POLE-PLACEMENT CONTROL FOR PNEUMATIC POSITIONING SYSTEM

NUR AIN BINTI MOHD JOMLI

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

POLE-PLACEMENT CONTROL FOR PNEUMATIC POSITIONING SYSTEM

NUR AIN BINTI MOHD JOMLI

This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

Faculty of Electronic and Computer Engineering
Universiti Teknikal Malaysia Melaka

2021

DECLARATION

I declare that this report entitled "Pole-Placement Control for Pneumatic Positioning System" is the result of my own work except for quotes as cited in the references.

Signature	:	
Author	:	NUR AIN BINTI MOHD JOMLI
Date	:	28 JUNE 2021

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with Honours.

Signature	:	
Supervisor Name	:	DR. SITI FATIMAH BINTI SULAIMAN
Date	:	28 JUNE 2021

DEDICATION

"My beloved family, this is for all of you…."

ABSTRACT

Controlling a pneumatic positioning system especially in terms of its accuracy, stability, and good transient response is very challenging due to the nonlinearities issue. Therefore, a pole-placement controller based on second-order Auto-Regressive with eXogenous input (ARX) model was proposed as a new control strategy to control the pneumatic positioning system. Pole-placement controller is chosen since it has the ability to guarantee stable closed-loop system performance. In this study, a mathematical model of the pneumatic system, which is the second-order ARX was determined using system identification technique. To evaluate the effectiveness of the pole-placement controller, the positioning response performance of the pole-placement controller was compared with the Proportional-Integral-Derivative (PID) controller. The simulation result based on MATLAB Simulink for positioning control of 100 mm distance shows that the control strategy using pole-placement effectively provide the pneumatic positioning response with 0 % of overshoot, compared to PID which produced >50 % of overshoot. Overall, the findings based on the transient response performances confirmed that the proposed pole-placement control strategy was proven accurate and stable to control the position of the pneumatic system used in this study. Hence, indicates that the control strategy using pole-placement is very effective and can be applied in industrial application.

ABSTRAK

Sistem kawalan penentu kedudukan pneumatik terutamanya dari segi ketepatan, kestabilan, dan tindak balas sementara yang baik sangat mencabar kerana masalah tidak linear. Oleh itu, pengawal penempatan tiang berdasarkan model kedua Regresif Automatik dengan eXogeneous (ARX) telah dicadang sebagai strategi kawalan baru untuk mengawal sistem penentu kedudukan pneumatik. Pengawal penempatan tiang dipilih kerana mempunyai kemampuan untuk menjamin prestasi sistem gelung tertutup yang stabil. Dalam kajian ini, model matematik utk sistem pneumatik iaitu ARX model kedua telah ditentukan menggunakan teknik pengenalan sistem. Bagi menilai keberkesanan pengawal penempatan tiang, prestasi tindak balas penentu kedudukan kawalan penempatan tiang dibandingkan dengan pengawal Derivatif Kamiran Berkadar (PID). Hasil simulasi berdasarkan MATLAB Simulink untuk kawalan kedudukan jarak 100 mm menunjukkan bahawa strategi kawalan menggunakan penempatan tiang secara berkesan memberikan tindak balas kedudukan pneumatic dengan 0 % tembakan lebihan, dibandingkan dengan PID yang menghasilan >50 tembakan lebihan. Secara keseluruhannya, penemuan berdasarkan prestasi tindak balas sementara menyatakan bahawa strategi kawalan penempatan tiang yang dicadangkan terbukri tepat dan stabil bagi mengawal kedudukan sistem pneumatik yang digunakan dalam kajian ini. Oleh itu, hasil menunjukakan bahawa strategi kawalan menggunakan penempatan tiang sangat berkesan dan dapat diterapkan dalam aplikasi industri.

ACKNOWLEDGEMENTS

Syukur Alhamdulillah, with His permission, this study is finally completed. Thanks to Allah S.W.T for the blessing of good health for me to perform this given responsibility to the best of my ability throughout this journey. Without His favour, this study may not be successfully completed. I would like to express my gratitude to my supervisor Dr. Siti Fatimah Binti Sulaiman for her guidance, patience, support and encouragement to this study. Beside that the feedback, time and advice that she give to me during this study is mean a lot to me.

