Universiti Teknikal Malaysia Melaka

Faculty of Electrical Engineering

COMPARISON OF LINEAR AND INTELLIGENT CONTROL FOR A NONLINEAR ELECTRO-HYDRAULIC ACTUATOR SYSTEMS

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

SAEED MOHAMMED ABDULGHANI MOHAMMED

**Bachelor of Electrical Engineering (Control,
Instrumentation and Automation)**

2017

APPROVAL

I hereby declare that I have read this report “comparison of linear and intelligent control for a nonlinear electro-hydraulic actuator systems” and found that it has complied the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Control, Instrumentation and Automation).

Signature : …………………………......

Supervisor Name : Dr. Rozaimi Bin Ghazali

Date : …………………………......

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

COMPARISON OF LINEAR AND INTELLIGENT CONTROL FOR A NONLINEAR ELECTRO-HYDRAULIC ACTUATOR SYSTEMS

SAEED MOHAMMED ABDULGHANI MOHAMMED

in fulfillment of the requirements for the degree of Electrical Engineering
(Control, Instrumentation and Automation)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

DECLARATION

I declare that this report entitled “Comparison of linear and intelligent control for a nonlinear electro-hydraulic actuator systems” is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Signature : ……………………….

Name : Saeed Mohammed

Date : ………………………….

DEDICATION

To my beloved mother and father

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ACKNOWLEDGEMENT

Firstly, I am grateful that Dr. Rozaimi Bin Ghazali is my supervisor for my Final Year Project 1. His guidance throughout the period of the final year project is very appreciated. His patience, motivation, and knowledge guide me to the right track of conducting this project. His guidance and corrections on writing the report have helped me a lot in term of writing a good and qualified technical report. Also, I would like to thank my panels Dr. Azrita Binti Alias and Pn. Nur Asmiza Binti Selamat.

Secondly, I am thankful to my friends for their enormous assistance and discussion with me throughout this Final Year Project. Through discussion we were able to exchange and share ideas with us, so I gained a lot of meaningful knowledge about my project.

Lastly, I am very thankful to my family who gives me the courage and confidence throughout the whole research of my Final Year Project. I keep receiving all the support from them to do my best in achieving the success whole university life.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ABSTRACT

Electro-hydraulic actuator systems perform a necessary role in industrial applications. The nonlinear electro-hydraulic actuator suffers from nonlinearities and time varying characteristics such as high speed, fast stop and the start of the hydraulic cylinder. The nonlinear properties challenging the position of the nonlinear electro-hydraulic actuator. In this report, development of linear and intelligent control techniques will be designed such as linear PID control, intelligent fuzzy logic control and hybrid fuzzy-PID control that can be used to control the tracking position of nonlinear electro-hydraulic actuator systems. Firstly, the mathematical model of electro-hydraulic systems will be represented using MATLAB and Simulink. Through simulation in MATLAB and Simulink, the appropriate procedure to tune PID parameters and fuzzy rules will be conducted. The fuzzy controller also will be utilized to tune the gain parameters which are (K_p, K_i and K_d) of the PID controller. The performance parameters such as the system steady-state error, overshoot and settling time are different control techniques will be assessed. Through the mathematical model of the process, the tuning method for PID, Fuzzy and Fuzzy-PID controllers will be conducted with considerations that should be made for that system. The linear and intelligent controllers have been evaluated using various tracking trajectories. It shows that hybrid Fuzzy-PID performs better as compared to PID and Fuzzy controllers. About 20% improvement of the tracking error has been obtained using the Fuzzy-PID controller. As conclusion integration between linear and nonlinear controllers will produce significant improvement for tracking performance particularly in nonlinear electro-hydraulic actuator systems.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ABSTRAK

Sistem penggerak elektro-hidraulik mempunyai peranan yang penting di dalam aplikasi industri. Penggerak elektro-hidraulik yang bersifat tidak linear telah terdedah kepada ciri-ciri ketaklinearan dan berubah berdasarkan masa seperti kelajuan yang tinggi kadar berhenti yang segera, dan pada permulaan silinder hidraulik. Ciri-ciri tak linear ini telah manambah cabaran dalam menentukan kedudukan penggerak elektro-hidraulik. Dalam laporan ini, pembangunan teknik-teknik kawalan linear dan kawalan pintar akan direka seperti kawalan linear PID, kawalan logic kabur pintar. Pada awalnya, model matematik untuk sistem elektro-hidraulik akan dipersembahkan dengan menggunakan perisian MATLAB dan Simulink. Melalui simulasi dalam MATLAB dan Simulink, prosedur yang sesuai untuk penalaan parameter PID dan 'Fuzzy Logic' akan dijalankan. Pengawal fuzzy juga akan digunakan untuk menala parameter-parameter pengawal PID termasuk (K_p, $K_i$dan K_d). prestasi untuk parameter-parameter ini seperti kesilapan ralat sistem, terlajak dan masa penetapan untuk teknik penalaan yang berbeza akan dinilai. Melalui proses model matematik, teknik penalaan bagi PID, Fuzzy Logic dan Fuzzy-PID akan dijalankan dengan pertimbangan yang perlu dibuat untuk sistem tersebut. Pengawal linear dan pengawal bijak telah dinilai dengan menggunakan pelbagai jenis penjejakan trajektori. Ia menunjukkan bahawa hibrid Fuzzy-PID memberi prestasi yang lebih baik berbanding dengan pengawal PID dan Fuzzy. Peningkatan sekitar 20% peningkatan ralat dari segi penjejakan trajektori telah diperolehi dengan menggunakan pengawal Fuzzy-PID. kesimpulannya, gabungan di antara pengawal linear dan bukan linear akan menghasilkan peningkatan yang ketara untuk prestasi penjejakan terutamanya dalam sistem penggerak electro-hidraulik yang tak linear.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

TABLE OF CONTENTS

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF FIGURES

UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF TABLES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF APPENDICES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 1

INTRODUCTION

1.1 Motivation

The actuator system is a device that makes mechanical movement by changing different types of energy to mechanical energy. The actuator produces the force that comes from several sources pneumatic pressure, hydraulic pressure and motive force. The actuators classified depend on the type of supply. The hydraulic actuator is the one type of actuator system used as a drive or transmission system that utilizes pressurized hydraulic fluid supply to actuate hydraulic machinery. For electro-hydraulic actuator required hydraulic fluid supply, control valve and cylinder. The hydraulic system used in many application such as power systems, braking systems and cranes[2].

The hydraulic actuator is widely used in industry and important equipment because it can produce large torques, capable of high power and good positioning with fast motion. The hydraulic circuit can transmit large force and is easy to control. Low power input is converted into a movement to control a high-power hydraulic actuator. The hydraulic control used in a wide number of application such as ships and electromagnetic, manufacturing system, flight simulation and paper machines[3].

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The nonlinear electro-hydraulic systems suffer from nonlinearities and time varying characteristics such as high speed, fast stop and start of the hydraulic cylinder that produced by flow and pressure and effect on dynamic behaviors. The nonlinear properties causing a backlash in the control valve, actuator friction, distinction in fluid volume that make the system models and controller designs more complex [4].

The nonlinear properties that produced by pressure and flow rate of the electro-hydraulic system are looking for a suitable controller to achieve success performance. There are many controllers used as a feedback to improve the behavior and nonlinearities of the nonlinear electro-hydraulic actuator system. That feedback controller or controller design employed to dealing with nonlinear electro-hydraulic actuator systems over the past decades including intelligent control, linear control and nonlinear control [5].

1.2 Problem Statement

The furthermost a suitable modeling of the system could be controlled by developed a control strategy. The difference between the output response and the actual system must be close that means the system stable. The model and parameters ($\mathrm{K_p}$, $\mathrm{K_i}$ and $\mathrm{K_d}$) are unknown by applying the mathematical model to overcome those limitations. The nonlinear electro-hydraulic actuator model needs to evaluate in non-linear models, intelligent models and linear models. The nonlinear electro-hydraulic system suffers from uncertainties, nonlinearities, disturbances and time-varying. Therefore, a prepare control strategy needs to be designed to increase the robustness and stability of the system[6].

To increase robustness and stability of nonlinear electro-hydraulic actuator system by utilizing controller design to enhance the position following of the nonlinear electro-hydraulic system. The PID, Fuzzy and Fuzzy-PID controllers will develop the nonlinearities behavior of nonlinear electro-hydraulic actuator systems. The mathematical model of nonlinear electro-hydraulic systems is approximated using MATLAB and Simulink. The Fuzzy rules is the suitable method to tune the parameters gain ($\mathrm{K_p}$, $\mathrm{K_i}$ and $\mathrm{K_d}$) of the PID controller through simulation in MATLAB and Simulink.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1.3 Objective

The objectives of this project are: -

i. To develop the mathematical model of a nonlinear electro-hydraulic actuator systems.
ii. To design linear and intelligent controllers that are capable to achieve the tracking position of the nonlinear electro-hydraulic actuator.
iii. To evaluate the performance of the developed linear and intelligent controllers in terms of transient response, steady state error and RMS values.

1.4 Scope of Work

The scope of this project will be focused on improving the tracking position of the electro-hydraulic actuator by using controller design. This project will be done based on two parts, the first part of a mathematical model for electro-hydraulic actuators will be identified by determining the mathematical model for each component of the nonlinear electro-hydraulic system then approximate by using MATLAB and Simulink. The second part, simulation by using a Fuzzy logic, PID and Fuzzy-PID controllers of system modules to make the output value equal or near to the desired value and control the single ended cylinder of the nonlinear electro-hydraulic actuator system. Also, the parameters (K_p, K_i and K_d) will be improved and Fuzzy logic methods are highlighted to choose the best method that can tune the PID controller recursively to improve the nonlinearities characteristic of the actuator and make the system more stable. Analyse the electro-hydraulic actuator behavior such as rise time, settling time, overshoot and steady-state error by adjusting the gain of the controller. MATLAB and Simulink are chosen as the platform to design and simulate the mathematical model and the proposed controller.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the theory, and basic principles of linear, nonlinear, and intelligent control is presented. Besides that, the basic concept of the nonlinear electro-hydraulic actuator with the review of previous related works is included in this chapter.

2.1 Introduction

In the world of technology, the nonlinear electro-hydraulic actuator has been researched for quite a long time by many researchers. The aims are basically to improve the controller that is used to solve many problems for nonlinear electro-hydraulic actuator system in fluid power technology. This advanced research will help enhance the position following of the system[7].

The nonlinear electro-hydraulic actuator is a device uses fluid to generate energy and to drive hydraulic machine. The advantage such as high force rendered nonlinear electro-hydraulic actuator system to be widely implemented in industrial applications and it can maintain high loading capabilities for a longer period and the hydraulic cylinder has nonlinear properties high speed that challenging the position tracking. To develop the nonlinear properties by applying feedback control to the system that capable of improving the position tracking of the nonlinear electro-hydraulic actuator system.

The control system is utilized to adjust the behavior of a system so it behaves on in a particularly desirable method over time. The control system contains several characteristic stabilities when the system is stable should be fast as a possible response, rise time and the error of the system must be zero, that is mean the error of the reference output and the output of the system should be close. The system divided into two categories open loop and closed loop systems. In the closed loop system, the stability achieved by measurements and making an adjustment to the system. The close loop in control system consists of the desired value or reference value, the controller (PI, PD,

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

PID and fuzzy logic), the process and plant (actuator system) and the feedback or measured output (sensor). The Figure 2.1 shows the structure of closed loop system[8][9].

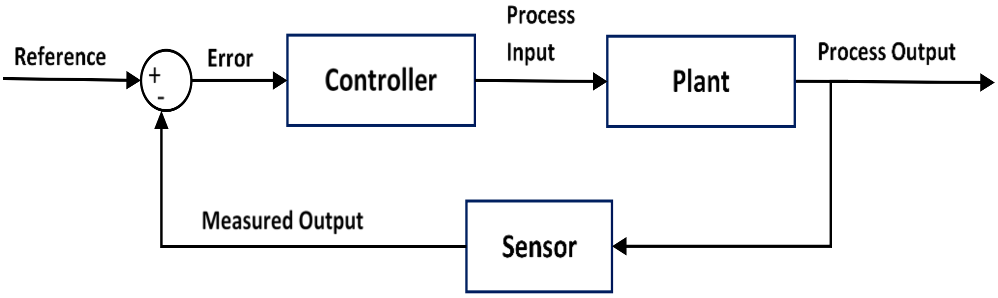


Figure 2.1: The structure of closed loop system

The sensor measures the output value to identify the error value and then subtracted with input value (desired value). This error value flows to the controller to adjustment and produces the process input then do some calculation and modify it to get the new process output.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2.2 Linear Control

Linear control is a controller design used widely to the system in the industrial application that deals with superposition principle. The linear differential equations apply to the system when the output values proportional to the input values. Types of classes system have parameters that do not change with time (linear time invariant). This way of controller design used in a nonlinear electro-hydraulic actuator to achieve the best performance [10][11]. By utilized several controllers P, PD, PI, PID and linear quadratic regulator (LQR). This type of control widely used in industries because easy to implement and grow the specific plant.

The PID controller is the of the one most common close-loop linear controller utilized in industries. PID control is one of the oldest and classical control used to for nonlinear electro-hydraulic actuator. The PID controller utilize a three mean performance types proportional, integral and behaved as single mode and the derivative is seldom used on it is own in control systems[11]. The PID utilized to develop the overshoot, transient response, steady state error and fast rise time. Due to the various advantage of the PID controller is widely used for industrial applications in the nonlinear electro-hydraulic actuator [12]. The PID calculate the desired actuator output by computing proportional, integral, and derivative the combining those three parameters to get a stable output [13], [1]. It provides excellent control behavior of nonlinear electro-hydraulic actuator system by obtaining the gain value of P, I and D. Figure 2.2 shows the structure of a PID controller[8].

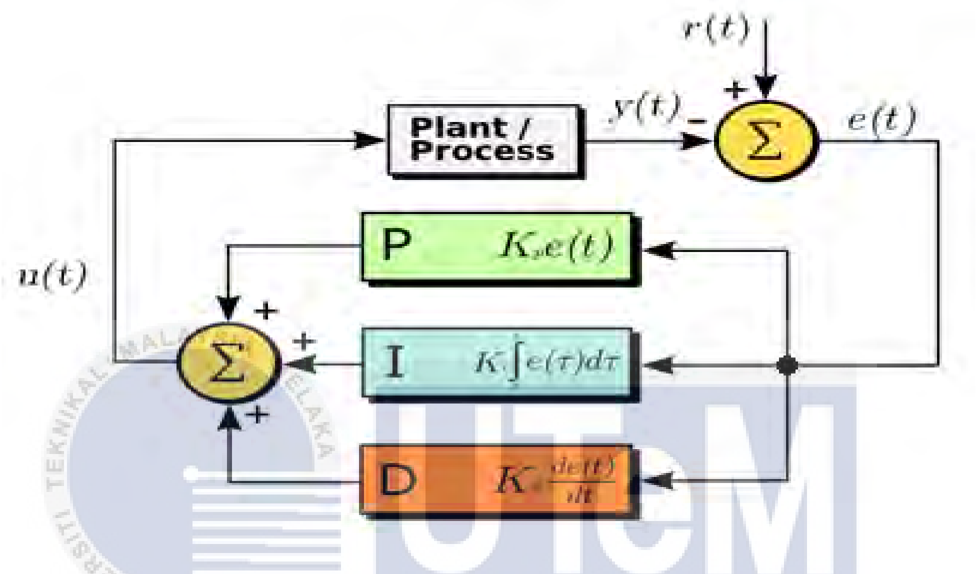


Figure 2.2: The process PID controller

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The PID controller is used to illustrate the performance of the nonlinear electro-hydraulic actuator. To study the stability of the system, require the values of the parameters gain which are K_p, K_i and K_d. The changes of this parameter affect the transient response (rise time, settling time and overshoot) and steady-state error of the system [14].

2.3 Nonlinear Control

Nonlinear control is a field of control theory used when the system is time-variant and nonlinear. The nonlinear control widely used in many applications it deals with a wider type of systems that do not follow the superposition principle[12]. The mathematical techniques of nonlinear become more accurate that used to handle all the real-time systems. The nonlinear controller design used in many applications to achieve the perfect performance of the system and used to dealing with the nonlinear electro-hydraulic system. Nonlinear control includes several feedback controllers employ for trajectory tracking control of nonlinear electro-hydraulic actuator such as sliding mode control (SMC) [5].

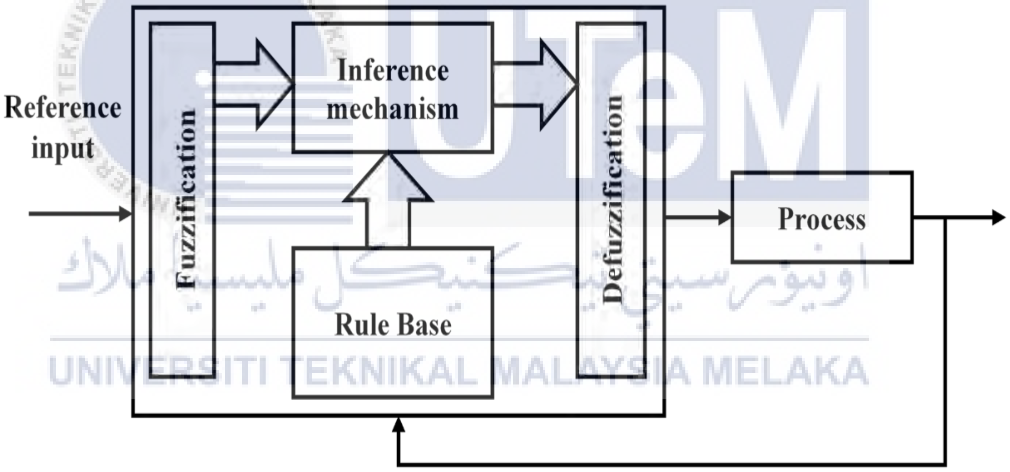
The sliding mode control (SMC) is a common method in nonlinear control field used the discontinues control application to change dynamics of the nonlinear system. The sliding mode control is the most suitable approach to maintaining the stability of the controlling classes models that are subjected to external disturbances and parameters variation. Tracking error of the system needs to be minimized by using discrete and continues sliding mode control and trajectory tracking. The aim of SMC to control the nonlinear electro-hydraulic actuator (the plant) by using feedback loop that compares the desired value and the output value to make the system stable [15].

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2.4 Intelligent Control

The intelligent control used to reduce a human who achieves and performs the control task or to get the solution of control problems. The intelligent control is a type of control techniques that employs various methods of artificial intelligence computing such as neural network, fuzzy logic and genetic algorithms [16]. The intelligent control is widely used in industrial application such as automation, manufacturing, communication, robotics, and traffic control. The intelligent control used to control and stabilize the performance of the actuator systems. The neural network is a mathematical representation or computer algorithm used to solve problems in almost all spheres of science and technology. Neural network includes two steps system identification and control. The artificial neural network is a network of neurons in a brain interconnected as a group of nodes each circle considered as artificial neurons and used the arrow to connected between the input and the output. The artificial neural network is utilized as a feed-forward in many applications to identify the dynamic model for the system such as nonlinear electro-hydraulic actuator [3][17].

The fuzzy logic control is a method of artificial intelligence designed to control something usually mechanical. The fuzzy logic used to develop the nonlinear electro-hydraulic system. The fuzzy logic consists of four components which are, the rule base, fuzzification, inference mechanism and defuzzification [18]. The fuzzy logic consists of two inputs go through the fuzzification. Finally, defuzzification converts the fuzzy output to signal send to the plant. This component is the structure of fuzzy logic control used to identify the reference input and transfer it to another form. The output consists of the signal send to control the actuator system. Figure 2.3 shows the fuzzy control system [1].



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 2.3: The Fuzzy logic control system

A Fuzzy controller is employed to control the system when the output value of the system is far away from the target value. There are two inputs for Fuzzy logic which including, the derivative of error $\frac{d_e(t)}{dt}$ and the feedback error e(t) for the output connected to the plant (actuator). Fuzzy logic design to enhance the behavior of nonlinear electro-hydraulic actuator [12][19].

2.5 Review of Previous Related Works

There are several of design methods and different controller used to control the position of the nonlinear electro-hydraulic actuator system. Some of the previous related work is explained below:

In [13], the nonlinear electro-hydraulic actuator is used in industry related to some characteristic high speed, quick reversal possible, fast stop and the start of the cylinder. The nonlinear electro-hydraulic actuator has large torque into inertia ratio with increase result in the acceleration capability. The tracking position challenging by the nonlinear properties of the nonlinear electro-hydraulic cylinder. The self-tuning fuzzy PID controller is designed to control the tracking position variation of the nonlinear electro-hydraulic actuator. The self-tuning fuzzy designed to achieve the performance of the nonlinear electro-hydraulic system and tuning the PID. The mathematical model identifies by employing identification system.

