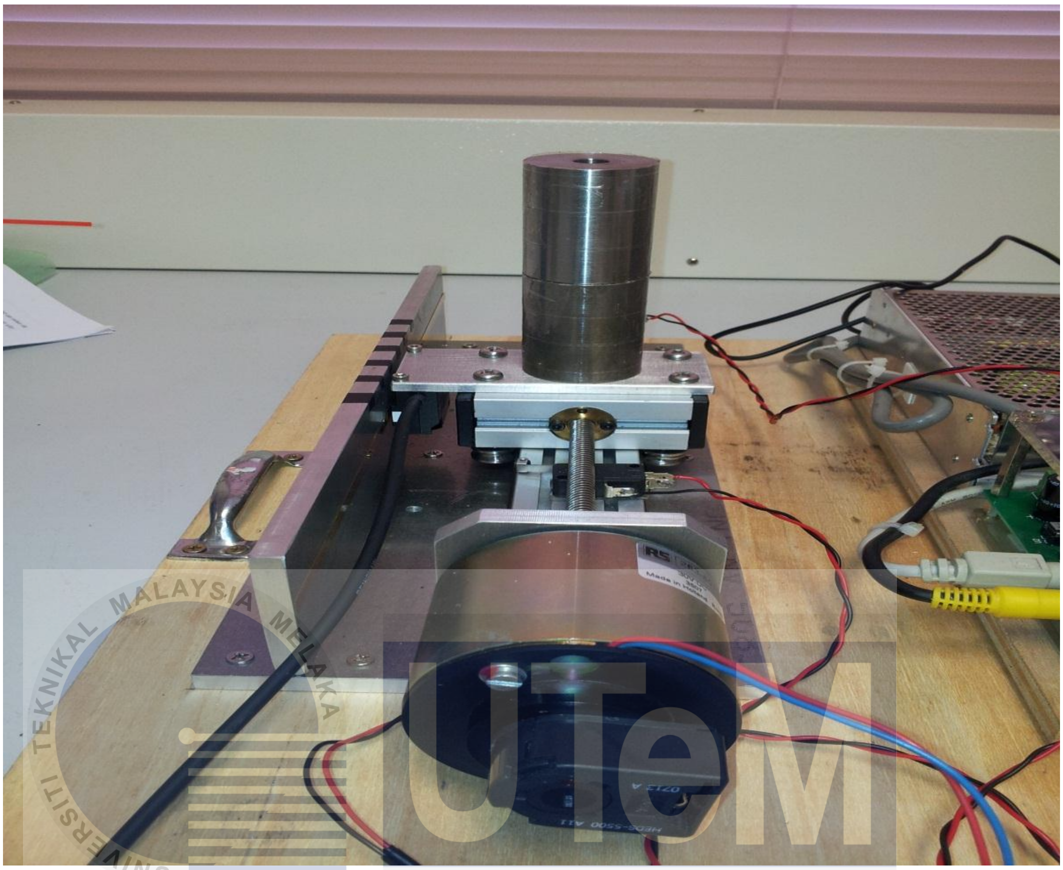

Figure A9: Hardware with adding load.