I would like to appreciate to all my family members especially my parents, who give me endless support with valuable motivation to make me keep moving in completing this study. Thank you for your understanding and patience.

I would also like to appreciate all my friends for their support and advice all the way from beginning to the end of this study. I pray that Allah S.W.T will give you His good blessings.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ARX	:	Auto-Regressive with eXogenous input
PID	:	Proportional-Integral-Derivative
MPC	:	Model Predictive Controller
SISO	:	Single-Input Single-Output
MIMO	:	Multi-Input Multi-Output
MRI	:	Magnetic Resonance Imaging
PWM	:	Pulse Width Modulation
R&D	:	Research and Development
ANN	:	Artificial Neural Network
PSoC	:	Programmable System on Chip
ZN	:	Ziegler-Nichols
YAG	:	Yttrium Aluminum Garnet
DAQ	:	Data Acquisition
RTWT	:	Real-Time Windows Target
I/O	:	Input/ Output
ARMAX	:	Auto-Regressive Moving Average with eXogenous input
OR	:	Output Error
BJ	:	Box-Jenkins
GUI	:	Graphical User Interface

FPE	:	Final Prediction Error
MSE	:	Mean Square Error
PP	:	Pole-Placement
e_{ss}	:	Steady-state error
OS	:	Overshoot
t_r	:	Rise time
t_s	:	Settling time

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

This chapter provide a brief overview of the study, including the main reason why the study was proposed and the objectives of the study. The scope and limitation of the study is also described in this chapter. The organization of the thesis is presented at the end of this chapter.

1.1 Background Study

A system that convert compressed air and turning the compressed air into mechanical energy that are used in wide range application are called pneumatic actuator. Pneumatic actuator is also considered as an element of physics and engineering that uses pressurized air or gases to move or operate. In automated production and automation control systems, the pneumatic actuator systems are widely used [1]. The pneumatic actuator system is not only utilized in industrial equipment, but also support our everyday lives in medical equipment. Pneumatic actuator also has a benefits over hydraulic which compromise environment contaminations as well as manufacturing cost [1]. Pneumatic systems have become a more important aspect in the robotics and automation industries due to the rapid development of actuators. In any application, a pneumatic actuator proposes a better option than electrical and hydraulic actuators due its low implementation costs [1]. Pneumatic actuator also offers the advantages of a clean, and safe. Therefore, the pneumatic actuator has a lots of benefits compared to hydraulics actuator, such as lightweight and simplified structure, clean, compact, economical, easy to maintain and safe for high temperature operation and explosiveness environment [2].

In 1992, Strickland *et al*. [3] created an intelligent actuator system by incorporating a motor, amplifier, sensor, microcontroller, and communications media into one single unit as a new approach to servo system design. Few years later, D. Saravankumar *et al.* (2017) developed some compact pneumatic servo systems, which capable of regulating position and speed. The development of the new compact pneumatic cylinder fitted with multiple micro pneumatic control valves and micro sensor in a single system has proved the use of computer technology in the pneumatic actuator[4].

The pneumatic actuator was reported applied in food packaging for production line system [5]. The pneumatic actuator was also developed for robot construction, which used to attach the ceramic tile. Pneumatic actuators are also applied in manufacturing. An applications of pneumatic actuators in manufacturing are such jack hammers, power drills, and blow molding [6]. In 2008, the Intelligent Pneumatic Actuator as an

Intelligent Chair Tool was used to explore distributed physical human interface computer interaction. [7]. Two years later, pneumatic actuators were introduced as a clinical robotic assistant Pneumatic actuator was used to improve detection and treatment of Magnetic Resonance Imaging (MRI) guided prostate biopsy and brachytherapy for precise needle positioning control [8].

There are many approach was reported to manage the pneumatic actuator positioning system such as Proportional-Integral-Derivative (PID), pole-placement, Model Predictive Controller (MPC), and fuzzy logic. [9]. Following a review of the earlier compositions on pneumatic positioning system, it was established that using a pole-placement controller as a control strategy for pneumatic positioning systems is appropriate.