In [10], this paper represented for a nonlinear electro-hydraulic actuator that suffered from external disturbances and physical uncertainties. In this paper, designed the PID controller to control the position following of the nonlinear electro-hydraulic system. The proportional, integral and derivative used as feedback controller to achieve the perfect performance of nonlinear electro-hydraulic actuator system in a wide rang of external disturbances and physical uncertainties by comparing the desired value and the output value to make the system closely that means the system is stable. By using the via a Q4 Quanser DSP card to implemented the PID controller in MATLAB.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The researchers in [3], they have completed research on the artificial neural network based PID controller to improve the tracking for a nonlinear electro-hydraulic servo system. The control scheme is developed for the artificial neural network based PID controller to achieve high precise tracking control of nonlinear electro-hydraulic systems. They used two controllers which are PID controller and cerebellar model articulation controller are structured in a parallel connection. The outputs summation of the controller proposed perfect system includes the tracking ability for nonlinear electro-hydraulic servo system. In order to achieve high stability of the system, The PID controller is utilized as a feedback. The neural network is supervised by the cerebellar model articulation controller (CMAC) as a feed-forward compensator to determine the inverse system. The error between the total control input and the output of the CMAC is minimized and used CMAC to determine the control action by the learning algorithm.

2.6 Summary of the Review

Based on the previous works, there are many types of control technique that can be used to control the tracking position of nonlinear electro-hydraulic actuator systems such as linear PID control, intelligent fuzzy logic control, hybrid fuzzy-PID control, linear quadratic regulator control and nonlinear sliding mode control. In the review, each control techniques use various type of tuning methods. All the controllers may successfully control of the nonlinear electro-hydraulic actuator but the output system response is different. Parameters such as the system overshoot, settling time and steady-state error is different for each control techniques. By using PID controller, the system can be adjusting to having less overshoot, no steady state error, faster settling and rising time. From that, PID, Fuzzy, and Fuzzy-PID show great potential to improve the tracking position of the nonlinear electro-hydraulic actuator system. However, there is no much works do comparison studies for these types of controller in term of transient response and steady state error.

اونيۈرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 3

METHODOLOGY

This chapter describes the project methodology that is used to implement the project. The methodology of this project is a guideline that will explain the procedures of the project flow path. This project methodology is briefly explained in this chapter. Methodology helps to make sure the project is developed systematically, smoothly, and successfully to obtain better results.

3.1 Project Methodology

Basically, this project starts by studying the nonlinear electro-hydraulic system and the controller techniques basic principle. After completing the research and literature review of the project, the model plant is simulated and the behavior of the system is analyzed. Basically, the mathematical model for the existing plant is derived based on Euler-Lagrange method. The model plant is developed in MATLAB/ Simulink.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The control of nonlinear electro-hydraulic actuator suffers from nonlinearities that produce by flow and pressure that effect on the system behavior. In this project, however, the main objective is to improve the tracking position of the nonlinear electro-hydraulic actuator. The controller used to obtain a perfect performance of the system. After determined the nonlinear model of (EHA), the linear control and intelligent control were designed. The PID, fuzzy and fuzzy-PID controllers are expected to provide better system performance and transient response with specific system requirements which are a small steady-state error, small overshoot, faster rise and settling time[10].

The last stage of this project is to evaluate the system stability performance using PID, Fuzzy and Fuzzy-PID controllers. The transient response and the steady-state error of the controller are obtained in this stage by using MATLAB and Simulink with the aid of graphs. The overall flowchart of this project shown in Figure 3.1.

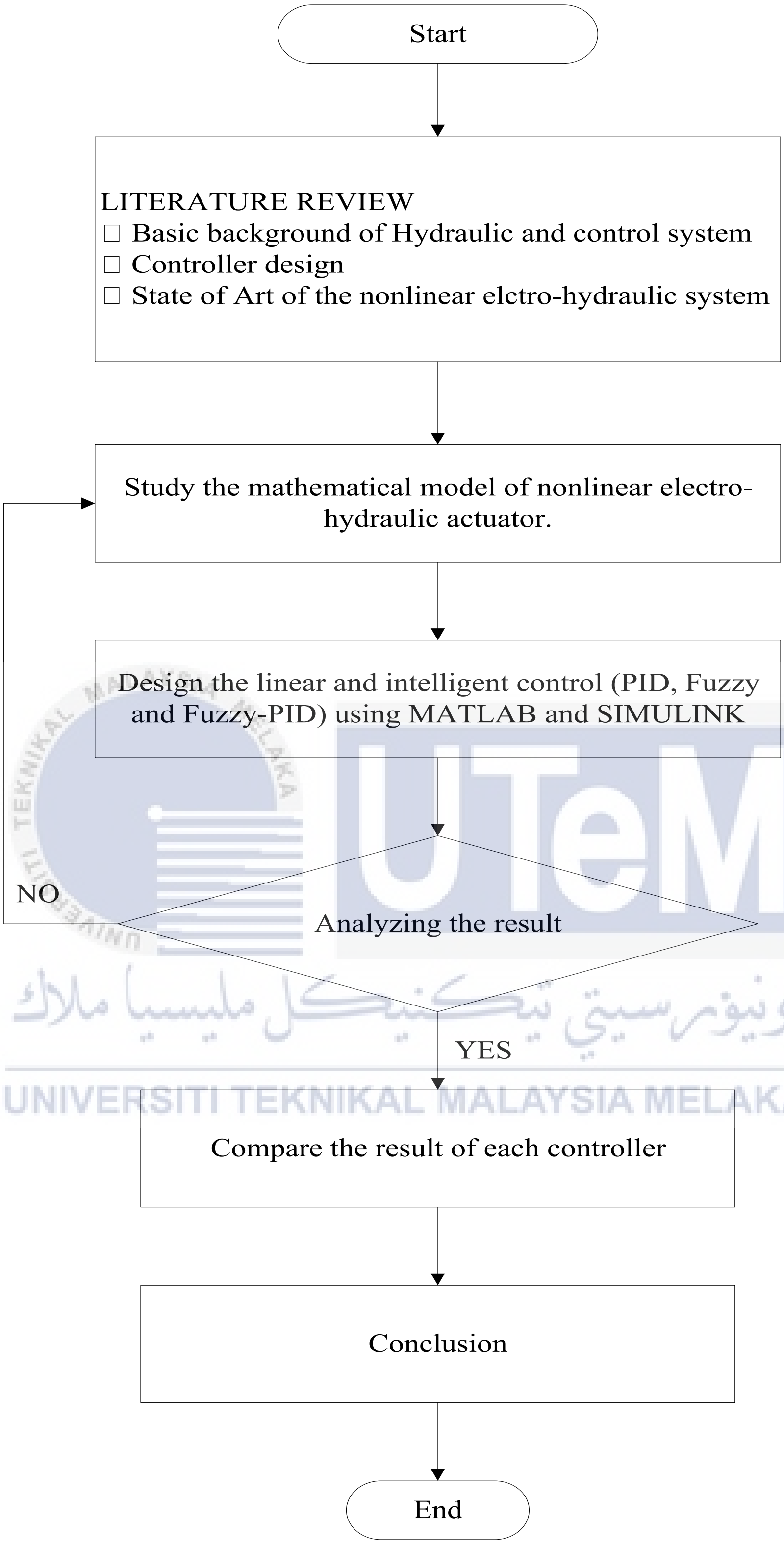


Figure 3.1: Overall flowchart of the project

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

3.2 Modeling of Nonlinear Electro-Hydraulic Actuator

From the mathematical model, calculation of the system variables and parameters can determine the equations of transfer function of nonlinear electro-hydraulic actuator systems. Figure 3.2 shows the servosystem electro-hydraulic of this project[2][17].

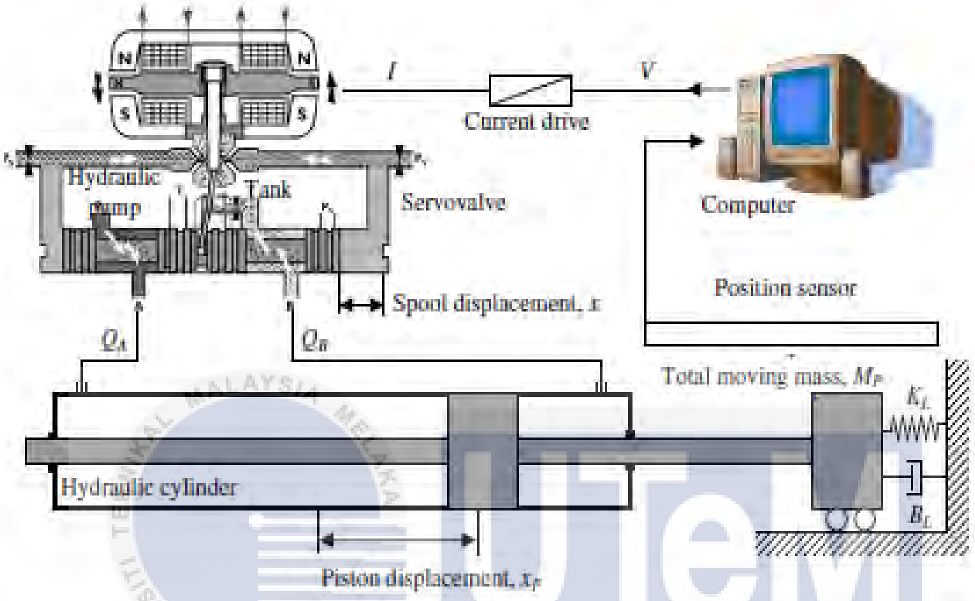


Figure 3.2: The servosystem electro-hydraulic model

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The equation of each component must be known to determine the model of the electro-hydraulic actuator. The electrical characteristic of servovalve of the torque motor represented in first order equation (3.1).

$$\mathrm{V} = \frac{dI}{dt} L_c + \mathrm{R_c I} \tag{3.1}$$

where L_c is coil inductance the valve, $\mathrm{R_c}$ is the resistance of the coil, V is the voltage control and I is the current of the coil. The test functions are applied to determine the behavior of actuator system. The theoretically of hydraulic servovalve illustrated by the general second order equation (3.2).

$$\frac{d^2\mathrm{x}}{dt^2} + 2\zeta\omega_n \frac{\mathrm{dX}}{\mathrm{dt}} + \omega^2 = \frac{\mathrm{I}}{\mathrm{I_{sat}}} \omega_\mathrm{n} \tag{3.2}$$

where X is the displacement of servovalve spool, n is the natural frequency, γ is the damping ratio, $\frac{\mathrm{I}}{\mathrm{I_{sat}}}$ is the normalized input current, $\mathrm{I_{sat}}$ is the saturation current for torque and I is the input. The flow rate through the servovalve of the hydraulic system is directly proportional to spool motion and square root under (constant load and varying load) condition. An ideal servovalve has a perfect geometry and written as:

$$\mathrm{Q} = \mathrm{K.x.}\sqrt{\Delta \mathrm{P_v}} \tag{3.3}$$

where x is the displacement of servovalve spool, K is the gain of servovalve and the $\Delta \mathrm{P_v}$ is the total pressure of $\mathrm{P_S}$, $\mathrm{P_T}$ and $\mathrm{P_L}$. The servovalve spool contain of two control ports, two return ports and supply. The flow rate through the return port, control port and supply expressed as:

$$\mathrm{Q_a} = \mathrm{Q_{as}} - \mathrm{Q_{ar}} \quad , \quad \mathrm{Q_b} = \mathrm{Q_{bs}} - \mathrm{Q_{br}} \tag{3.4}$$

$$\mathrm{Q_s} = \mathrm{Q_{as}} + \mathrm{Q_{rs}} \quad , \quad \mathrm{Q_r} = \mathrm{Q_{ar}} + \mathrm{Q_{by}} \tag{3.5}$$

UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The relation between the control port A and B are represented by this equation:

$$Q_{as} = K_{as}.\sqrt{P_s - P_a}.\begin{cases} x_0 + x & , \ x \geq 0 \\ {x_0}^2 (x_0 + k_{as} x)^{-1} & , \ x < 0 \end{cases} \tag{3.6}$$

$$Q_{ar} = K_{ar}.\sqrt{P_a - P_r}.\begin{cases} {x_0}^2 (x_0 + k_{ar} x)^{-1} & , \ x \geq 0 \\ x_0 - x & , \ x < 0 \end{cases} \tag{3.7}$$

$$Q_{bs} = K_{bs}.\sqrt{P_s - P_b}.\begin{cases} {x_0}^2 \ (x_0 + k_{bs} x)^{-1} & , \ x \geq 0 \\ x_0 - x & , \ x < 0 \end{cases} \tag{3.8}$$

$$Q_{br} = K_{br}.\sqrt{P_b - P_r}.\begin{cases} x_0 + x & , \ x \geq 0 \\ {x_0}^2 \ (x_0 + k_{br} x)^{-1} & , \ x < 0 \end{cases} \tag{3.9}$$

The module electricity used to identify the compressibility of the electro-hydraulic fluid by dP/β= −dV/V and the change in volume can be represented as:

$$\frac{dV}{dt} = -\frac{V}{\beta}.\frac{dP}{dt} \tag{3.10}$$

where the β is the bulk modulus. After integrating the equation (3.10).

$$P_a = \frac{\beta}{V_a}\int (Q_a - \frac{dV_a}{dt})dt \tag{3.11}$$

$$\begin{gathered} q_a = K_{line}.(P_a - P_b) \\ q_a = K_{lex}.P_b \\ q_b = K_{lex}.P_b \end{gathered} \tag{3.12}$$

$$P_a = \frac{\beta}{V_{line} + A_p.(X_s + X_p)}\int (Q_a - q_{ab} - q_a - \frac{dV_a}{dt})dt \tag{3.13}$$

$$P_b = \frac{\beta}{V_{line} + A_p.(X_s - X_p)}\int (\frac{dV_a}{dt} + q_{ab} - q_a - Q_b)dt \tag{3.14}$$

The cylinder of the hydraulic consist of two chamber A and B. Each chamber has volume and pressure as shown in above equations P_a is the pressure and V_a is the volume of chamber A. K_{line} and K_{lex} are the leak coefficients and V_{line} is the volume of the pipe. q_A and q_B are the flow rate through each chamber in hydraulic cylinder.

$$F_p = (P_a - P_b)A_p \tag{3.15}$$

$$F_p = M_p.\frac{d^2x_p}{dt^2} + B_l.\frac{dx_p}{dt} + K_l.X_p + F_s \tag{3.16}$$

The force exerted by the hydraulic cylinder against the load as shown in equation (3.15). Then define the dynamic equation that includes mass M_p of the hydraulic system equation (3.16). F_s is the friction force, B_l is the damping coefficient and K_l is the spring stiffness. After known the mathematical model for each component of hydraulic has to determine the mathematical models for electro-hydraulic actuator by representing each equation in the Simulink environment as shown in Figure 3.3.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

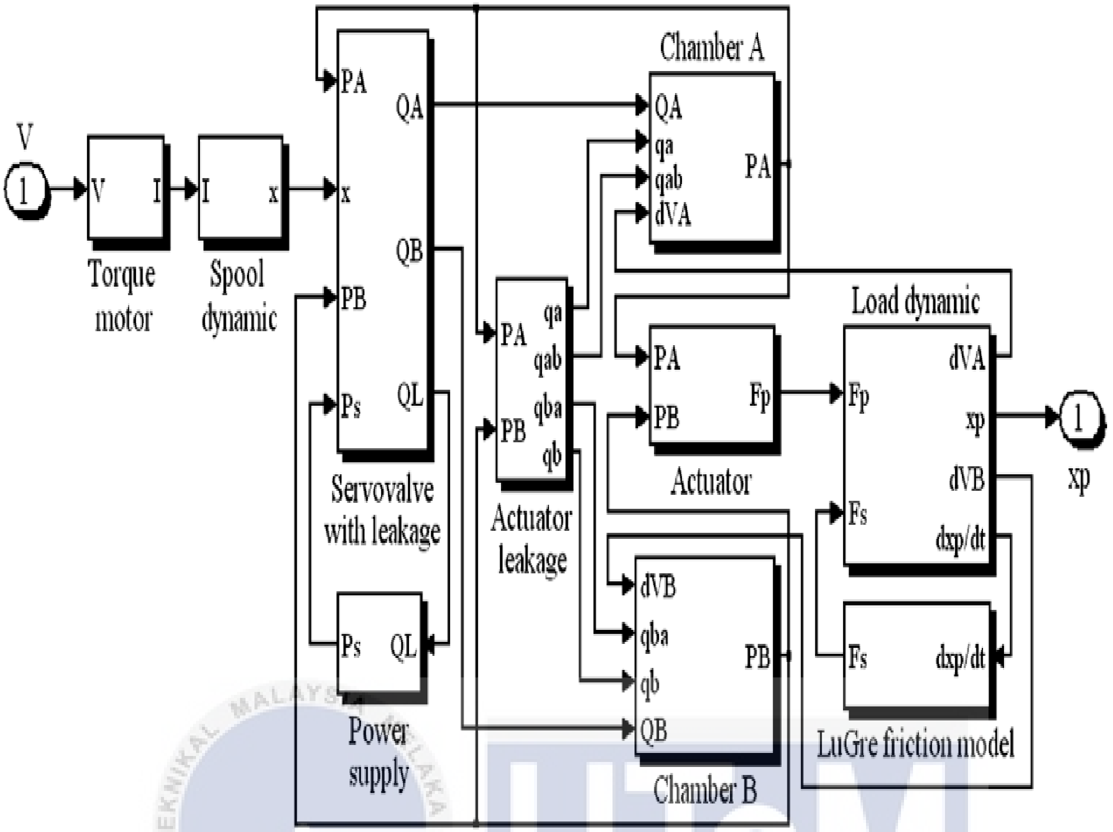


Figure 3.3: The block diagram of the nonlinear electro-hydraulic actuator by using Simulink

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

3.3 PID Controller

The PID controller is widely used in electro-hydraulic actuator because easy to implement and stable. The PID controller is expected to provide better system performance and transient response with specific system requirements which are a small steady-state error, small overshoot, faster rise and settling time [11]. The proportional, integral, derivative controller defined by:

$$u(t)= K_p e(t) + K_i \int e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \tag{3.17}$$

A proportional gain $K_p$causes decreasing of rise time meanwhile an integral gain K_i has the effect of eliminating the steady-state error. However, it will badly affect the transient response and affect the system in term of time [12]. Lastly, a derivative gain K_d function is to improve the transient response and stability of the system other than reducing the overshoot. Effects of each of controllers gain K_p, K_i, and K_d on a closed-loop system are summarized in Table 3.1.

Table 3.1: Comparison between controller gains

Controller Gain	Overshoot	Settling Time	Dead Time	Steady-State Error
$\boldsymbol{K_p}$	Increase	Decrease	Minor changes	Decrease
$\mathbf{K_i}$	Increase	Decrease	Increase	Eliminate
$\mathbf{K_d}$	Decrease	Minor changes	Decrease	Minor changes

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

By using various methods to tune the PID controller to stabilize the nonlinear electro-hydraulic actuator system. Firstly, PID controller is design using Ziegler-Nichols technique by tuning the parameter values K_p, K_i and K_d to improve the transient response and steady state error of system. The design of PID related to the below equation [11].

$$G(s) = K_p + \frac{K_p}{T_i s} + K_p T_d s$$

$$G(s) = K_p(1 + \frac{1}{T_i s} + T_d s)$$

By using MATLAB/Simulink, PID controller is designed to obtain better system performance by setting the value of K_i and K_d to zero then increase the value of K_p to ultimate gain value K_u until the single be sustained oscillation with period P_{cr} measured in second [20]. The sustained oscillation can be achieving by measuring the period within full wave cycle as shown in Figure 3.4.

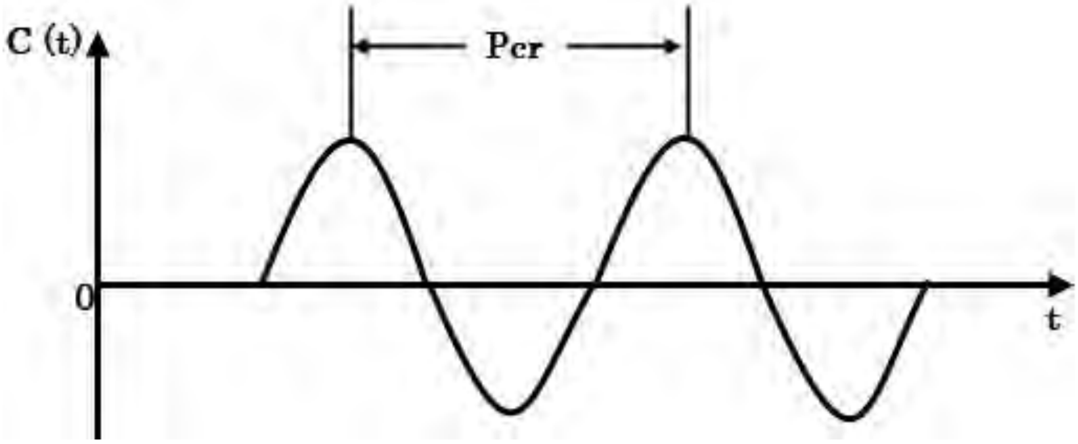


Figure 3.4: Sustained oscillations waveform

Applying the obtained K_u and P_{cr} values to the formula to calculate the parameter values according to Table 3.2 (K_p, t_i and t_d), then use this value in PID controller to achieve the position for the nonlinear electro-hydraulic actuator systems.