Pole-placement control is designed based on poles location [10]. Users or the designers are free to assign the location of poles, as long as the location of poles must be inside the unit circle (-1 to +1). This are the main reason why a pole-placement controller can guarantee a stable closed-loop performance of the system [11]. The pole-placement controller is also more stable than PID controller in terms of transient response performance (to control the pneumatic positioning system) [12]. Most of the pole-placement method utilized self-turning control; therefore, make it capable to adapt with any payload and time varying parameters [12]. In another study [13], to counteract the external force, including gravity force in the pneumatic system, a self-turning of balance pressure control was conducted using the pole-placement controller. The study proved that the pole-placement controller was able to adapt changeable plant parameters, including balancing term. In addition, the parameter vectors of the pole-placement controller algorithm were calculated by identification equation; therefore, make it suitable for Single-Input Single-Output (SISO) and complex system, such as Multi-Input Multi-Output (MIMO) [14].

Given the background and consideration of this study, a pole-placement controller was proposed as the main controller in order to improve the positioning control performance of pneumatic system used in this study.

1.2 Problem Statement

Accurate positioning control is very important in most operations in the industries. Inaccurate positioning control may affect the operations in the industries and at the same time may cause the industries to suffer losses. For pneumatic positioning control system, controlling the pneumatic actuator system mostly with regard to the precision of the cylinder rod position is very difficult due to the complexity of the system itself and issues of parameter uncertainties and non-linearities within the system [15]. Controlling the pneumatic actuator positioning system also becomes tougher with the requirement to simultaneously consider the precision of system and other factors, like the interval and stability of the system [16].

1.3 Objectives

The specific objectives of this study are as follows:

i. To design an experimental setup for the modelling and data validation of the pneumatic actuator system.

ii. To propose the pole-placement controller based on ARX model as a control strategy for pneumatic positioning system.

iii. To evaluate the performance of pneumatic positioning control system using the proposed controller in terms of transient response.

1.4 Scope and Limitation

The scope and limitation of this study are presented as follow:

i. The mathematical model of pneumatic actuator system was set on using system identification technique. A linear Auto-Regressive with eXogenous input (ARX) model structure was considered to represent the dynamic characteristics of pneumatic actuator system used in this study.
ii. The pole-placement controller was engaged as the main control strategy to control the pneumatic positioning system.
iii. The pressurized supply air was kept at constant (0.6 MPa) throughout the experiments.
iv. The positioning control of pneumatic system was restricted to a maximum distance of 200 mm due to the limitation of the cylinder stroke itself.
v. The performance of the proposed pole-placement control was analyzed and compared with the PID controller.

1.5 Thesis Outline

Overall, this thesis consists of five chapters which were organized as follows:

Chapter 1 is an introduction chapter which provides a background regarding pneumatic actuator system; including its advantages over other types of actuators, its applications, and controllers used to control its positioning system. In this chapter, the addressed issues, objectives, and scope of work were presented.

Chapter 2 reviews the literature related to pneumatic positioning systems. This chapter first summarizes the pneumatic actuator system and pneumatic positioning system used in this study. Following that, this chapter examines recent trends in control strategies provided in previous research and presents recommended strategies for improving actuator control in pneumatic positioning systems.

Chapter 3 describes the methodology and process flow during the implementation of this study. The detail information about the components and operations of the pneumatic actuator system used in this study were provided at the beginning of this chapter. In the following, the experimental setup for modelling process and the data validation process of the system using system identification technique, followed by the preliminary procedure in the design of the proposed control strategy, are described in details.

Chapter 4 introduces the results of modelling and controlling of the pneumatic positioning system. This chapter demonstrates the ability of the proposed strategy to control the position of the pneumatic system. The ability of the proposed control strategy to control the pneumatic positioning system was compared with the PID control technology, and the simulation results are given at the end of this chapter.

Chapter 5 summarizes the overview of study. The results of this survey and the recommendations for future research were also covered in this chapter.

CHAPTER 2

LITERATURE REVIEW

This chapter summarizes previous research on pneumatic actuators, including modelling and control of pneumatic positioning systems. This chapter first describes the industrial applications, advantages and limitations of pneumatic actuator systems. This chapter also introduces the pneumatic actuator system used in this study and the methods used to model it. The Subsequently, this chapter reviews several control methods used to control the position of the pneumatic system. The reasons for the selection of pole-placement controller to control the pneumatic positioning system were also explained in this chapter.

2.1 Overview of Pneumatic Actuator System

A machine component that control or drive a mechanism or device are called pneumatic actuator. The most common actuator systems in industry are pneumatic actuators, hydraulic actuators, and electric actuators. [17]. However, this study only focused on the employment of pneumatic actuator system.

Due to its dominance, for instance high reliability, simpler and lighter structure, clean and efficient (because it is easily accessible with low power) and low maintenance, the pneumatic actuator system is considered to be the most efficient system and most commonly used drive in industries. In addition, the pneumatic actuator system can also react at high speeds, which is why it is the first choice for various applications requiring such functions. This actuator is also suitable to be used in a challenging and unpredictable environment, such as in nuclear environment due to its strong ability to with stand high-temperature and explosive environments [17].

The pneumatic actuator system was also reported applied in applications that involves movement between two hard stops and various others industrial applications such as industrial robotics, automotive, manufacturing system, and monitoring application system [18]. The widespread used and advantages offered by pneumatic actuator system especially in various industrial applications has make Research and Development (R&D) activities on pneumatic actuator system increased considerably [19]. Nevertheless, in order to achieve excellent positioning control performance, pneumatic actuator system has a several limitations to consider. This are also the main reason why the industrial use of pneumatic actuator systems is limited to specific application only. Saravanakumar *et al.* (2017) [4] also highlighted similar issues; the demand for pneumatically designed system with high speeds and accurate positioning control system is high. However, some recent studies have also mentioned these issues as important factors affecting the accuracy and precesion of pneumatic positioning systems. A significant number of studies have been carried out to enhance the accuracy of the pneumatic positioning system [20].

2.1.1 Modern Pneumatic Actuator System

Apart from R&D activities, enhancement in computer technology also contributed to the development of more compact, sophisticated, modern, and intelligent pneumatic actuator system. Basically, a modern pneumatic actuator system essentially combines a pneumatic actuator, a microprocessor, a valve, and various sensors into a osystem.

In 2005, Suzumori *et al.* introduced the first compact servo-pneumatic system with high performance positioning control, known as small-type intelligent actuator system [21]. In the study, Suzumori *et al.* for both speed and positioning control, a servo-pneumatic mechanism was designed. The servo-pneumatic system was equipped with several micro sensors such as acceleration sensor, force sensor, position sensor, and speed sensor. Microprocessor and microvalves in one system to achieve the suggested design. Suzumori *et al*. further demonstrated the potential of the developed small-type intelligent actuator system to appreciate a compact servo-pneumatic system with encouraging exploratory results. Reportedly in the study, Suzumori *et al.* added that with positioning precision between 0.3 mm and 1.0 mm and without overshoot, it had been easier to regulate the connecting rod position at any desired position between both ends of the rod stroke.

Four year later, a new compact pneumatic actuator system was developed by Faudzi *et al.* [22]. The pneumatic actuator system utilized in this study was of this type. The pneumatic actuator system developed by Faudzi *et al*. is an upgraded version of previous pneumatic actuator system by Suzumori *et al.* Table 2.1 shows the comparison of specifications between previous pneumatic actuator system by Suzumori et al. and pneumatic actuator system used in this study, which developed by Faudzi *et al.*

Table 2.1: Comparison of specifications between pneumatic actuator system by Suzumori et al. and Faudzi et al.

Items	Pneumatic actuator system by Suzumori et al.	Pneumatic actuator system by Faudzi et al.
Components	Stripe rod and Encoder	Encoder, tape stripe code on a guide rod, pressure sensor, valves, and PSoC board
Length	133 mm	388 mm
Actuator diameter	10 mm	40 mm
Rod diameter	3 mm	16 mm
Rod stroke length	40 mm	200 mm
Laser stripe pitch	0.338 mm	0.01 mm
Maximum force at 0.6 MPa	8.5 N	120 N

Referring to Table 2.1, it is evident that the components and size of the pneumatic positioning system used in this study are different from the previously developed pneumatic actuator system by Suzumori *et al.* In contrast to the previous version by Suzumori *et al.,* the pneumatic system in this study contains a larger cylinder and more durable components, such as a new position sensor with higher precision, a new tape type stripe code for added durability, and a new upgraded circuit design. This new developed pneumatic system also distributes aloft positioning precision; therefore, a pitch as small as 0.01 mm can be determined. In addition, this newly development pneumatic positioning system can also generate aloft force of up to 120 N at 0.6 MPa/ Otherwise stated, the invention of this new pneumatic actuator system addressed the slow response, low accuracy, and low force of earlier pneumatic actuator systems. In addition, the pneumatic system used in this study also has unique characteristics and functions that make it different from other commercial pneumatic actuator systems. Figure 2.1 and Figure 2.2 shows the different between the basic cylinder operation of pneumatic system used in this study and the commercial pneumatic system, respectively.