Table 3.2: PID controller formula

	K_p	t_i	t_d
P control	$K_u/2$	Inf	0
PI control	$K_u/2.2$	$P_u/1.2$	0
PID control	$K_u/1.7$	$P_u/2$	$P_u/8$

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

3.4 Fuzzy Logic

The Fuzzy logic is an intelligent control used as a feedback controller consist of input process and output phases [21]. The fuzzy logic used in electro-hydraulic to adjust the output of the system by setting the reference point flow that integral and derivative error to the input of Fuzzy logic as shown in Figure 3.5.

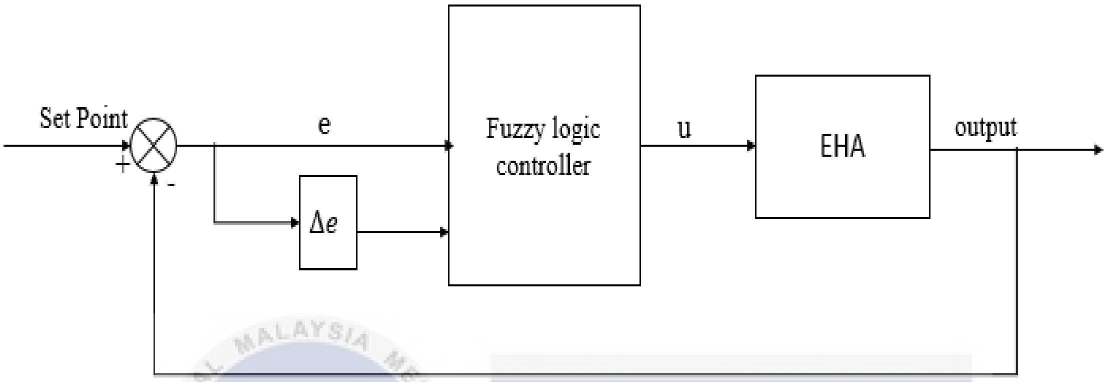


Figure 3.5: The block diagram of Fuzzy logic [1]

The input will identify by fuzzy inference rules and mapping of the membership function. That gain factors of the error effect on the behavior of the system that means the influence on the overshoot, rise time and settling time. The number of Fuzzy rules depends on the linguistic variables [20]. By using MATLAB/Simulink to design Fuzzy logic controller. Firstly, there are two inputs must be defined the error e(t) and the change of error de/dt and one output is the position as shown in Figure 3.6.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

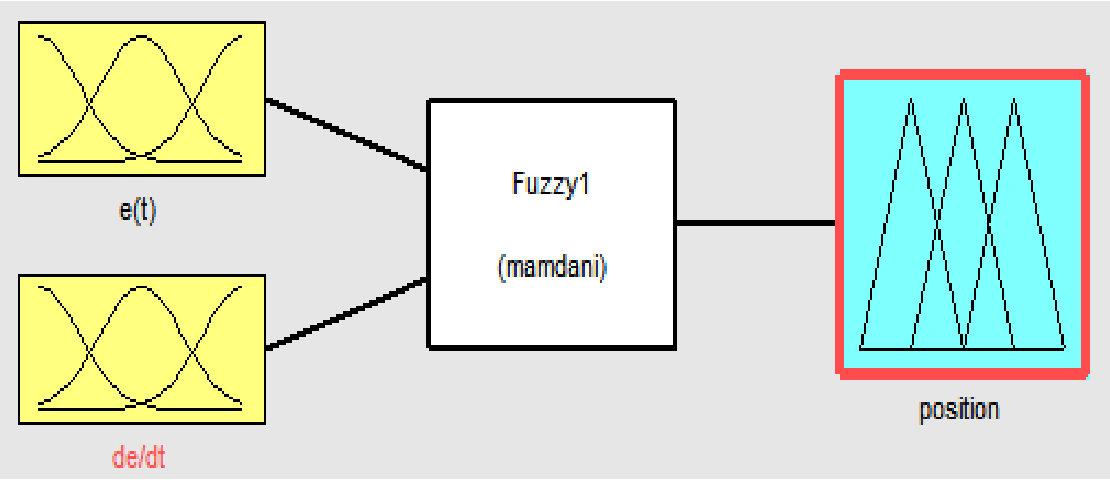
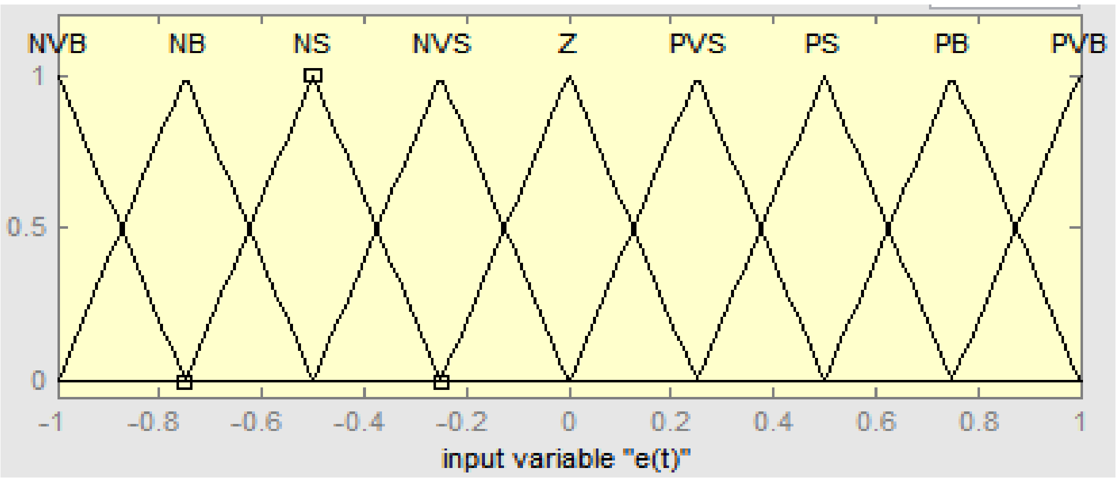


Figure 3.6: Input and output of Fuzzy logic controller

Figure 3.7 and 3.8 shows the membership function and the fuzzy set. The error in the position must be expressed in the interval by the range from -1 to 1 with nine linguistic terms in the position: negative very big (NVB), negative big (NB), negative small (NS), negative very small (NVS), zero (Z), positive very small (PVS), positive small (PS), positive big (PB) and positive very big (PVB). The fuzzy set in change of error are three linguistic presented as: negative (N), zero (Z) and positive (P) from -1 to 1. Finally, the range of the output is from [-1 1] and the fuzzy set are nine linguistic similarly with the input variable of error [NVB, NB, NS, NVS, Z, PVS, PS, PB, PVB].

UNIVERSITI TEKNIKAL MALAYSIA MELAKA



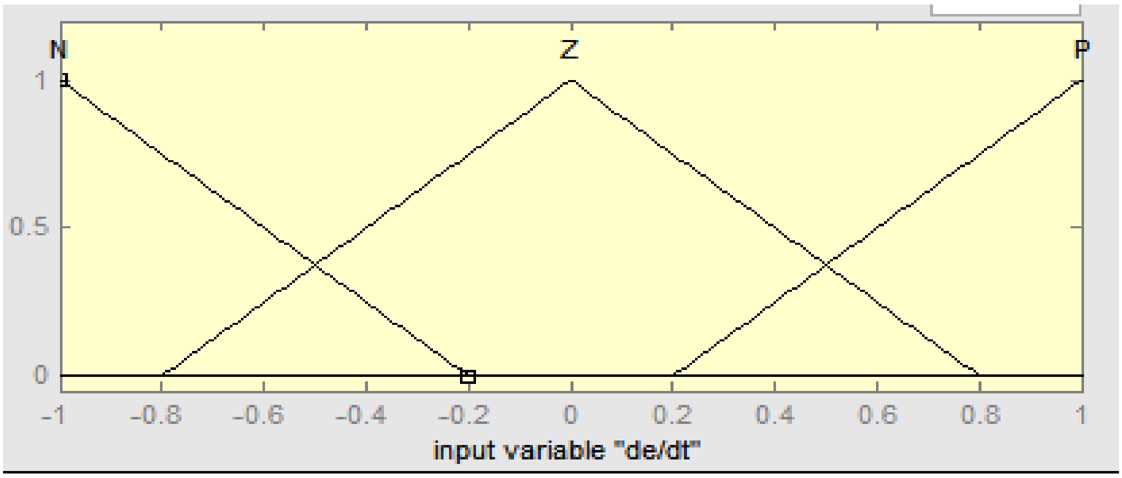
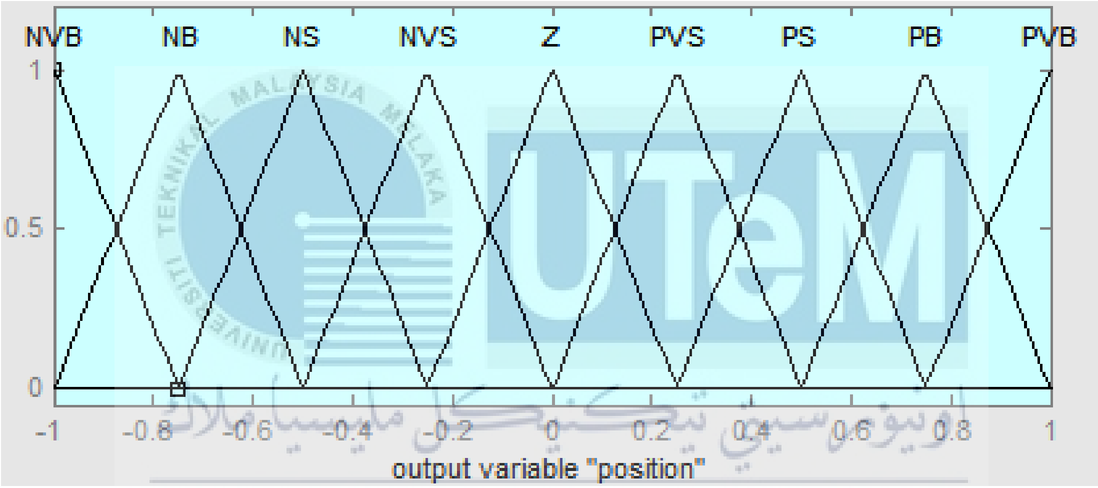


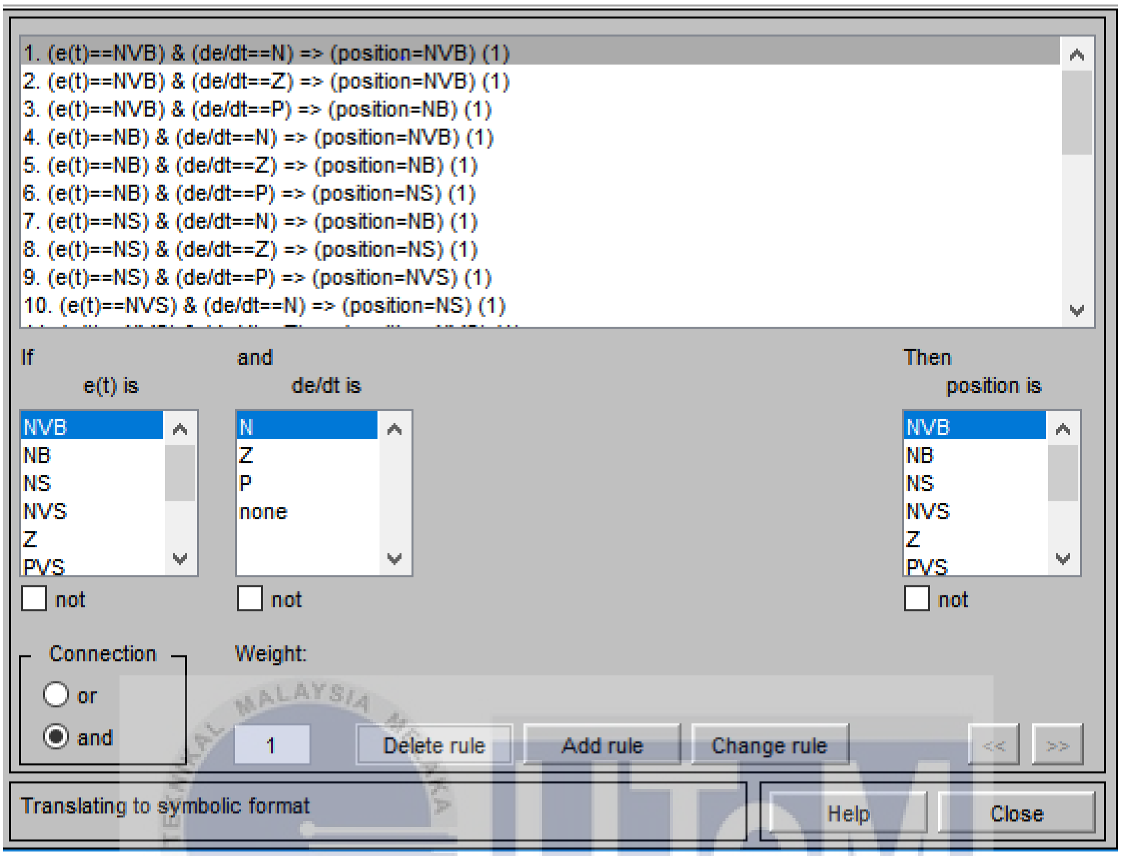
Figure 3.7: Input membership functions



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 3.8: Output membership functions

The fuzzy rules are depended on the number of input and output linguistic and related to characteristic of the processes. To set the fuzzy rules depended on the membership functions the error input has seven linguistic variables and three variables of change of error then we have 27 rules applied to design fuzzy logic controller as shown in Figure 3.9 and Table 3.3.



1. (e(t)==NVB) & (de/dt==N) => (position=NVB) (1)
2. (e(t)==NVB) & (de/dt==Z) => (position=NVB) (1)
3. (e(t)==NVB) & (de/dt==P) => (position=NB) (1)
4. (e(t)==NB) & (de/dt==N) => (position=NVB) (1)
5. (e(t)==NB) & (de/dt==Z) => (position=NB) (1)
6. (e(t)==NB) & (de/dt==P) => (position=NS) (1)
7. (e(t)==NS) & (de/dt==N) => (position=NB) (1)
8. (e(t)==NS) & (de/dt==Z) => (position=NS) (1)
9. (e(t)==NS) & (de/dt==P) => (position=NVS) (1)
10. (e(t)==NVS) & (de/dt==N) => (position=NS) (1)

If e(t) is NVB ☐ not

and de/dt is N ☐ not

Then position is NVB ☐ not

Connection: ○ or ● and

Weight: 1

Translating to symbolic format

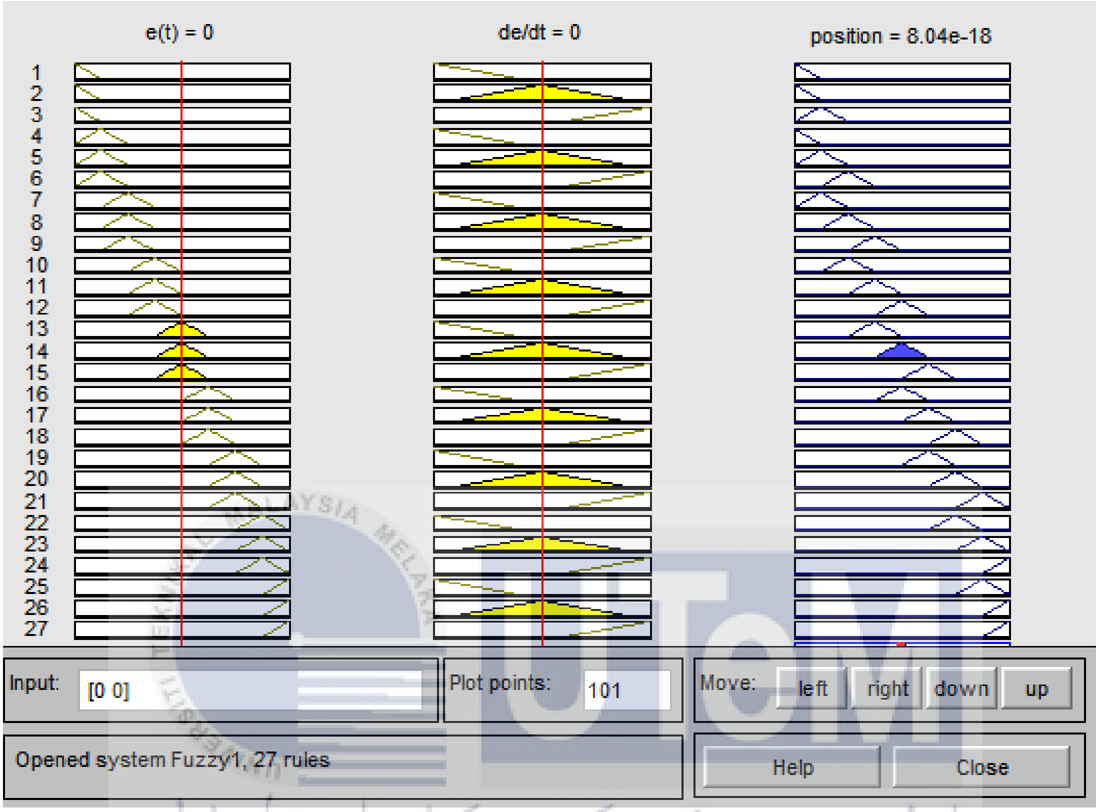
Figure 3.9: Rule editor of the system

اونيۏرسيتي تيکنيکل مليسيا ملاک
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Table 3.3: Fuzzy inference rules

	Error (e)								
de/dt	NVB	NB	NS	NVS	Z	PVS	PS	PB	PVB
N	NVB	NVB	NB	NS	NVS	Z	PVS	PS	PB
Z	NVB	NB	NS	NVS	Z	PVS	PS	PB	PVB
P	NB	NS	NVS	Z	PVS	PS	PB	PVB	PVB

In Figure 3.10 the rules viewer shown the processes to observe the functions for 27 rules of fuzzy logic, for example when the error is zero and the change of error is zero then the output will be zero. If change one of the rules that impact on the outcomes.



Input: [0 0]

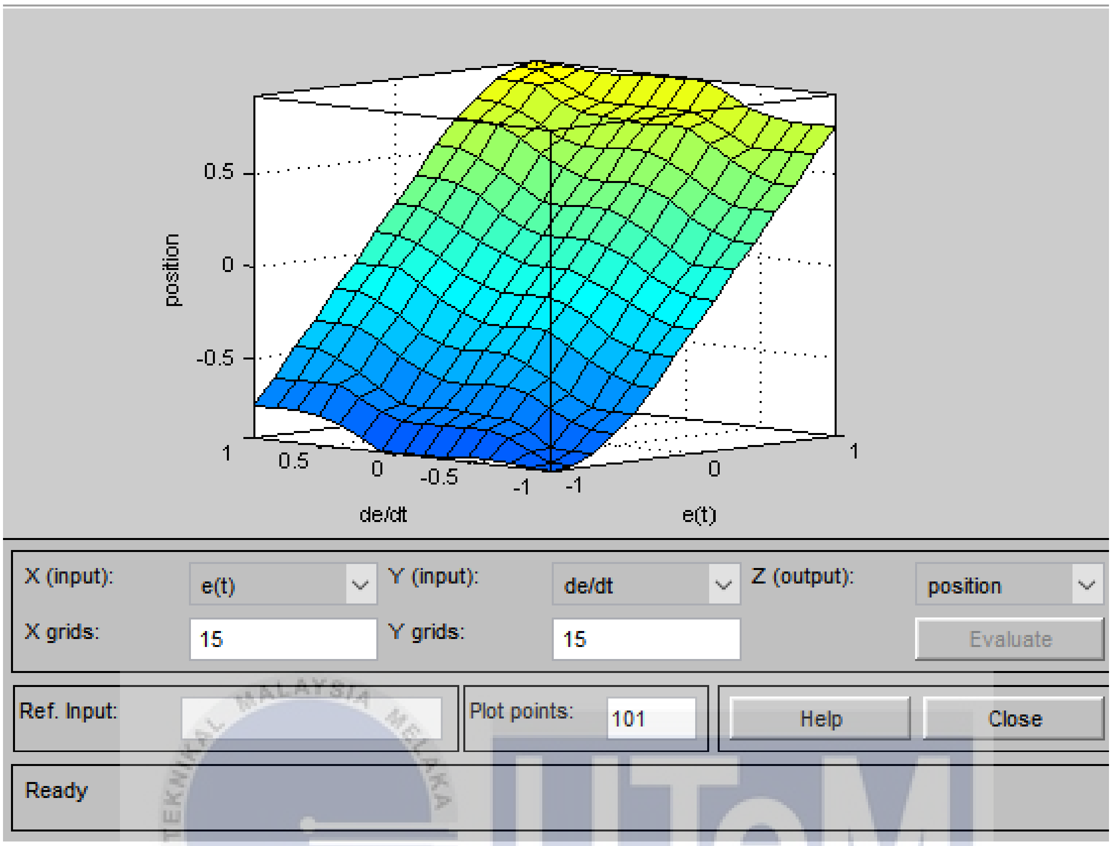
Plot points: 101

Opened system Fuzzy1, 27 rules

Figure 3.10: The rule viewer of the membership functions

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The Surface viewer show the relationship between the input and output if there is any change in the error or change of error we can see the base alteration as shown in Figure 3.11.