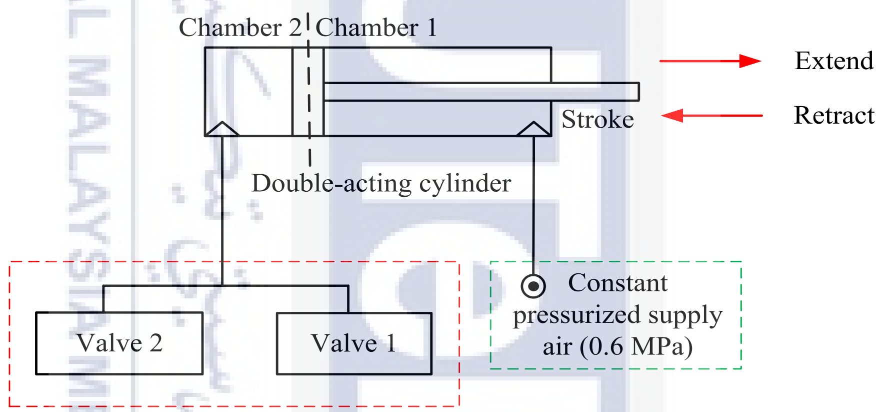


Figure 2.1: Basic cylinder operation of pneumatic system used in this study

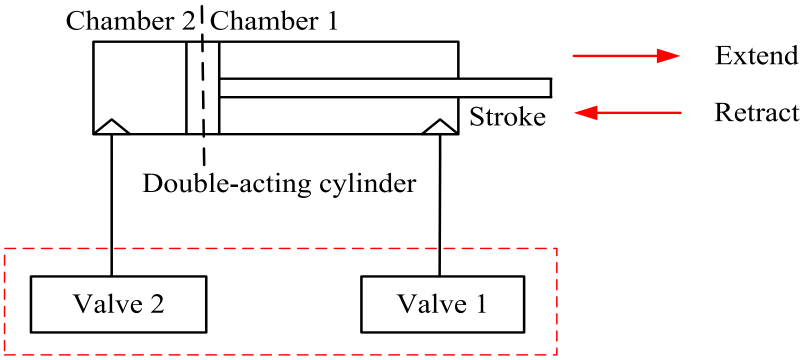


Figure 2.2: Basic cylinder operation of commercial pneumatic system

Referring to Figure 2.1 Figure 2.2, both pneumatic systems used double-acting type cylinder to operate. The use of double-acting cylinder in the pneumatic system allows stroke to move in two directions (extend and retract), as opposed to single-acting cylinder that allows stroke to move in one direction (usually for extension) only. As shown in Figure 2.1 and Figure 2.2, both systems used two valves to operate. However, the position of the valves for both systems were not same. In the pneumatic positioning system, the two valves are only used to control one chamber (chamber 2), while the other chamber (chamber 1) is fixed in air at constant pressure (in this case 0.6 MPa). Meanwhile, in the commercial pneumatic system, each valve is use to control single chamber (Valve 1 to control Chamber 1 and Valve 2 to control Chamber 2). In conclusion, only a chamber controls the pneumatic positioning system used in the study, whereas there are two chambers for other commercial pneumatic actuators. This makes the control of the pneumatic positioning system much easier since only one chamber needs to be considered during operation.

2.2 System Modelling for Pneumatic Actuator System

Fundamentally, the modelling of the pneumatic actuator system substantially used two techniques. First method is a theoretical approach and the second method is an experimental approach.

2.2.1 Modelling of Pneumatic Actuator System using Theoretical Approach

This section summarizes previous works that uses a theoretical method (or first-principles approach) to model the pneumatic actuator system. The basic theory of the dynamics of the pneumatic actuator system was first introduced by Carducci *et al.* (2006) [23]. By tuning a number of geometric and functional characteristics and parameters using non-linear optimization techniques, a comprehensive mathematical model of a pneumatic actuator controlled by two on/off two-way valves (using Pulse Width Modulation approach) was validated. The experimental data were collected by driving the on/off valves with five different duty cycles over a 20 ms interval and monitoring the actuator position with a potentiometer. In order to measure valve coefficients in all operating conditions, a particular experimental apparatus was designed.