X (input): e(t)
Y (input): de/dt
Z (output): position
X grids: 15
Y grids: 15
Ref. Input:
Plot points: 101
Ready

Figure 3.11: The surface of fuzzy logic controller

The output contains of nine linguistic variables of membership functions with rang from -1 to 1 as shown in Figure 3.11. The fuzzy controller has a nonlinear characteristic of mapping output. By adding the scaling factors to adjust the output response of fuzzy controller and prove the dynamic characteristics of the system. The factors K_1, K_2 and K_3 used to produce normalized input and output signals of fuzzy logic controller then will produce the stable output response with a suitable performance of the system.

UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

3.5 Fuzzy-PID Controller

The Fuzzy-PID controller is in the PID control based on fuzzy control theory. The fuzzy used to tuned the PID to optimized the best result for a nonlinear system. The PID is tuned by using fuzzy logic controller because the PID is not robust to control the position of the electro-hydraulic actuator when there is a large amount of parameter variation [19]. The Fuzzy-PID block diagram shows by Figure 3.12.

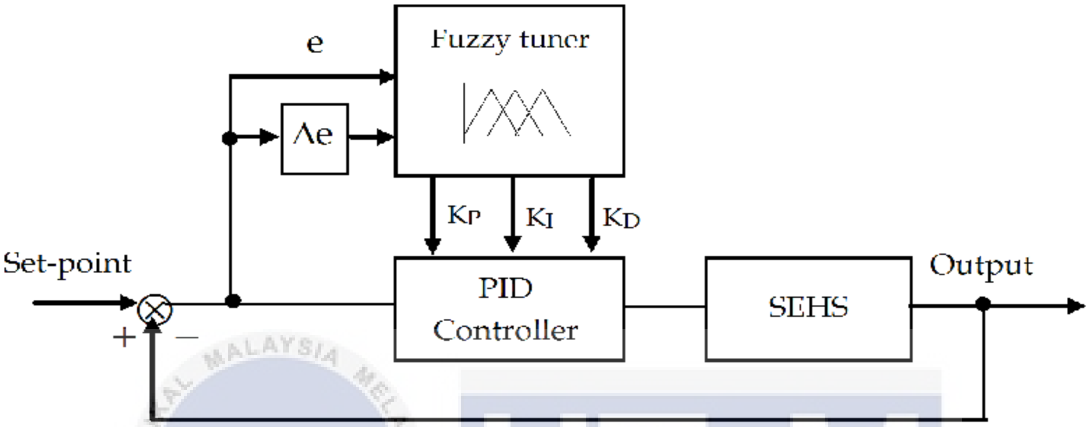


Figure 3.12: Fuzzy-PID block diagram

The conventional PID is used to set the ranges of input and output. The fuzzy is tuned the PID control to improve the tracking position and make the system stable. By changing the gain value of the parameter that effect on the transient response and steady-state error of the system. First, define the inputs and outputs of fuzzy logic that are the derivative is the change of error de(t)/dt and the feedback error of the output is e(t). The outputs of the fuzzy are K_p, $K_i$and K_d as shown in Figure 3.13.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

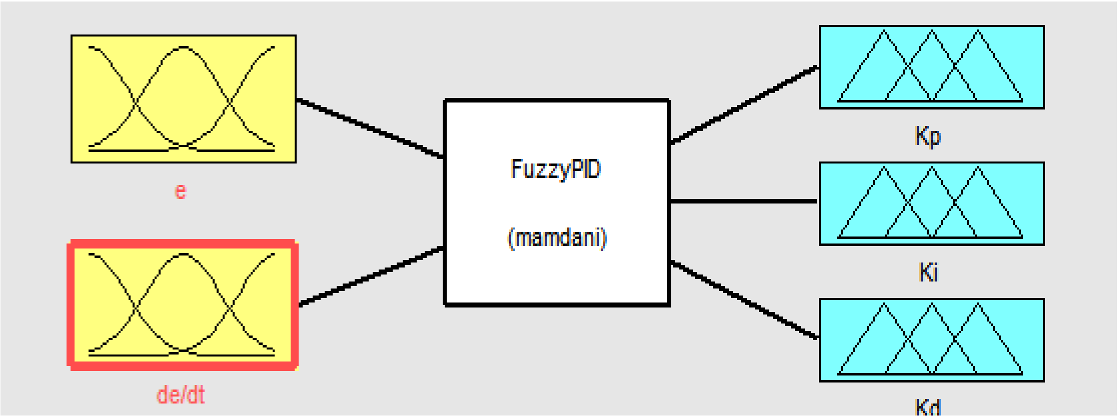
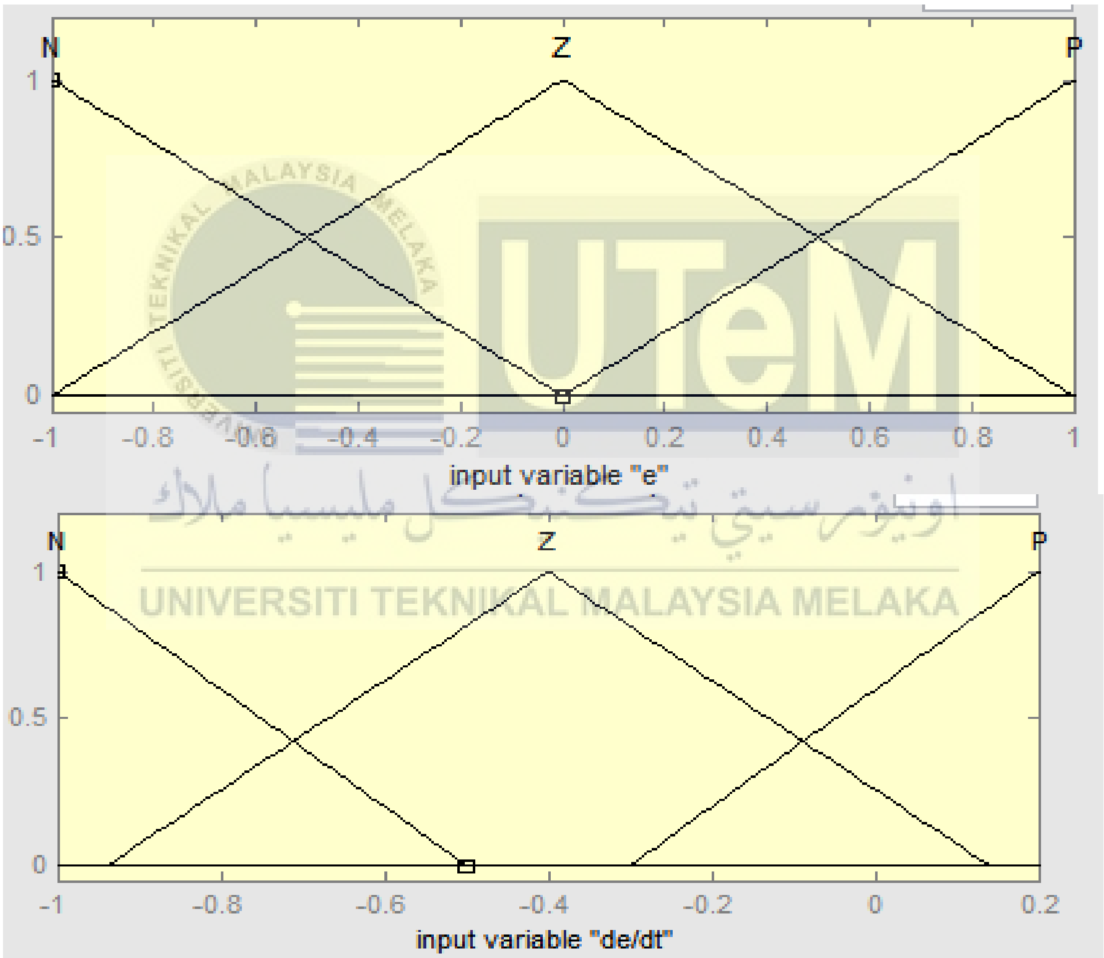


Figure 3.13: Inputs and outputs of Fuzzy-PID controller

Figure 3.13 and 3.14 presents the membership functions for inputs and outputs of fuzzy-PID controller. The error e(t) of the output must be expressed in the interval by the range from -1 to 1 with three linguistic terms in the position: negative (N), zero (Z) and positive (P). The fuzzy set in change of error are three linguistic presented as: negative (N), zero (Z) and positive (P) by the range from -1 to 0.2 as shown in Figure 3.13. Finally, the variables for three outputs K_p has five linguistic variables which are negative (N), negative small (NS), positive small (PS) and positive (P) then K_i and K_d have two linguistic with same membership functions Which are positive medium (PM) and positive big (PB) as shown in Figure 3.14.



UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
اونيۏرسيتي تيكنيكل مليسيا ملاك

Figure 3.14: Inputs membership functions

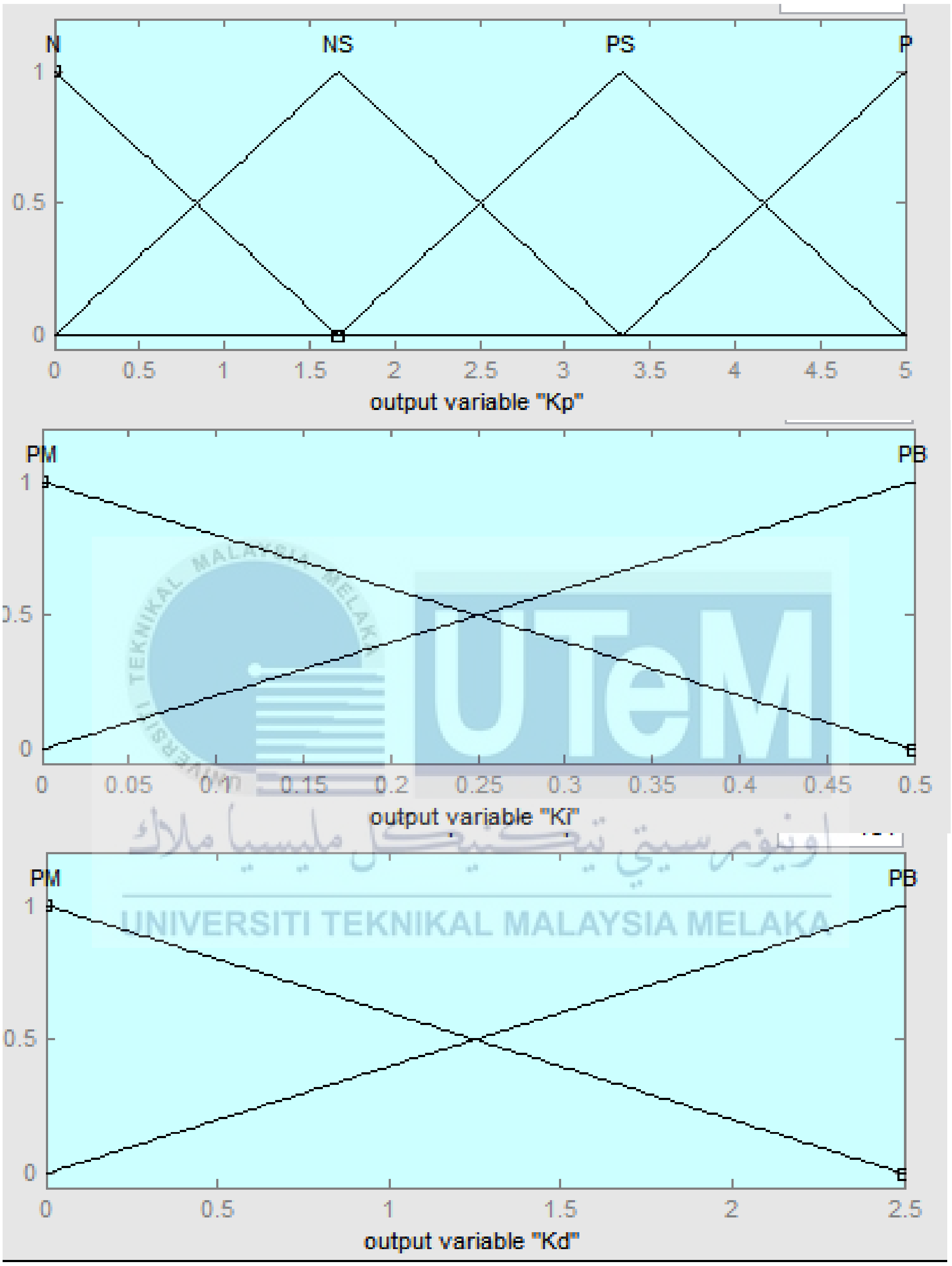
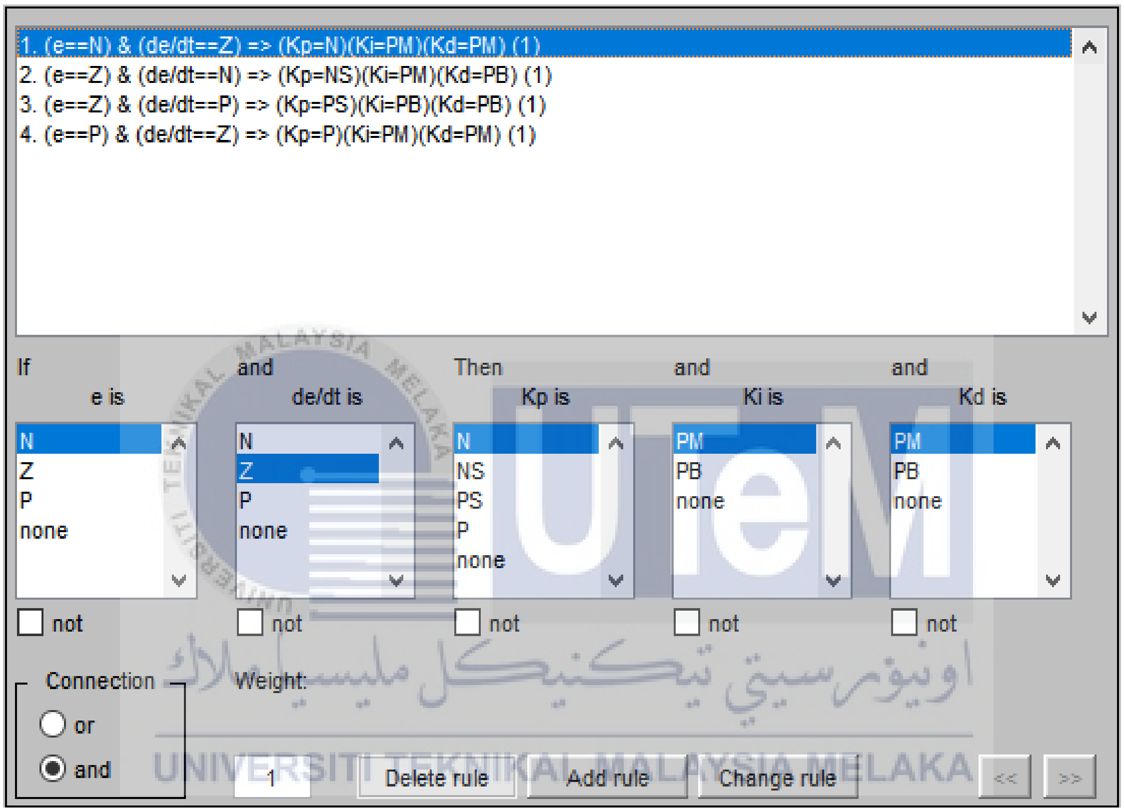


Figure 3.15: Output membership functions

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 3.15 shows the rules for fuzzy-PID related to characteristic of the processes. To set the fuzzy rules depended on the membership functions the error input has three linguistic variables and three variables of change of error then have four rules applied to design fuzzy-PID controller such as if the error is negative and change of error is zero then the outputs must be K_p negative, K_i positive medium and K_d positive medium as shown in Figure 3.15.



```
1. (e==N) & (de/dt==Z) => (Kp=N)(Ki=PM)(Kd=PM) (1)
2. (e==Z) & (de/dt==N) => (Kp=NS)(Ki=PM)(Kd=PB) (1)
3. (e==Z) & (de/dt==P) => (Kp=PS)(Ki=PB)(Kd=PB) (1)
4. (e==P) & (de/dt==Z) => (Kp=P)(Ki=PM)(Kd=PM) (1)
```

If e is N; and de/dt is Z; Then Kp is N; and Ki is PM; and Kd is PM

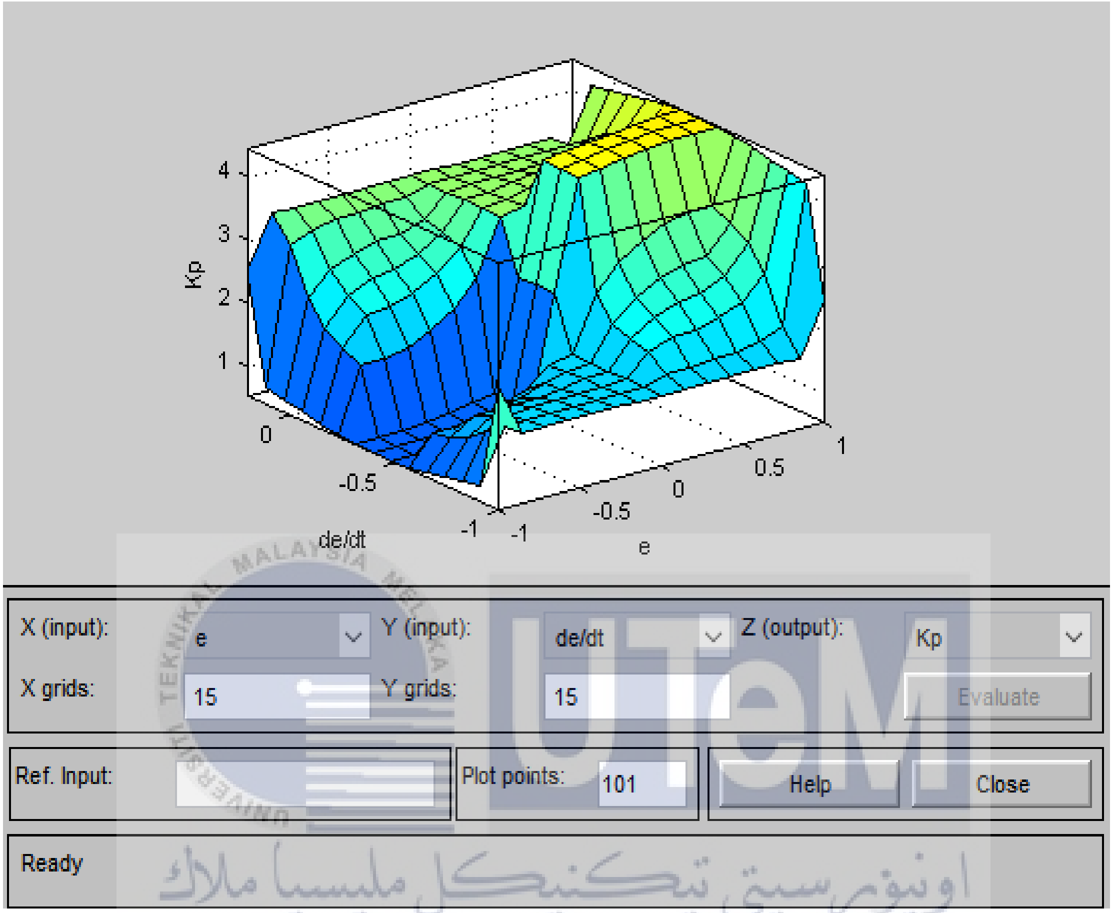
Connection: ○ or ● and

Weight: 1

UNIVERSITI TEKNIKAL MALAYSIA MELAKA
UTeM

Figure 3.16: The rule viewer of the membership functions

The Surface viewer shows the relationship between the input and output if there is any change in the error or change of error we can see the base alteration as shown in Figure 3.16.



X (input): e

Y (input): de/dt

Z (output): Kp

X grids: 15

Y grids: 15

Ref. Input:

Plot points: 101

Ready

Figure 3.17: The surface of Fuzzy-PID controller

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The scaling factors K_1, K_2 and K_3 added to adjust the nonlinear characteristic of fuzzy logic results. By using MATLAB/Simulink to design the whole system then applied centroid method of defuzzification to define the membership function and set four fuzzy rules to get the output results and send to PID controller.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the project data, and results for PID controller design are evaluated. The position of nonlinear electro-hydraulic actuator response with respective value of gain, proportional gain (K_p), integral gain (K_i) and derivative gain (K_d) are presented in this section. All the data of the system overshoot, rise time and settling time are presented in a table for the purpose of easy analysis. Moreover, open-loop system and closed-loop system simulation results are analyzed and discussed. The behavior of the nonlinear electro-hydraulic actuator is analyzed and discussed in this chapter.

4.1 Open-Loop Response of Nonlinear Electro-Hydraulic Actuator

The uncompensated system of nonlinear electro-hydraulic actuator is unstable. Open-loop for the nonlinear electro-hydraulic actuator is simulated by using MATLAB and Simulink as shown in Figure 4.1. The parameter used for servovalve, hydraulic cylinder can be seen in Table

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

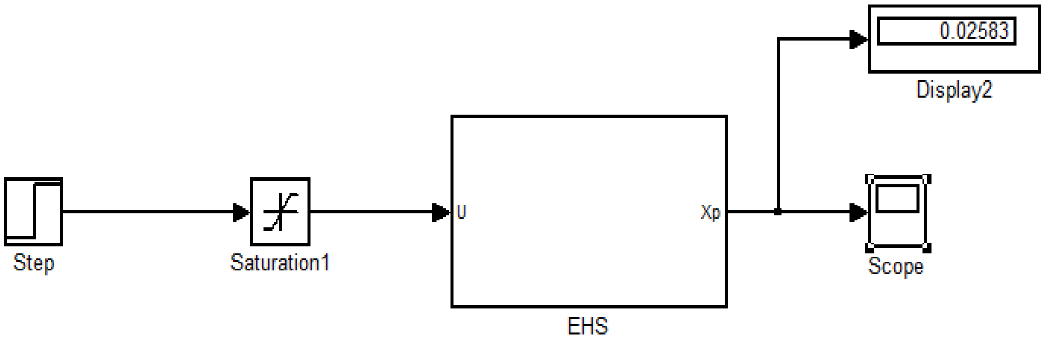


Figure 4.1: The open loop Simulink model

Table 4.1: Parameters of the hydraulic cylinder, servovalve of the actuator system

Symbol	Explanation	Value
A_p	Piston area	645 x10^{-6} m^2
B_l	Viscose damping coefficient	2000 Ns/m
I_{sat}	Saturation current for torque motor	0.02 A
K	The servovalve gain	2.38 x10^{-5}
L_c	Servovalve coil inductance	0.59 H
M_p	Total moving mass	9 Kg
P_r	Tank way pressure	0 pa
P_s	Pump pressure	2.1 x 10^7 pa
Q_{max}	Maximum pump volume	1.67 x 10^{-3} m^3/s
Q_r	Servovalve at 70 bar pressures	0.631 x $10^{-3}m^3$/s
R_c	Servovalve coil resistor	100 ohm
V_{sk}	Stribeck velocity	0.032 m/s
V_t	Volume between pump and servovalve	$0.0005m^3$
α_0	Coulomb friction	370 N
α_1	Stribeck friction	217 N
α_2	Viscous friction coefficient	2318 N/m/s
X_s	Total stroke of piston	0.1 m
ω_n	Servovalve natural	534 rad/s
β	Bulk model of hydraulic fluid	1.4 x 10^{-9} N/m^2
σ_0	Bristles stiffness coefficient	5.77 x10^6 N/m
σ_1	Bristles damping coefficient	2.28 x 10^{-4} N/m/s
K_l	Spring stiffness	10 Nm
k	The leakage coefficient	2.93 x 10^{-1}

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

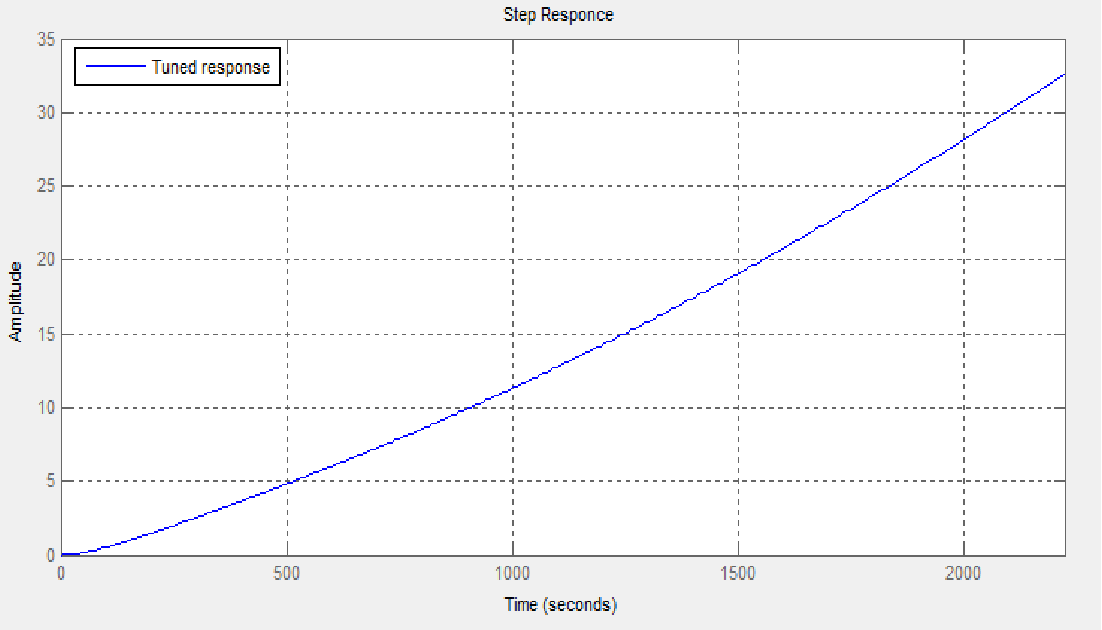


Figure 4.2: The open loop response of nonlinear electro-hydraulic actuator

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

4.2 PID Controller Design

In order to stabilize the position for nonlinear electro-hydraulic actuator system design PID controller. PID controller is design auto tune and Ziegler-Nichols techniques by using MATLAB/Simulink.

4.2.1 Auto Tune Technique

First, PID controller is designed auto tune technique as shown in Figure 4.3. Figure 4.5 shows results of position response for nonlinear electro-hydraulic actuator. The system is stable since it has 217 seconds settling time, 144 seconds rise time and 10.9 degrees overshoot.

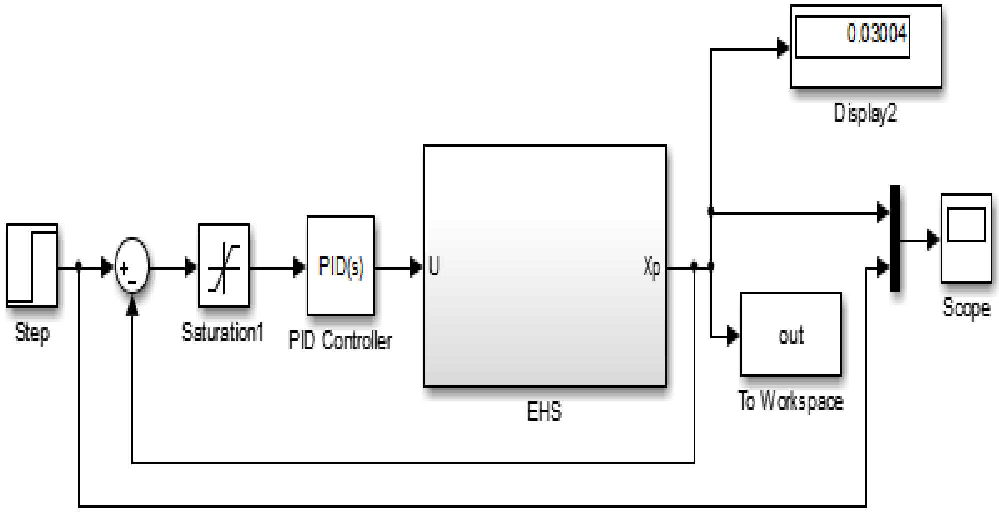
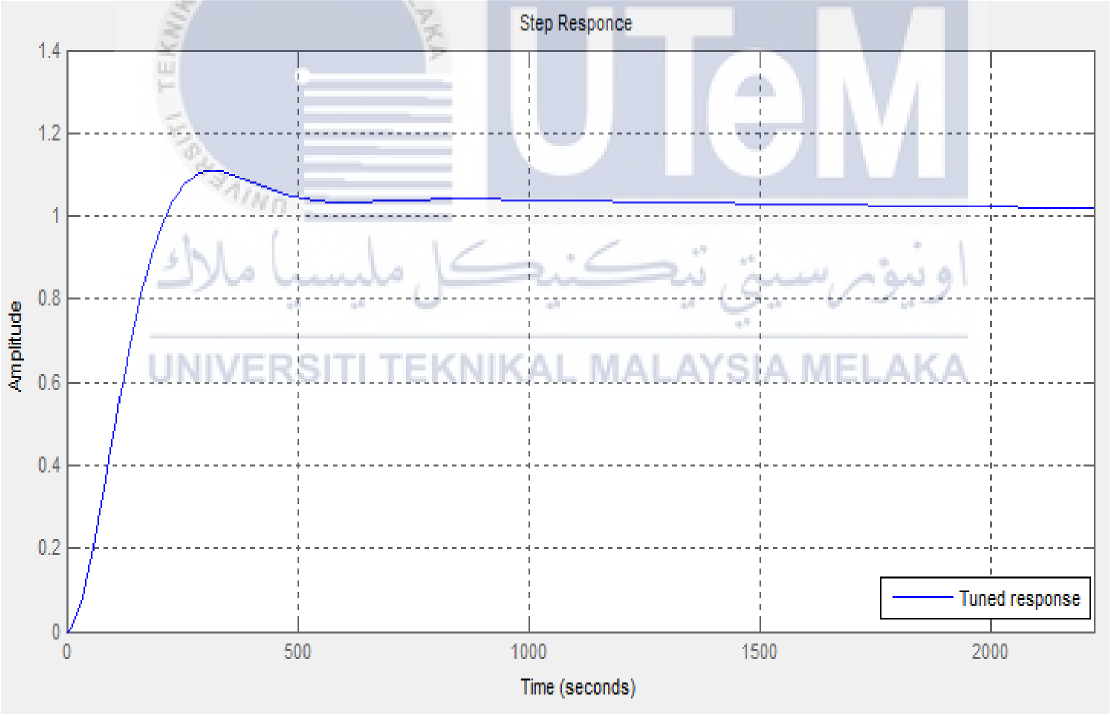
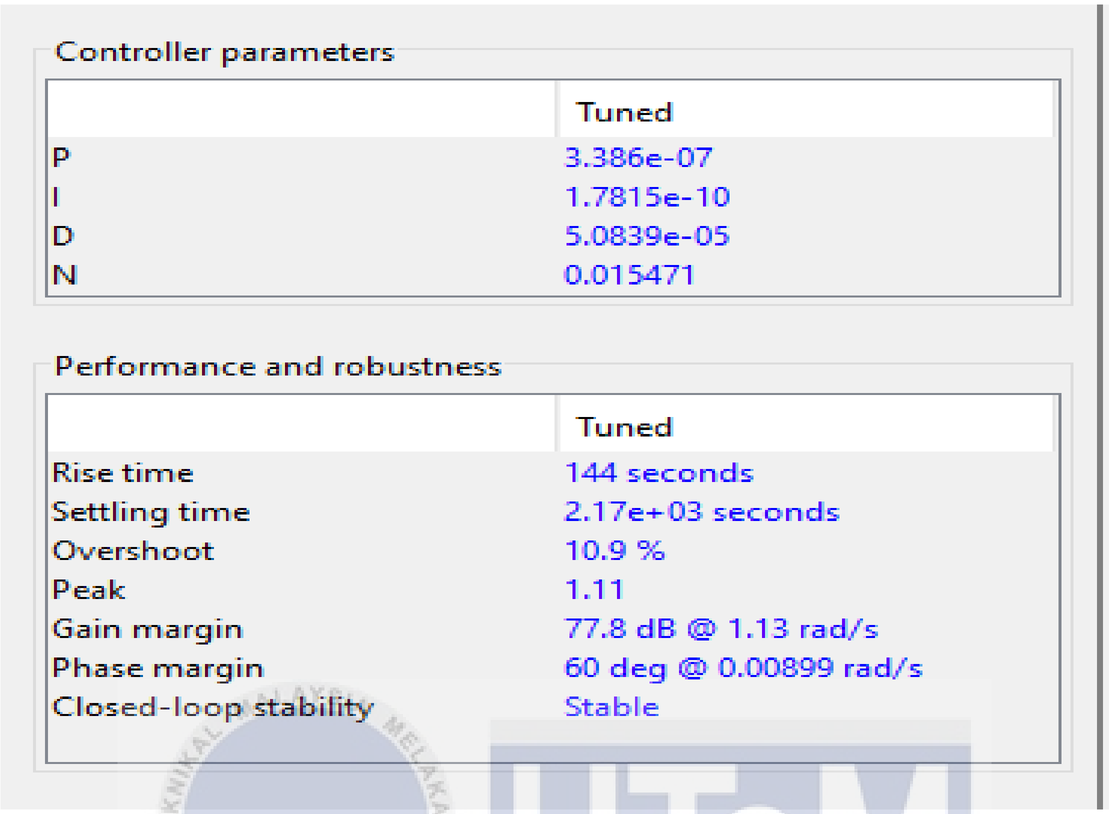


Figure 4.3: The closed loop Simulink model



اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 4.4: The closed loop response of nonlinear electro-hydraulic actuator



Controller parameters

	Tuned
P	3.386e-07
I	1.7815e-10
D	5.0839e-05
N	0.015471

Performance and robustness

	Tuned
Rise time	144 seconds
Settling time	2.17e+03 seconds
Overshoot	10.9 %
Peak	1.11
Gain margin	77.8 dB @ 1.13 rad/s
Phase margin	60 deg @ 0.00899 rad/s
Closed-loop stability	Stable

Figure 4.5: Controller performance

4.2.2 Ziegler-Nichols Technique

For the second design, PID controller is designed Ziegler-Nichols technique by using MATLAB/Simulink. PID controller is designed with setting the value of gain are by using the closed loop Ziegler-Nichols formal. By tuning the PID controller the position behavior for nonlinear electro-hydraulic actuator systems are analysed and discussed.

First, design the PID controller to obtain the parameter value from Ziegler-Nichols by setting the value of $K_i = 0$ and $K_d = 0$ then increase the value of K_p to ultimate gain value K_u until the response become sustained oscillation then measuring the value of $P_{cr}$for full wave cycle in seconds.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

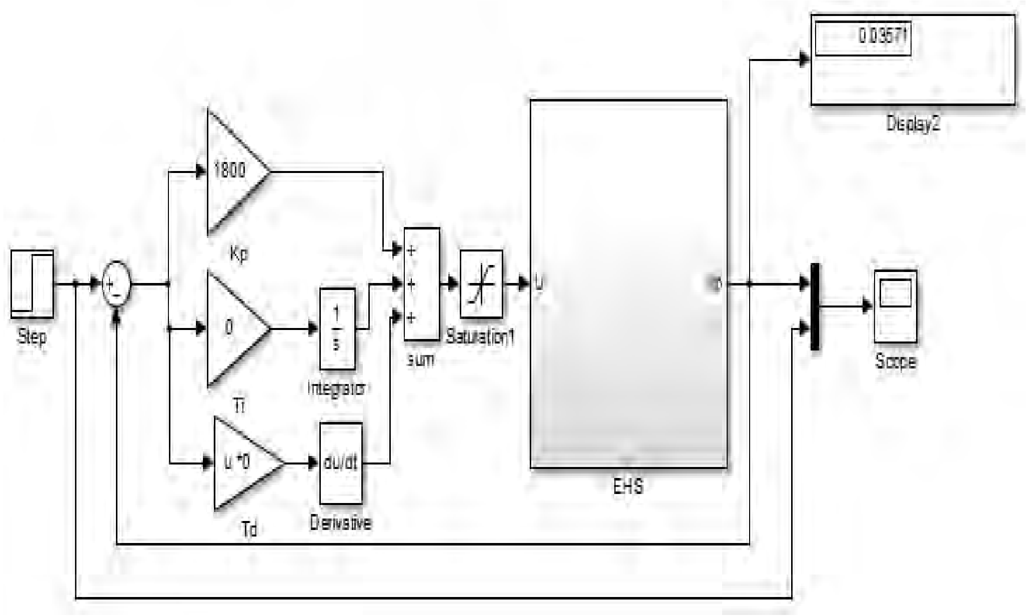
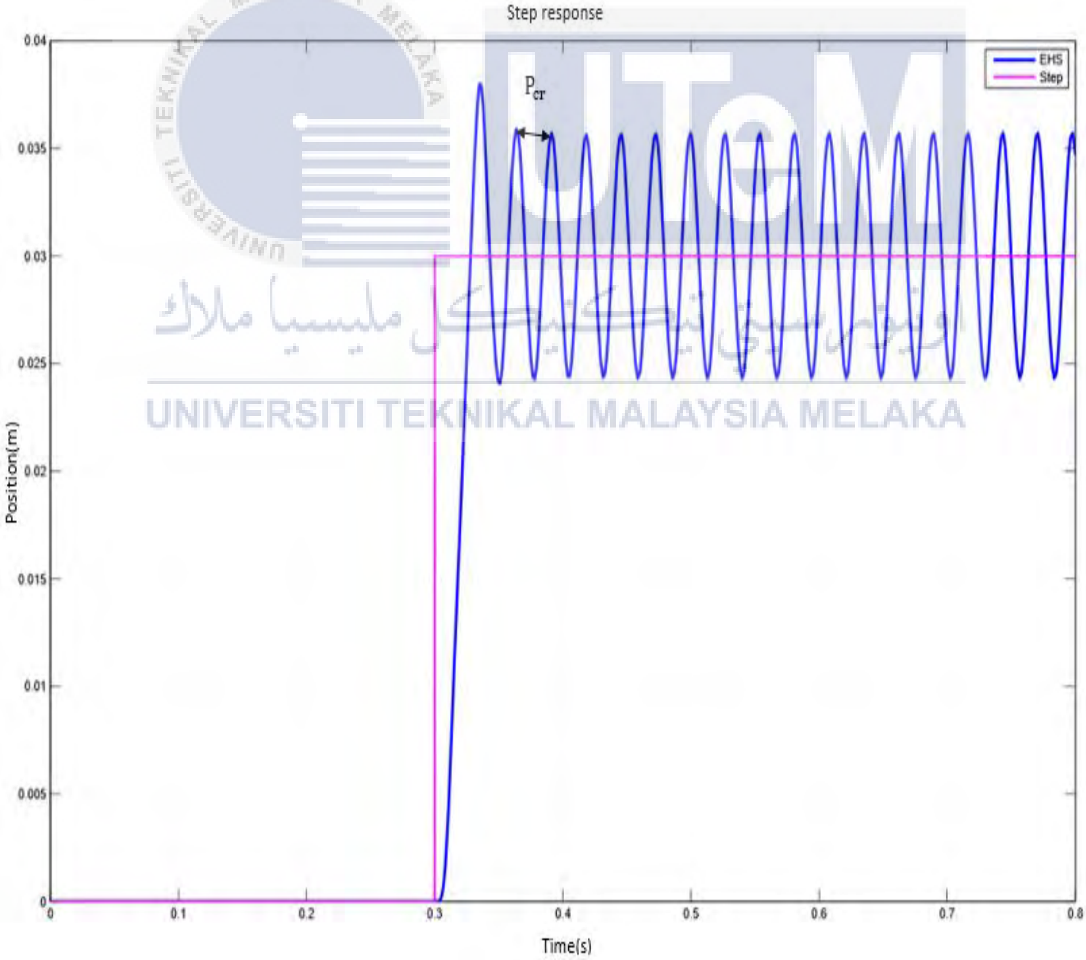


Figure 4.6: The block diagram of PID controller



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 4.7: Sustained oscillation

Figure 4.7 shows the sustained oscillation response and by measuring the periodic for full wave cycle $P_{cr} = 0.391 - 0.363 = 0.028$ second then substitute the value of $K_u = 1800$ and P_{cr} to calculate and obtain the parameter value of PID controller according to the Table 4.2.