The components of the pneumatic system were divided into five categories. Those components were considered as subsystems of a larger pneumatic system, and mathematical models for each component were developed, which could then be coupled in a variety of ways to build a comprehensive pneumatic system model. To accommodate the five types of components, a library was created. Users can choose from a library of components to create a complete pneumatic system based on the design requirements.

2.2.2 Modelling of Pneumatic Actuator System using Experimental Approach

The detailed mathematical model of dual-action pneumatic actuators controlled with proportional spool valves using experimental approach was developed by Hazim *et al.* (2009) [23]. Effects of nonlinear flow through the valve, air compressibility in cylinder stroke, leakage between chambers, end of stroke inactive volume, and time delay and attenuation in the pneumatic lines were carefully considered. System identification, numerical simulation, and model validation experiments were conducted for two types of air cylinders and different connecting tubes length, showing very good agreement. The mathematical model was then applied in optimizing the high-performance nonlinear force controllers for teleoperation, haptic interfaces, and robotics applications.

2.3 Control Strategies for Pneumatic Positioning System

Aside from Research and Development (R&D) action, the pneumatic actuator system is also used in industrial applications such as hammers, drills, squeezes, and packaging. Due of its fast response and precise positioning capabilities, pneumatic actuator systems are in high demand, especially in motion control application and further research to develop control strategies of pneumatic actuator systems is being stimulate by [4] Saravankumar *et al.,* 2017). The pneumatic actuator systems have a variety of control strategies from the most basic controllers such as Proportional-Integral-Derivative (PID) control to advanced intelligent controllers such as fuzzy logic control and Artificial Neural Network (ANN) control. However, regardless of the strategy applied, the stability of the closed-loop system must first be ensured. It is also important that the strategy developed is applicable in a practical setting in real time for various applications of pneumatic actuator systems [24].

Various control strategies were also reported to control the positioning system of the pneumatic actuator used in this study. Sub-section 2.3.1 and Sub-section 2.3.2 reviews the control strategies using PID and pole-placement to control the pneumatic positioning system.

2.3.1 Controlling the Pneumatic Positioning System based on Proportional-Integral-Derivative (PID) Control

The positioning system of the pneumatic actuator used in this study was reported first controlled using Proportional-Integral-Derivative (PID) control [7]] (Faudzi *et al.,* 2009). The cylinder stroke of pneumatic positioning system, the position is controlled by the PID. In the study, the PID controller was designed as a unified control system within a Programmable System on Chip (PSoC) to control position and pressure (to drive the valve). The two inputs (from the encoder and pressure sensor readings) are loop feedback and are used as input to the PSoC, while the input to the valve are from the processed output. Since all required parameters are selected directly from the computer through the local control algorithm in PSoC, it is easier to control positioning and pressure through a unified control system. In 2013, Osman et al. presented the simulation and experimental results of pneumatic positioning system using PID controller with respect to three dissimilar technique of PID control tuning parameters [25].

2.3.2 Controlling the Pneumatic Positioning System based on Pole-Placement Control

The employment of pole-placement controller to control regulate the position of the pneumatic actuator system used in this study was first reported done by Faudzi *et* *al.* in 2015 [26].In the study, Faudzi et al. used three different pole locations (-0.25, -0.50, and -0.75) in designing the pole-placement controller. In order to evaluate the performance of the pole-placement controller, PID controller based on Ziegler-Nichols (ZN) tuning was used for comparison. The simulation results in the study shows that the longer the period required for the cylinder stroke to stick out to the target position, the farther the pole was from the origin (refer pole located at 0.01, 0.10, 0.50, 0.90), and vice versa. Although the pneumatic positioning system using pole-placement with the pole located at 0.90 improved the response time of the cylinder stroke, however, there was a minor overshoot appeared at the beginning of the simulation. This was consistent with study by Asif *et al*. [27] which concludes that overshoot always appeared when the system was controlled by pole-placement. The study farther evidences the potentiality of the pole-placement with the pole located at -0.50 in supplying higher response time compared to the PID controller. Moreover, with the pole-placement feedback control, the output of the closed-loop control system appeared to be more stable than the PID controller.