Table 4.2: PID controller formal

	K_p	t_i	t_d
P control	900	Inf	0
PI control	818.18	0.0226	0
PID control	1058.82	0.01355	0.00339

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

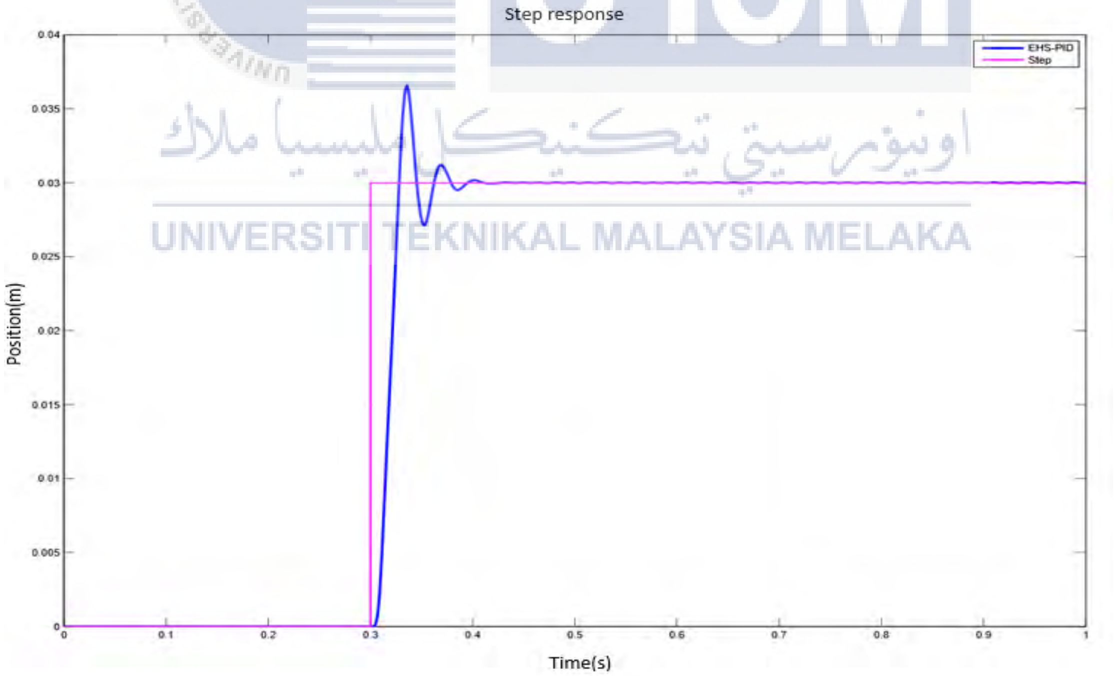
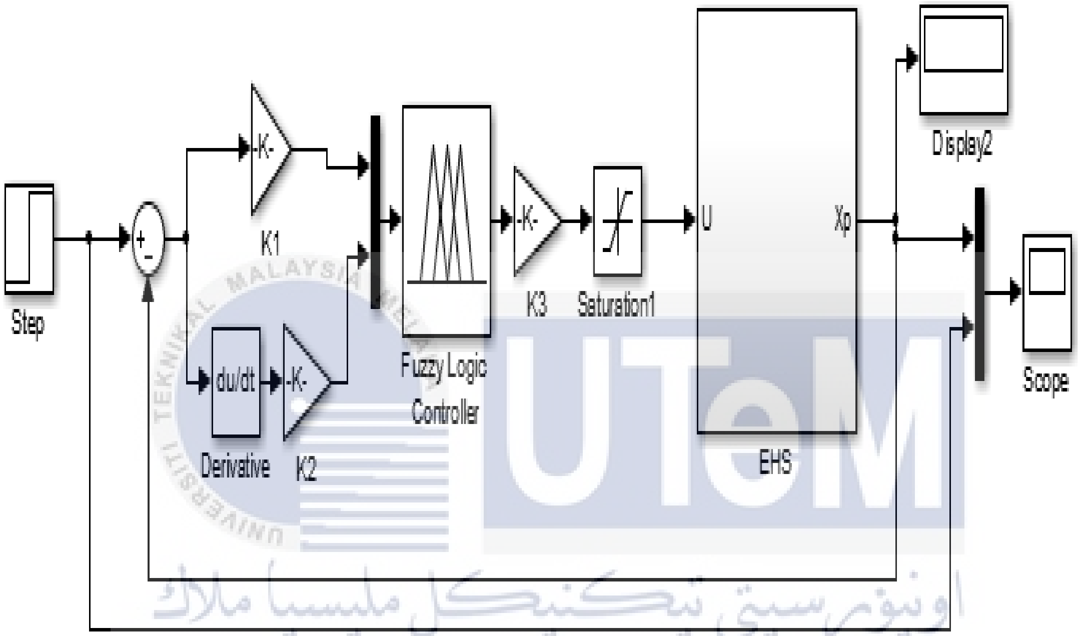


Figure 4.8: The output response of nonlinear electro-hydraulic actuator system using PID-ZN

4.3 Fuzzy Logic Controller Design

To stabilize the nonlinear electro-hydraulic actuator design fuzzy logic controller by using MATLAB/Simulink and evaluate the performance of the position. The set point set as the desired tracking inputs to be step input and respectively to the output response. Figure 4.9 shown the instructor for nonlinear electro-hydraulic actuator system and the fuzzy controller with scaling factor to adjust the output response.



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 4.9: Fuzzy logic controller Simulink model

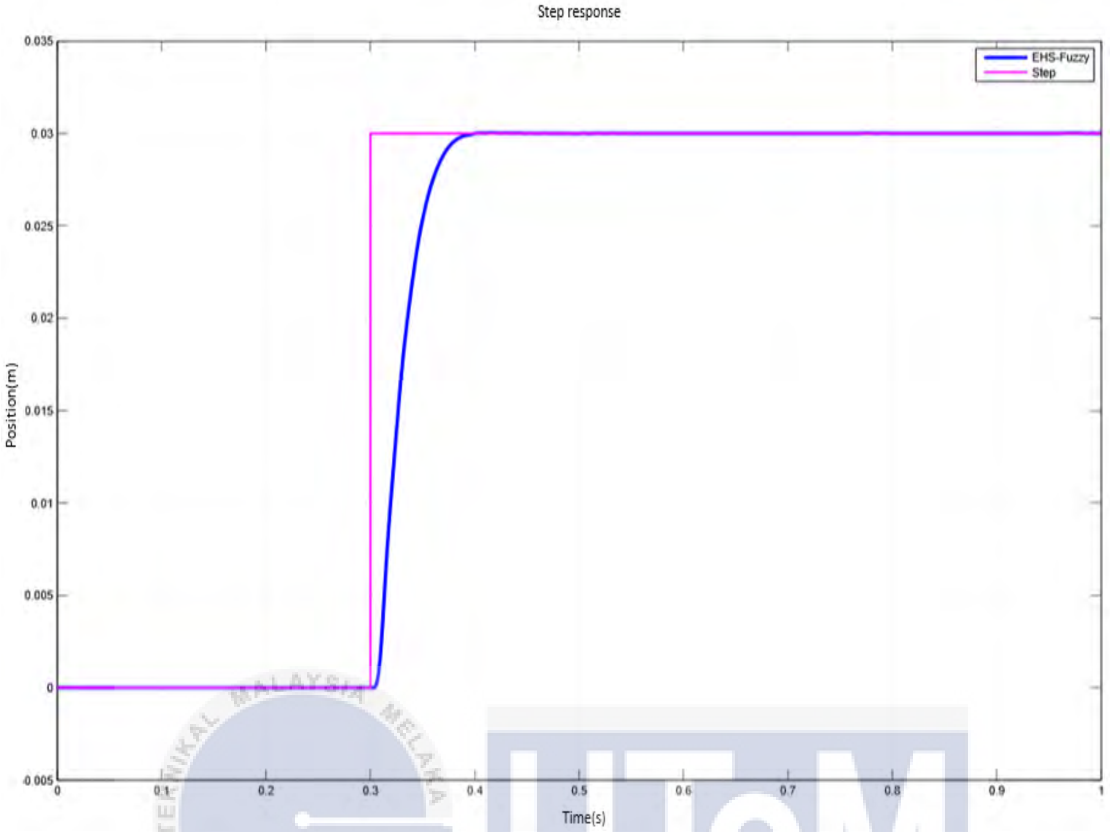
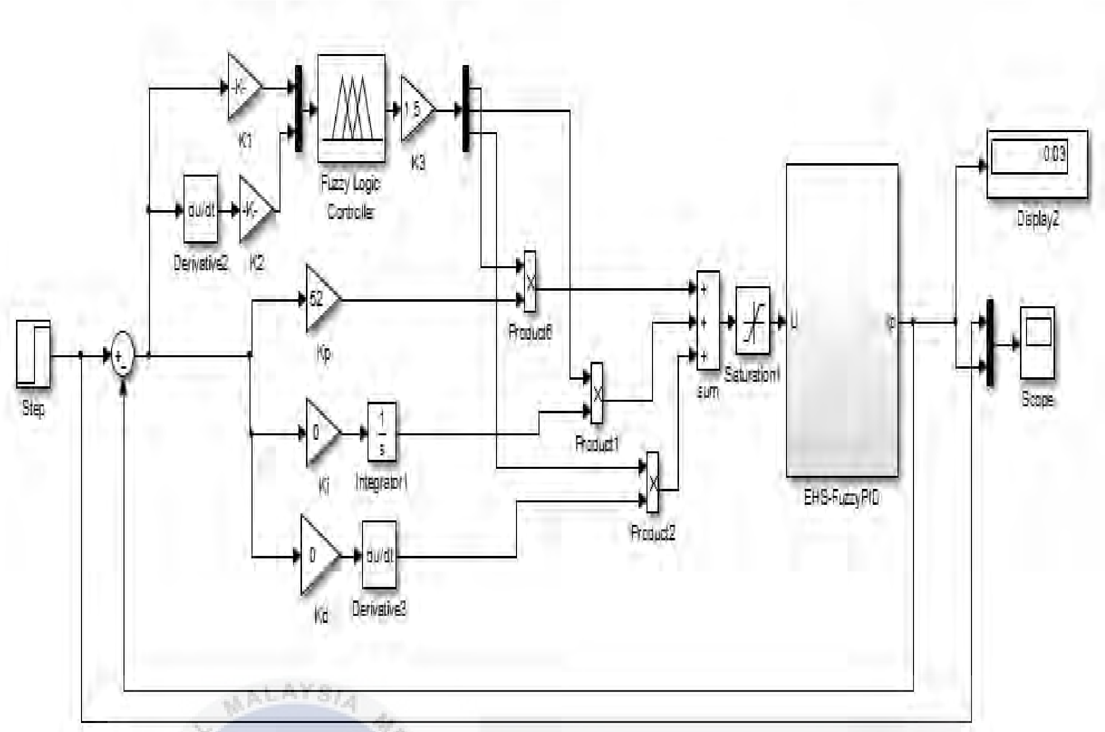


Figure 4.10: The output response of nonlinear electro-hydraulic actuator system using fuzzy logic controller

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

4.4 Fuzzy-PID Controller Design

To control the position tracking error of nonlinear electro-hydraulic actuator system the Fuzzy-PID controller designed by using MATLAB/Simulink as shown in figure. The parameter values of PID controller tuned by fuzzy logic based on the membership function. The scaling factors K_1, K_2 and K_3 set to 20.5, 0.458 and 1.5 to produce and adjust the output response of fuzzy logic and change the parameter values of PID by using trial and error method to suggest the suitable value to obtain the performance of the position.



Figure**Error! Use the Home tab to apply 0 to the text that you want to appear here.**4.11: Fuzzy-PID controller Simulink model

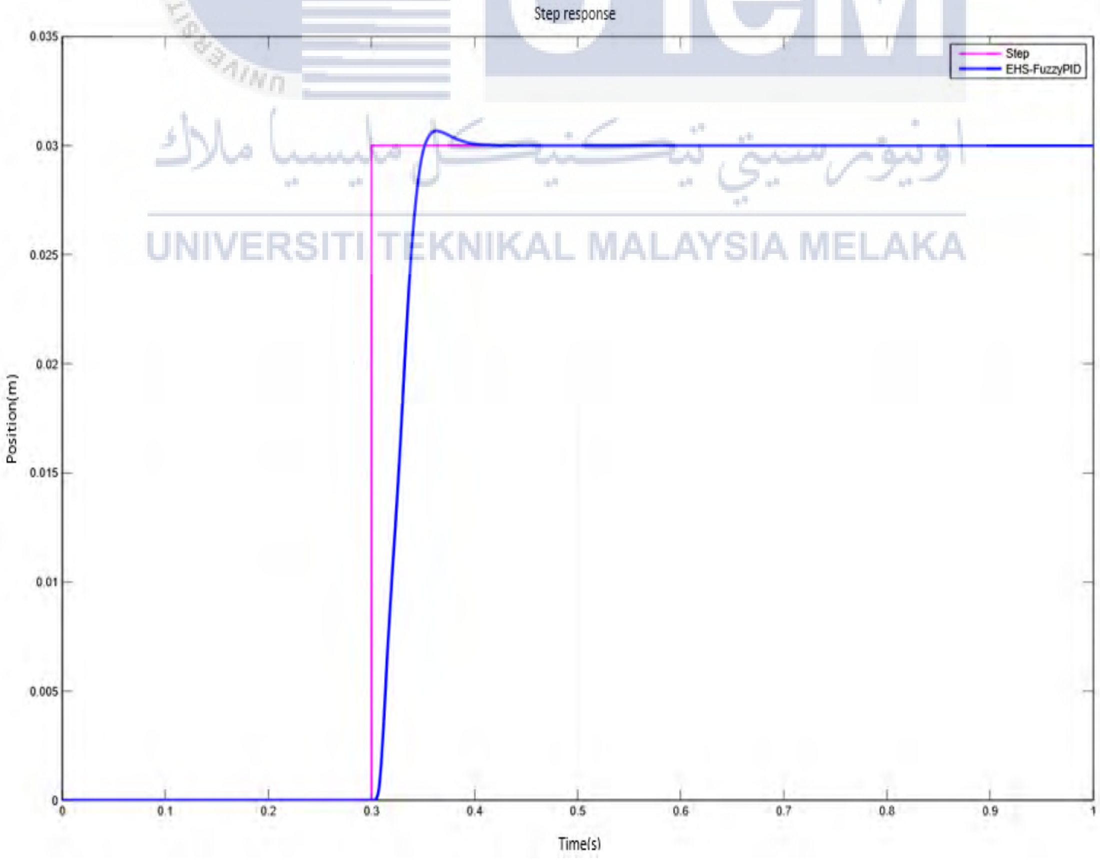


Figure 4.12: Response of Fuzzy-PID controller to a step reference

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

4.5 Analyses and Discussion

Figure 4.8 shows the position response for nonlinear electro-hydraulic actuator systems. The PID controller improve the performance of the system such as settling time, over shoot, rise time and steady state error. Based on Ziegler-Nichols design presented, the value parameter K_p, K_i and K_d give the system better performance results with 23.33% overshot, 0.447 seconds settling time, 0.3257 seconds rise time and zero steady-state error. The position tracking error is reduced by optimize the PID controller by using MATLAB/Simulink software.

Figure 4.10 presents the performance behavior of nonlinear electro-hydraulic actuator systems controlled by Fuzzy logic controller. The simulation output response obtained by step and sinusoidal references inputs. The scaling factors K_1, K_2 and K_3 set to 23.5, 0.456 and 10.5. The results obtained with 0.3333% overshoot, 0.42 second settling time, 0.345 second rise time and zero steady state error that is mean the nonlinear electro-hydraulic actuator systems more stable and the position tracking error reduced.

Figure 4.12 presents the position response of nonlinear electro-hydraulic actuator systems that controlled by Fuzzy-PID controller. The output response obtained by step and sinusoidal reference inputs. It shows the performance results of 2% overshoot, 0.4113 second settling time, 0.34 second rise time and zero steady state error that is mean the difference between step input and the output is zero. The nonlinear electro-hydraulic actuator systems are more stable and the position tracking error reduced.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The simulation results are analysed to show the performance of the desired controller. To evaluate the position tracking performance the block diagram for PID, Fuzzy and Fuzzy-PID controllers are designed to nonlinear electro-hydraulic actuator systems. The results are compared for each controller with respectively the desired input step and sinusoidal references to the system as shown in Figure 4.13 and 4.14.

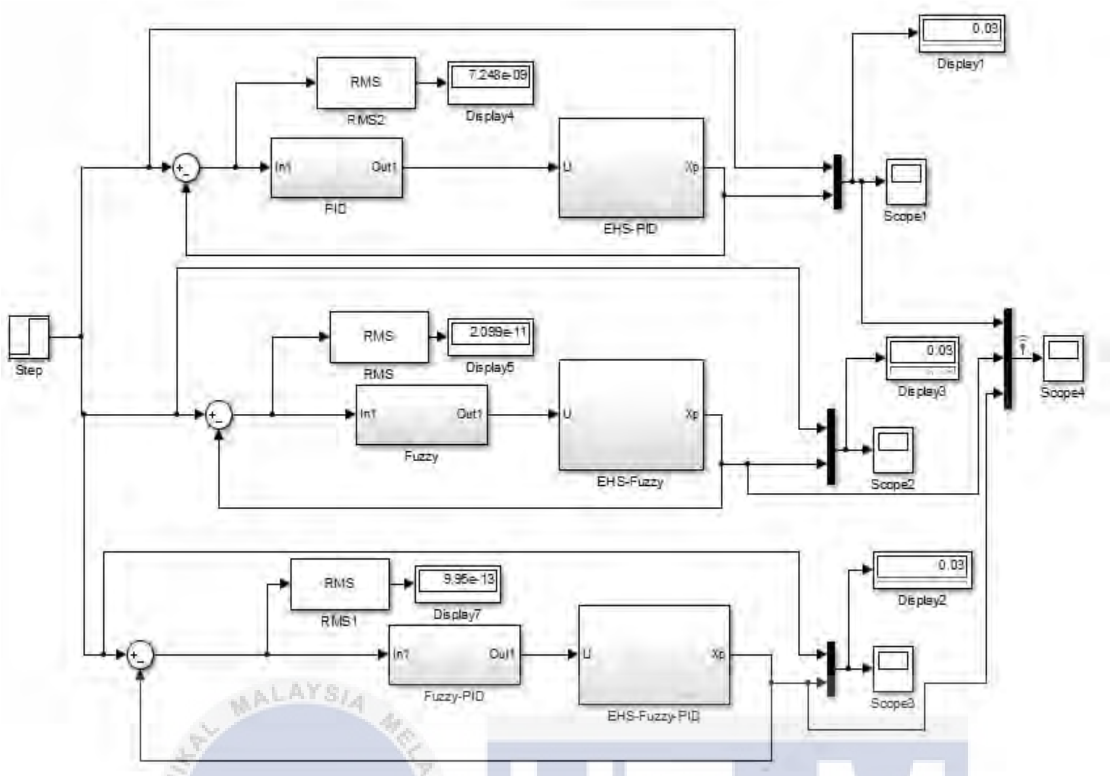


Figure 4.13: Simulink model of PID, Fuzzy logic and Fuzzy-PID controller to a step reference

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

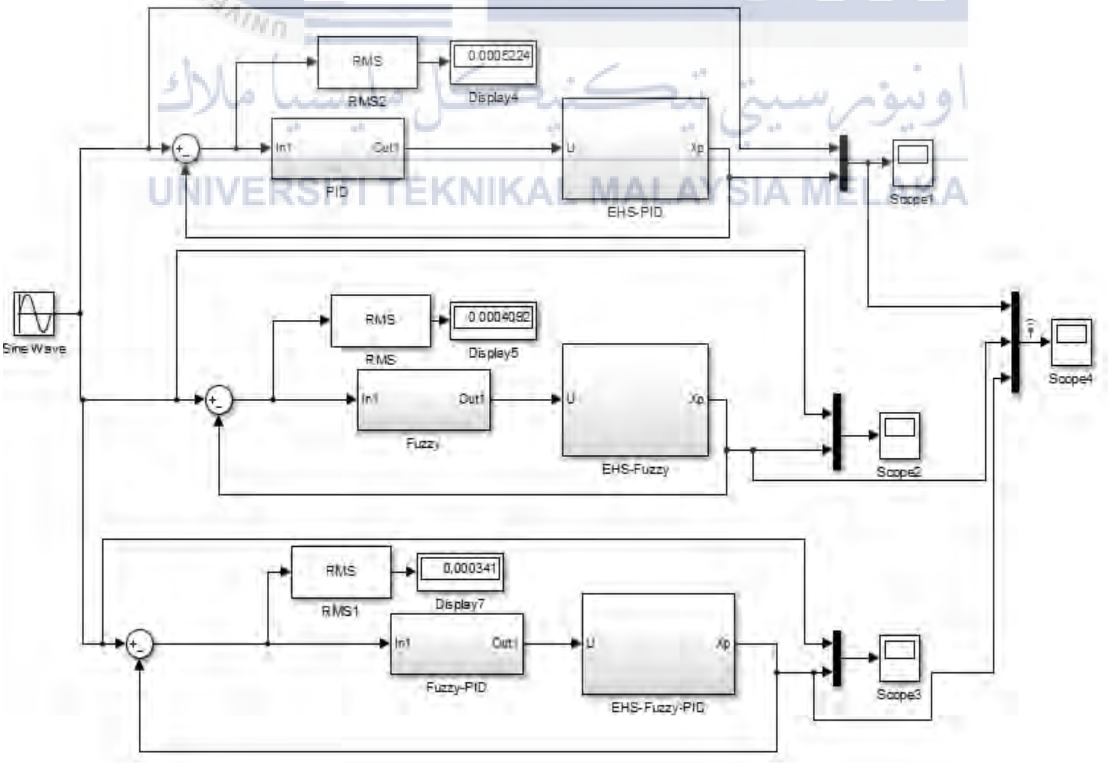


Figure 4.14: Simulink model of PID, Fuzzy logic and Fuzzy-PID controller to sinusoidal reference

Figure 4.15: Response of the controllers to a step reference

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

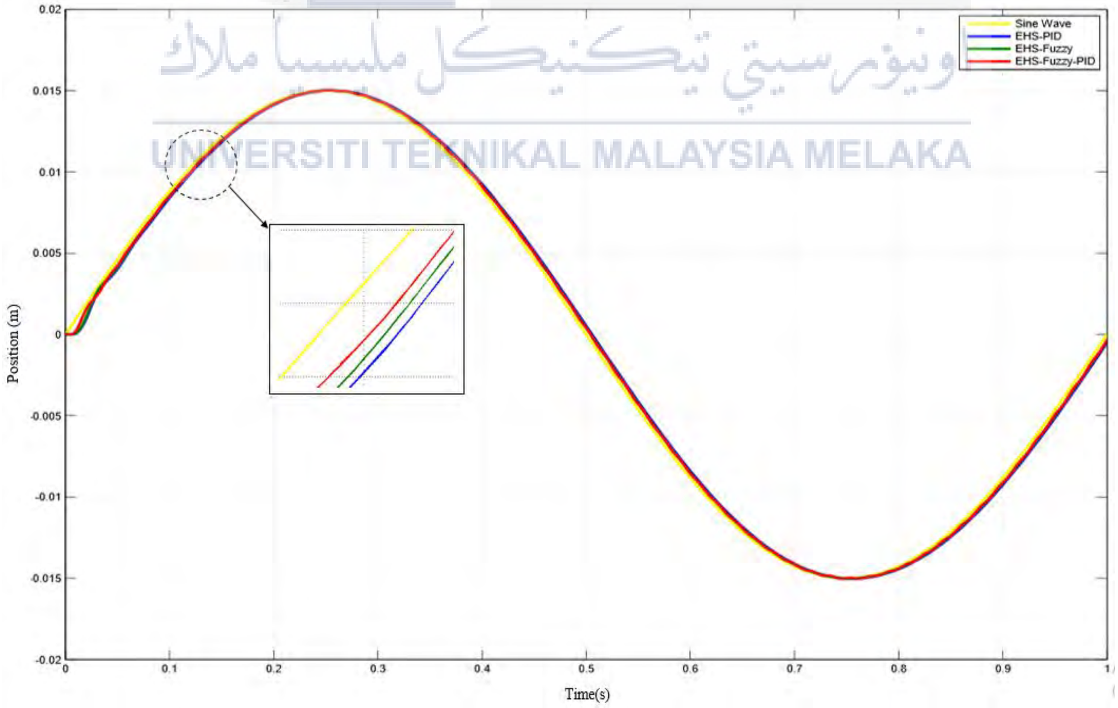


Figure 4.16: Response of the controllers to a sinusoidal reference

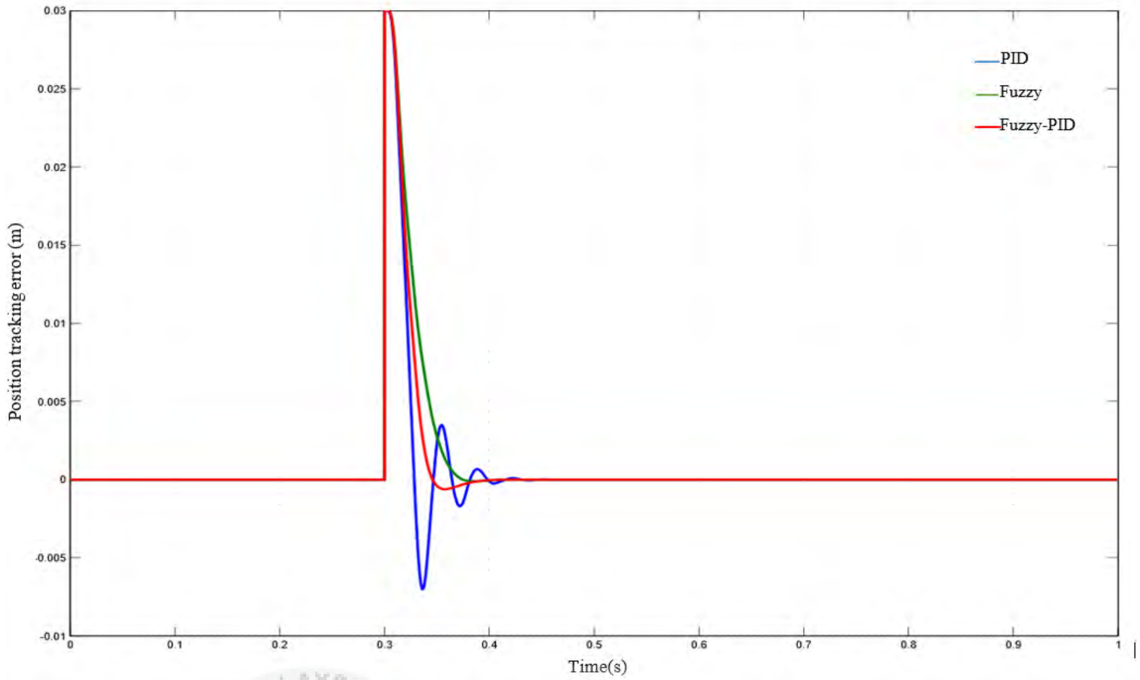


Figure 4.17: Position tracking error of the controllers for a step reference

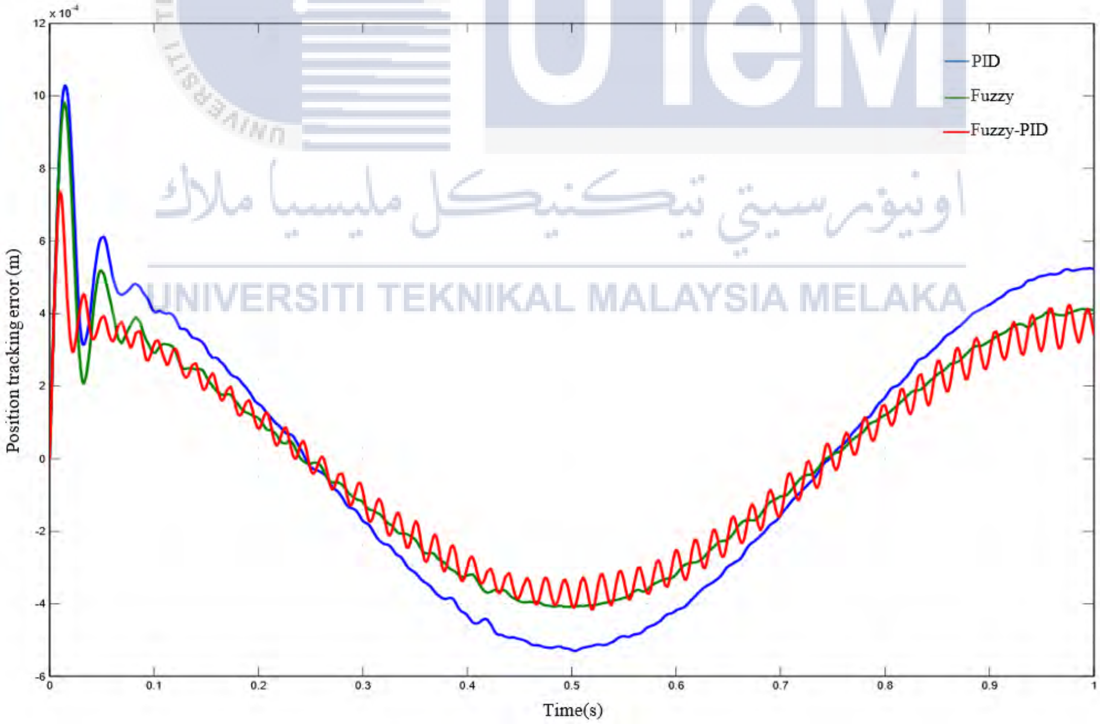


Figure 4.18: Position tracking error of the controllers for a sinusoidal reference

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Table 4.3: The performance of the controllers to a step reference

	Overshoot %	**Settling time (second)**	**Rise time (second)**	**Peak time (second)**	**Steady-state error**
PID	23.33	0.447	0.3257	0.3365	0
Fuzzy logic	0.3333	0.42	0.345	0.3855	0
Fuzzy-PID	2	0.4113	0.34	0.3574	0

Figures 4.15 and 4.16 show the simulation results of the step and sinusoidal references with PID, Fuzzy logic and Fuzzy-PID controllers. From the results, the controllers reduced the position tracking error of nonlinear electro-hydraulic actuator systems. Figure 4.15 shows the step reference with results of PID, Fuzzy and Fuzzy-PID by comparing the performance for each controller such as overshoot, settling time, rise time, peak time and steady state error. Related to Table 4.3 shows the performance of PID, Fuzzy and Fuzzy-PID are 23.33%, 0.3333% and 2% that means the Fuzzy logic controller have less overshoot, for settling time 0.447 second, 0.42 second and 0.4113 second that shows the Fuzzy-PID controller is faster than PID and Fuzzy controllers, for rise time 0.3257 second, 0.345 second and 0.34 second the PID is faster, for peak time 0.3365 second, 0.3855 second and 0.3574 second the PID controller is faster and zero steady state error for all controller. Table 4.4 illustrated the RMS values for PID, Fuzzy and Fuzzy-PID controllers (7.248x10^{-9}, 2.099x10^{-11} and 9.95x10^{-13}) that shows the RMS values for the Fuzzy-PID controller is less than that PID and Fuzzy controllers.

Figure 4.16 shows the response of PID, Fuzzy and Fuzzy-PID controllers to a sinusoidal reference by analyse the graph for each controller. The output response for Fuzzy-PID is near to the sinusoidal reference then PID and Fuzzy logic that is mean the different between the sinusoidal input and Fuzzy-PID response less than the PID controller and Fuzzy logic. Table 4.4 shows the RMS values for the controllers (5.224x10^{-4}, 4.092x10^{-4} and 3.41x10^{-4}) to a sinusoidal reference. Table 4.4 illustrates the RMS values for the Fuzzy-PID controller is less than that of the PID and

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Fuzzy logic controllers. Whereas the Fuzzy logic controller has a lower value of RMS than that of the PID controller. Figures 4.17 and 4.18 shows the position tracking error of the controllers to a step and sinusoidal references. The Fuzzy-PID controller has the lower error than that of the PID and Fuzzy logic controllers.

Table 4.4: RMS values of the controllers to a step and sinusoidal reference

	RMS value of step	**RMS value of sinusoidal**
PID	$7.248\text{x}10^{-9}$	$5.224\text{x}10^{-4}$
Fuzzy logic	$2.099\text{x}10^{-11}$	$4.092\text{x}10^{-4}$
Fuzzy-PID	$9.95\text{x}10^{-13}$	$3.41\text{x}10^{-4}$

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The Fuzzy-PID controller obtain better performance for nonlinear electro-hydraulic actuator systems with step and sinusoidal references compared to PID and Fuzzy logic controllers and the position tracking error reduced. Table 4.4 illustrates the Fuzzy-PID controller has the lower RMS values to a variation references input than that PID and Fuzzy logic controllers. Fuzzy-PID controller achieved the best performance for the system with less overshoot, faster settling time, faster rise time and zero steady state error.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In this chapter, the conclusions of the project as well as recommendation for future development are discussed. The project outcome is concluded in this chapter. As for future development and studies, some suggestions are highlighted to improve the project.

5.1 Conclusion

In conclusion, considering the simulation results, the control technique designed and developed to the mathematical model of the nonlinear electro-hydraulic actuator system. The mathematical model of the nonlinear electro-hydraulic actuator is approximated using MATLAB and Simulink. The PID, Fuzzy logic and Fuzzy-PID controllers were successfully developed and applied to the mathematical model of nonlinear electro-hydraulic actuator systems in a wide range of physical uncertainties and external disturbances. By using auto tuning and Ziegler-Nichols methods to tune the PID controller, the system is tuned to improve transient response and the steady-state error of the system so that the tracking position achieves the design requirements. The result was compared with PID, Fuzzy logic and Fuzzy-PID controllers. The linear and intelligent controllers have been evaluated using various tracking trajectories. It shows that hybrid Fuzzy-PID performs better as compared to PID and Fuzzy controllers. About 20% improvement of the tracking error has been obtained using the Fuzzy-PID controller. From the results and analysis that had been discussed in Chapter 4, the Fuzzy-PID controller achieved better performance of nonlinear electro-hydraulic actuator systems and the position tracking error reduced.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

5.2 Recommendation

It is recommended that different types of control technique such as Fuzzy logic and neural network with PID controller that are used to control the tracking position error for nonlinear electro-hydraulic actuator systems and compare the performance between the controllers. Fuzzy logic and neural network controllers are a robust controller and provide faster response compared to PID controller. Other control technique such as full state feedback control (FSF) and linear quadratic regulator control (LQR) is also recommended to control the position for nonlinear electro-hydraulic actuator systems.

UTeM
اونيۆرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

REFERENCES

[1] A. A. Aly, "A Hybrid of Fuzzy and PID Controller for Servo Electro-Hydraulic System," IEEE Conference on Industrial Electronics and Applications, vol. 6, no. 5, pp. 1595–1600, 2015.

[2] H. S. Zad and A. Ulasyar, "Robust Model Predictive Position Control of Direct Drive Electro-Hydraulic Servo System," in 2016 International Conference on Intelligent Systems Engineering (ICISE), 2016, p. 100–104.

[3] J. Yao, L. Wang, C. Wang, Z. Zhang, and P. Jia, "ANN-based PID controller for an electro-hydraulic servo system," Proc. IEEE Int. Conference. Autom. Logist. ICAL 2008, vol. 2, no. September, pp. 18–22, 2008.

[4] N. H. Izzuddin, A. 'Athif M. Faudzi, M. R. Johary, and K. Osman, "System identification and predictive functional control for electro-hydraulic actuator system," 2015 IEEE Int. Symp. Robot. Intell. Sensors, vol. 16, no. June, pp. 138–143, 2015.

[5] R. Ghazali, Y. M. Sam, M. F. A. Rahmat, and Zulfatman, "Point-to-point trajectory tracking with two-degree-of-freedom robust control for a non-minimum phase electro-hydraulic system," Proc. World Congr. Intell. Control Autom., pp. 2661–2668, 2012.

[6] D. M. Wonohadidjojo and M. Y. Hassan, "Position Control of Electro-hydraulic Actuator System Using Fuzzy Logic Controller Optimized by Particle Swarm Optimization," vol. 10, no. June, pp. 181–193, 2013.

[7] M. J. Willis, "Proportional-Integral-Derivative Control," Book, pp. 1–13, 1999.

[8] Z. Wanli, L. Guoxin, and W. Lirong, "Application of the Improved Variable Arguments PID in Asymmetric Hydraulic Cylinder Electro-hydraulic Servo System," 2015 IEEE Fifth Int. Conf. Big Data Cloud Comput., no. 1, pp. 223–226, 2015.

[9] D. Q. Truong, K. K. Ahn, and J. Il Yoon, "A Generation Step to Develop Steel Rolling Machine Performance Using An Electro-Hydraulic Actuator and An Online Tuning Modified-Grey Fuzzy PID Controller," IEEE 2010 International

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Conference, pp. 423–428, 2010.

[10] M. G. Skarpetis and F. N. Koumboulis, “Robust PID controller for electro - Hydraulic actuators,” IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA, pp. 6–10, 2013.

[11] Y. U. Jue, Z. Jian, and Y. U. Dehong, “Parameter optimization of PID controller based on Complex System Genetic Algorithm in Electro-hydraulic Servo Control System *,” IEEE Conference Publications no. 2011, pp. 30–35, 2012.

[12] A. Tadesse and M. Jungong, “Modeling and simulations on a fuzzy- PID position controller of electro hydraulic servo system,” 2015 12th IEEE Int. Conf. Fuzzy Syst. Knowl. Discov. FSKD 2015, pp. 96–103, 2016.

[13] R. Adnan, M. Tajjudin, N. Ishak, H. Ismail, and M. H. Fazalul Rahiman, “Self-tuning fuzzy PID controller for electro-hydraulic cylinder,” in Proceedings - 2011 IEEE 7th International Colloquium on Signal Processing and Its Applications, pp. 395 - 398, CSPA 2011, 2011.

[14] Zulfatman and M. F. Rahmat, “Application of Self-Tuning Fuzzy-PID Controller on Industrial Hydraulic Actuator,” Nternational J. Smart Sens. Intell. Syst., vol. 2, no. 2, pp. 246–261, 2009.

[15] C. Lizalde, a. Loukianov, and E. Sanchez, “Force Tracking Neural Control for an Electro-Hydraulic Actuator Via Second Order Sliding Mode,” Proc. 2005 IEEE Int. Symp. on, Mediterrean Conf. Control Autom. Intell. Control. 2005., pp. 292–297, 2005.

[16] H. S. H. Sun and G. T.-C. Chiu, “Motion synchronization for multi-cylinder electro-hydraulic system,” 2001 IEEE/ASME Int. Conf. Adv. Intell. Mechatronics. Proc. (Cat. No.01TH8556), vol. 1, no. July, pp. 636–641, 2001.

[17] M. Kalyoncu and M. Haydim, “Mathematical modelling and fuzzy logic based position control of an electrohydraulic servosystem with internal leakage,” Mechatronics, Article Journal, vol. 19, no. 6, pp. 847–858, 2009.

[18] M. Mihajlov, V. Nikoli, and D. Anti, “Position Control Of An Electro-Hydraulic Servo System Using Sliding Mode Control Enhanced By Fuzzy PI Controller,” vol. 1, pp. 1217–1230, 2002.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

[19] P. Pratumsuwan and A. Junchangpood, “Force and position control in the electro-hydraulic system by using a MIMO fuzzy controller,” Proc. 2013 IEEE 8th Conf. Ind. Electron. Appl. ICIEA 2013, pp. 1462–1467, 2013.

[20] N. Ishak, M. Tajjudin, R. Adnan, H. Ismail, and Y. M. Sam, “Real-time application of self-tuning PID in electro-hydraulic actuator,” in Proceedings - 2011 IEEE International Conference on Control System, Computing and Engineering, ICCSCE 2011, 2011, pp. 364–368.

[21] L. Shangguan, Z. Li, Z. Yang, M. Li, Y. Liu, and J. Han, “OTrack: Towards order tracking for tags in mobile RFID systems,” IEEE Trans. Parallel Distrib. Syst., vol. 25, no. 8, pp. 2114–2125, 2014.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPENDICES

Appendix A: Gantt Chart for Final Year Project 1

TASK	WEEK													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Project Introduction *Motivation *Problem statement *Objective *Scope	■	■	■	■									■	■
2. Literature review *****Basic background of hydraulic actuator *Linear, nonlinear and intelligent control * State of Art				■	■	■	■							
3. Methodology * Simulation flowchart * Modeling of electro-hydraulic actuator * Design the controller							■	■	■	■				
4. Primarily result										■	■	■		
5. Conclusion												■	■	
6. Presentation slide												■	■	■

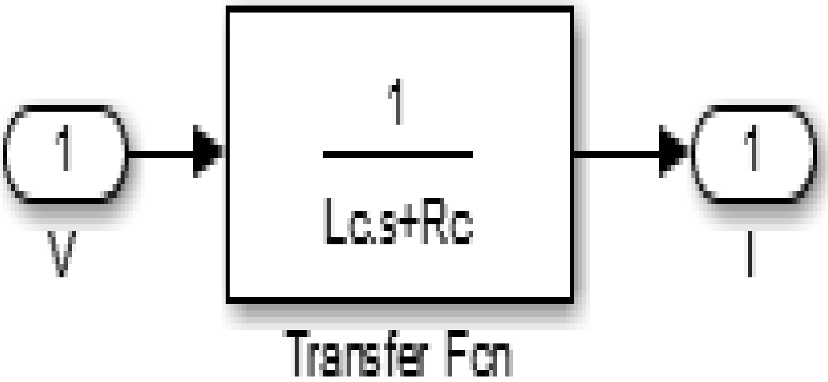
UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
اونيۏرسيتي تيكنيكل مليسيا ملاك

Appendix B: Gantt Chart for Final Year Project 2

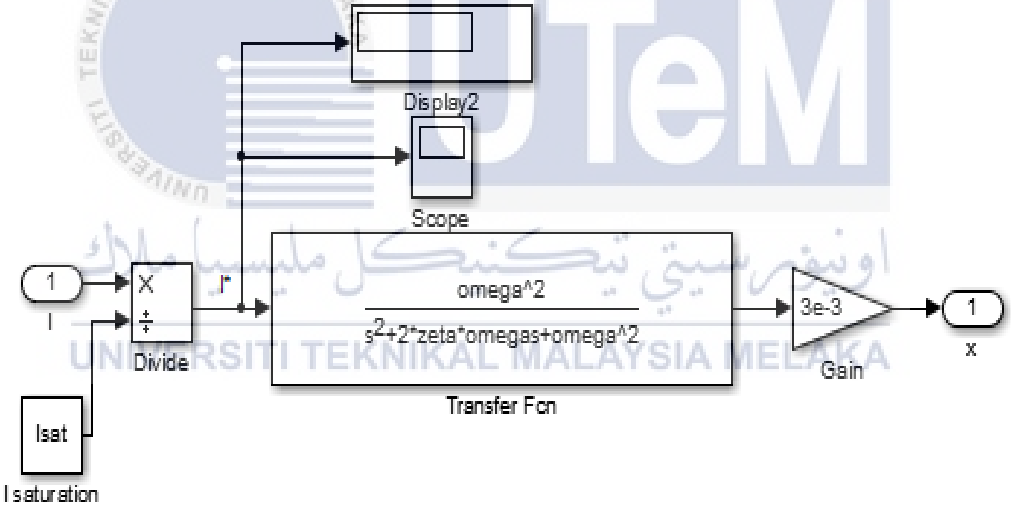
TASK \ WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LITERATURE REVIEW	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥							
METHODOLOGY			🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪					
RESULTS AND DISCUSSION						🟦	🟦	🟦	🟦	🟦	🟦	🟦			
DESIGN CONTROLLER						🟦	🟦	🟦	🟦	🟦	🟦	🟦			
1. DESIGN PID CONTROLLER 2. DESIGN FUZZY CONTROLLER 3. DESIGN FUZZY-PID						🟦	🟦	🟦	🟦	🟦	🟦	🟦			
ANALYSES AND DISCUSSION											🟪	🟪	🟪		
CONCLUSION													🟥		
REPORT SUBMISSION													🟩	🟩	
1. DRAFT REPORT													🟩	🟩	
2. SLIDE PRESENTATION													🟩	🟩	
PSM 2 SEMINAR															🟨