2.4 Summary

The modelling and controlling method for the pneumatic actuator system used in this study was reviewed in this chapter. Based on the reviews, an experimental approach (or system identification technique) was considered as a suitable approach to model the pneumatic system used in this study. Since the pneumatic system used in this study is considered complex and most of the information regarding its components are not available; thus, the use of theoretical approach is not suitable for this study. Hence, this study opted to employ the system identification technique as an approach to model the pneumatic system. For the controlling part, this study opted to develop the pole-placement controller as the main controller to control the positioning system. Based on the previous studies, pole-placement controller is capable to control pneumatic positioning system, provides good transient response performance, and guarantee stable closed-loop system.

CHAPTER 3

METHODOLOGY

This chapter describes the methods and procedures used to carry out this study. This chapter begins with a flowchart-based overview of the study. In particular, the methodological process used in this study is described in detail. Following that, the procedures for modelling the pneumatic actuator system using the system identification technique were also presented in this chapter. Following that, at the end of this chapter, the methodology for designing the pole-placement controller and the Proportional-Integral-Derivative (PID) controller was described.

3.1 Methodology Flowchart

Basically, this study consisted of four primary stages which is Literature Review, System Modelling, Controller Design and Simulation Test, and Performance Analysis. Figure 3.1 illustrates the methodology flow of this study.