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Appendix C1: Torque motor model

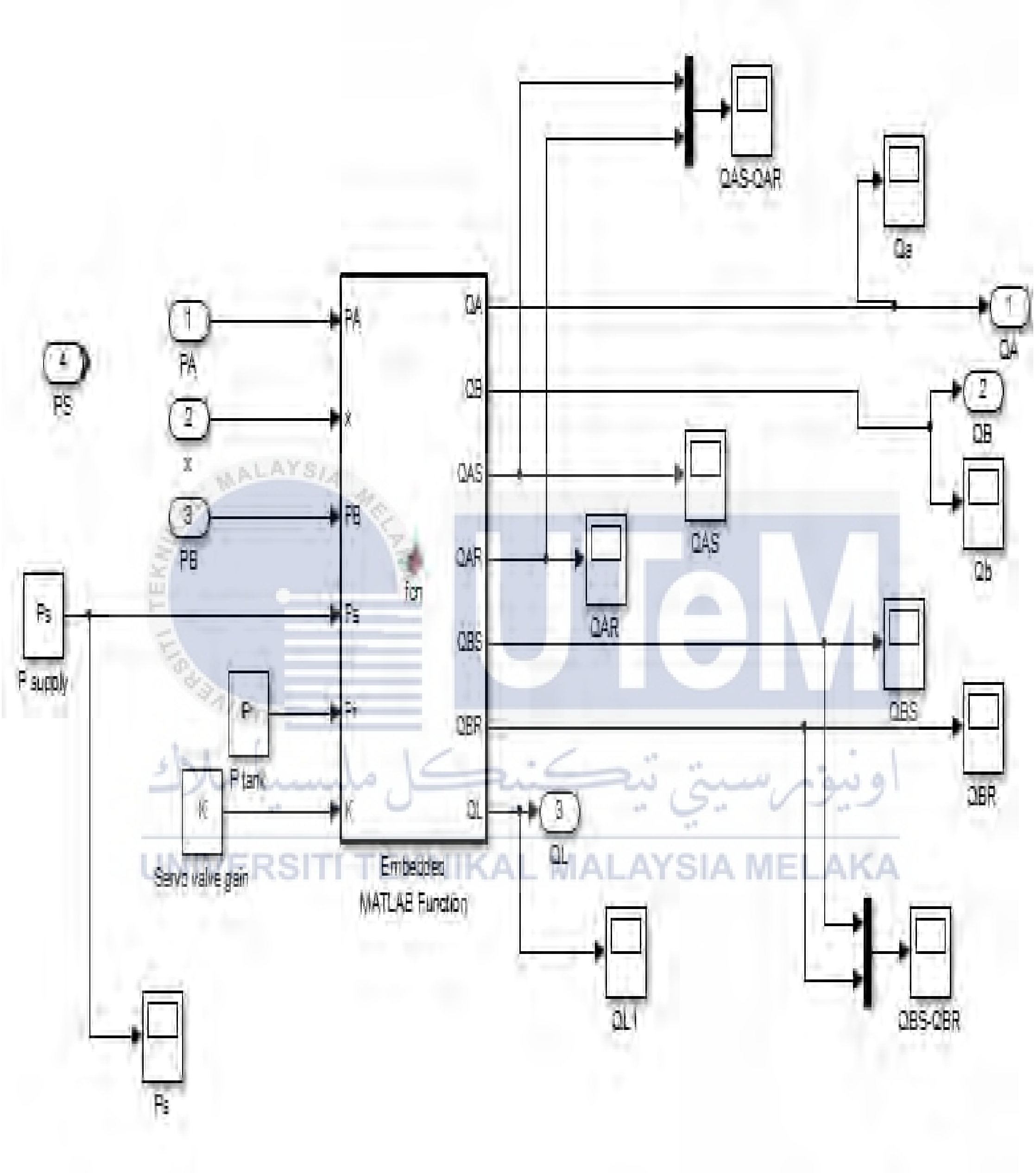


Appendix C2: Spool dynamic model



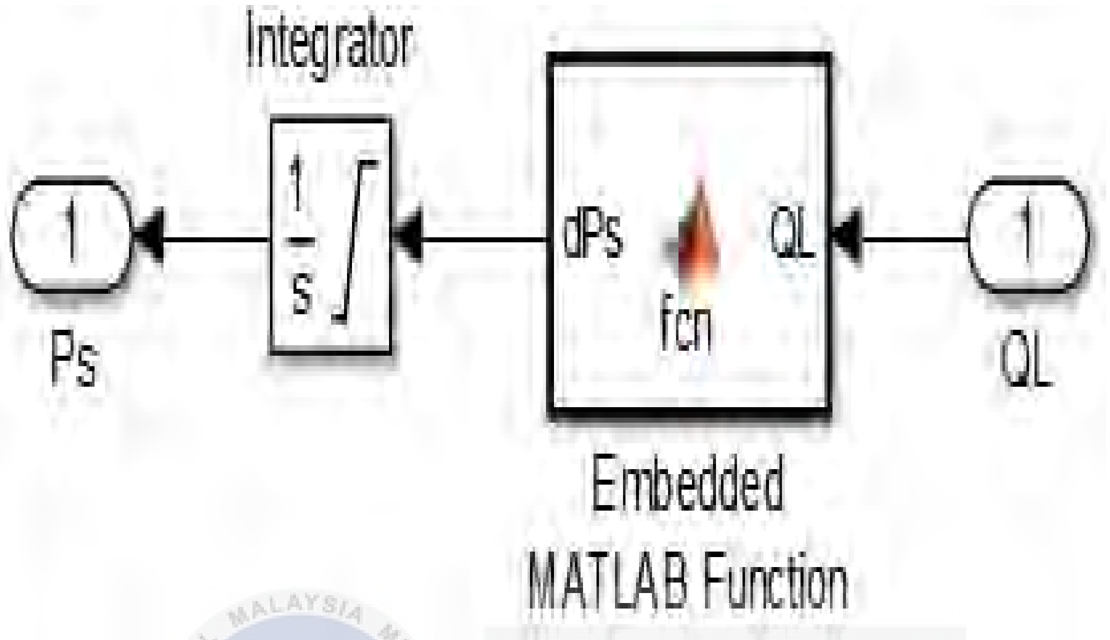
UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Appendix C3: Model of servovalve with leakage



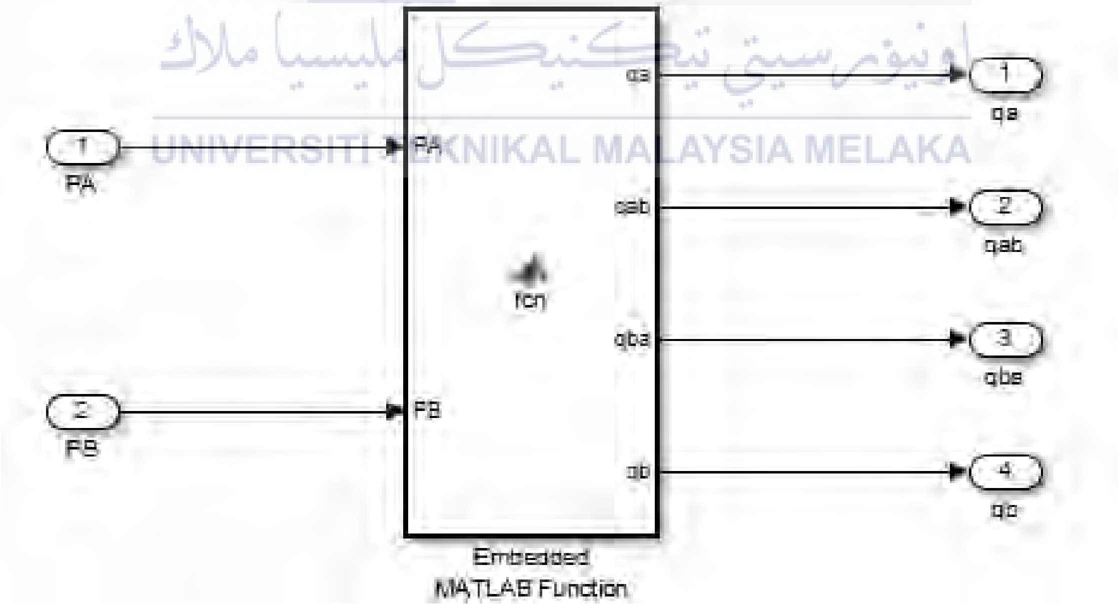
UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Appendix C4: Pump dynamic

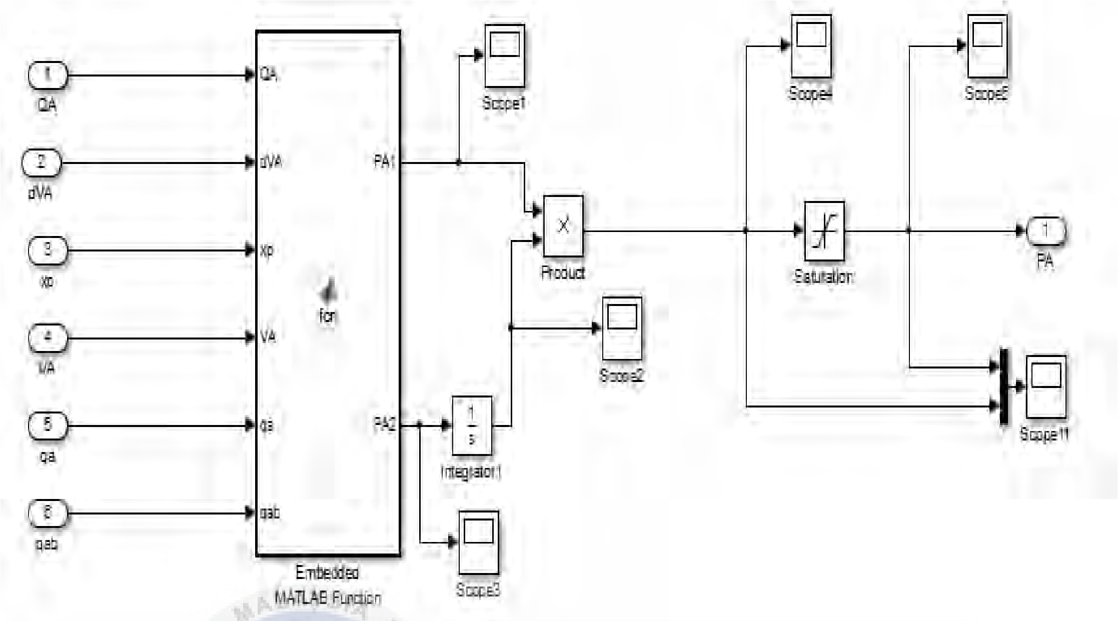


UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
اونيۏرسيتي تيكنيكل مليسيا ملاك

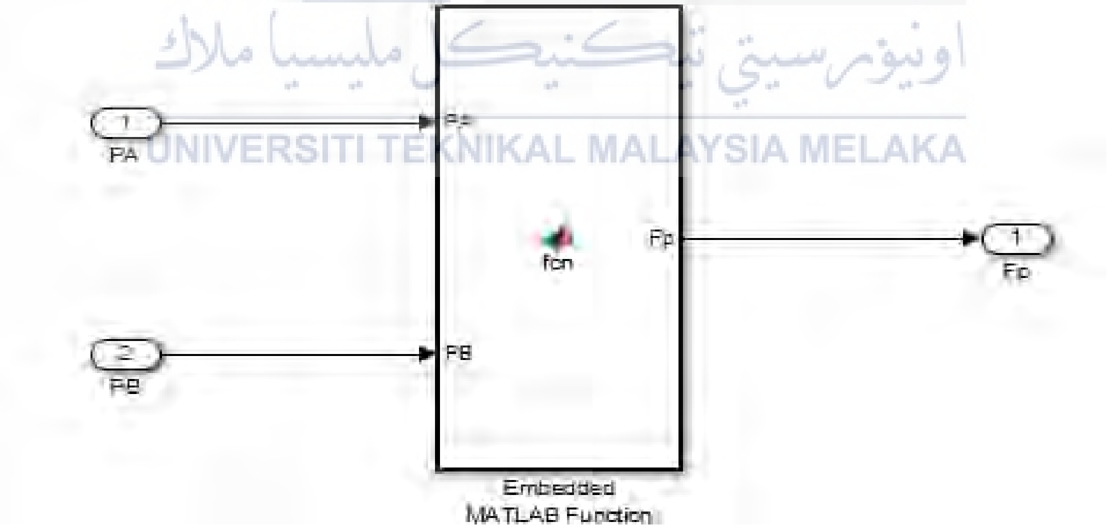
Appendix C5: Actuator leakage



Appendix C6: The modeling of chamber A

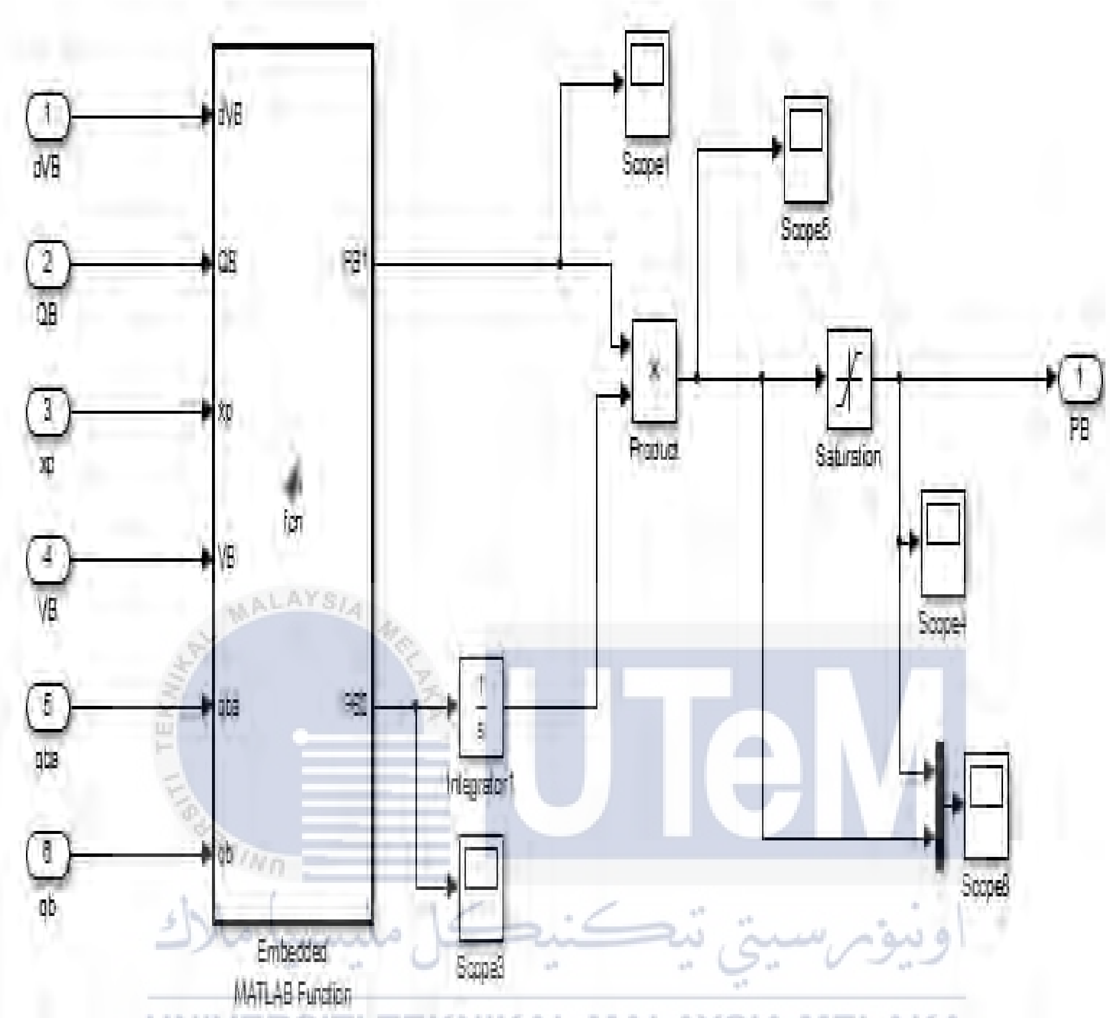


Appendix C7: Force from cylinder equation



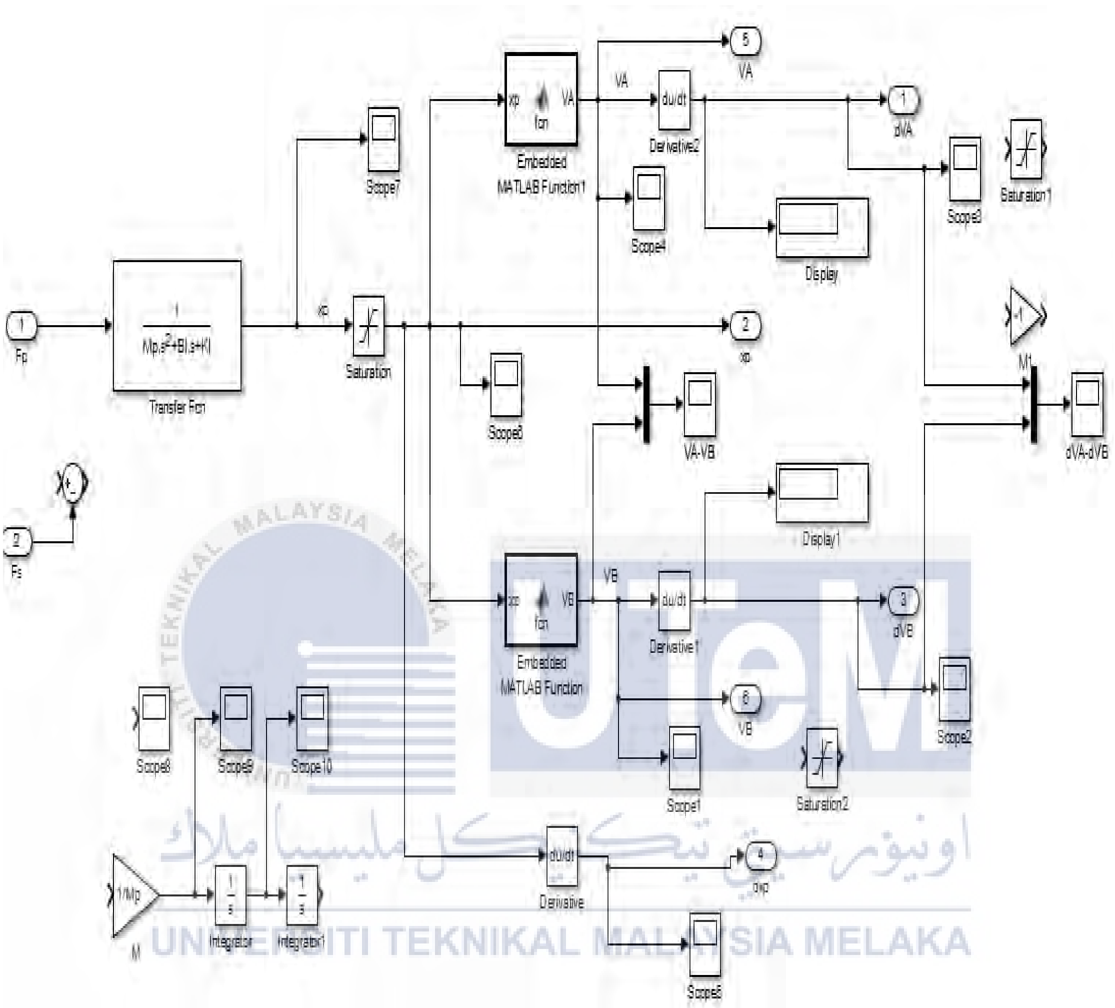
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك

Appendix C8: Chamber B model



UNIVERSITI TEKNIKAL MALAYSIA MELAKA
اونيۏرسيتي تيكنيكل مليسيا ملاك

Appendix C9: Load dynamic of the cylinder



UNIVERSITI TEKNIKAL MALAYSIA MELAKA