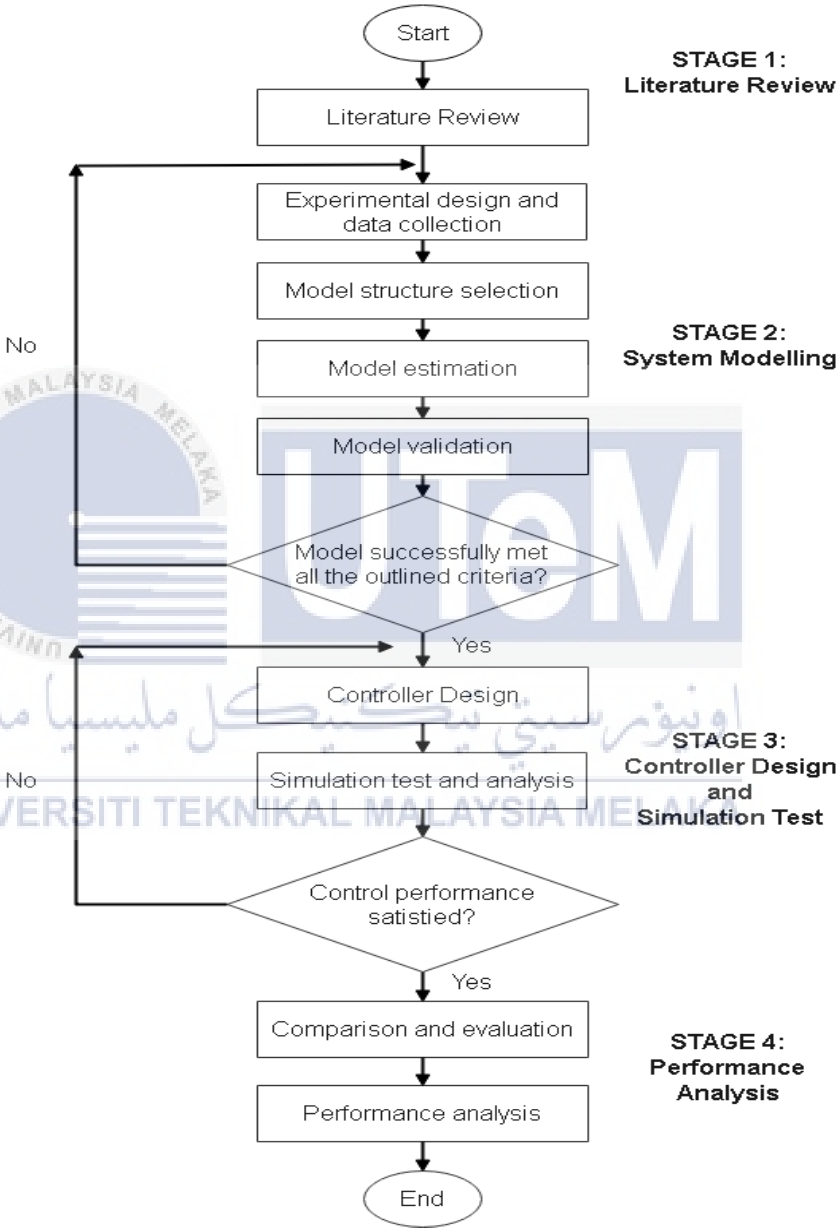


Figure 3.1: Flowchart for methodology framework

The first stage of this study, as shown in Figure 3.1 is the literature review. The main objective of this stage is to highlight the main issues related to the pneumatic actuator positioning system.

In the second stage of this study, which is the system modelling stage, the empirical method of system identification technique was used to determine the mathematical model of the pneumatic actuator system. In other words, at this stage, the mathematical model of the pneumatic actuator system was derived from the measured input and output data obtained from the experimental work. Auto-Regressive with eXogenous input (ARX) was chosen as the model structure to represent the actual pneumatic actuator system used in this study. The identified model is then validated according to the criteria outlined in the system identification procedure to confirm that it is accepted as a model that represents the pneumatic actuator system under study.

Next, for the third stage of this study, the new control strategy was proposed for pneumatic positioning system which is pole-placement controller. The proposed controller was aiming to improve the transient response performance of the system, provide accurate position control of the pneumatic system, and also stable. MATLAB Simulink was used for designing and simulating the proposed controller in this study. The performances of the proposed controller were then being accessed with the respect to the transient response, accuracy, and stability of the closed-loop system.

In the final stage which is Stage 4 of this study, the performance of the proposed pole-placement controller to control pneumatic actuator system was compared with the PID controller. Then, the performance of both controllers based on simulation tests were analyzed in order to determine the necessary improvements.

3.2 Pneumatic Actuator System Components

The real pneumatic actuator system used in this study and its main components are shown in Figure 3.2. The pneumatic actuator system used in this study was a double-acting cylinder type (KOGANEI-HA: twin-port cylinders). It has two air inlets, one exhaust outlet, 40 mm diameter, 200 mm stroke length, and it can provide a maximum driving force of 120 N at 0.6 MPa. The detail specifications of this cylinder are listed in Table 3.1.

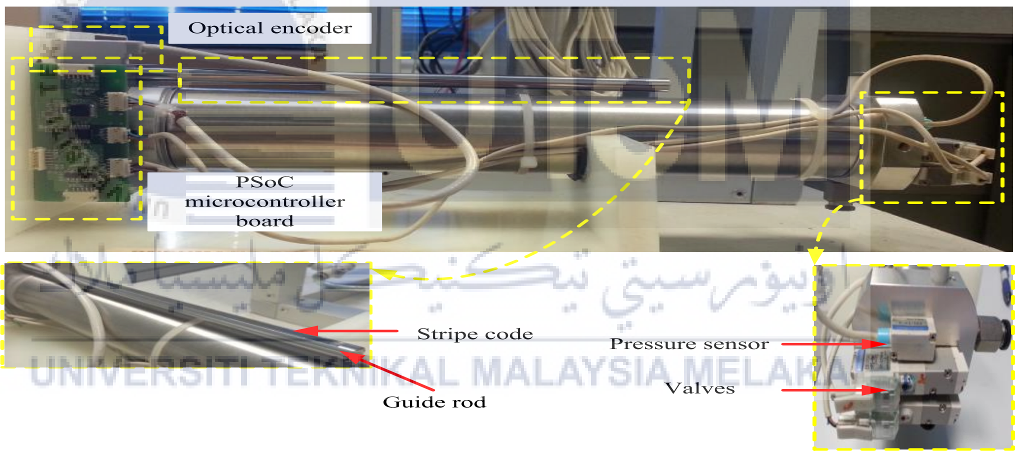


Figure 3.2: Main components of the pneumatic actuator system used in this study

Table 3.1: Specifications of KOGANEI-HA: twin-port cylinders

Item	Specification
Type of operation	Double-acting (extend and refract)
Media	Air pressure
Operating pressure range	0.1 ~ 0.7 MPa
Size of Bore	40 mm
Length of stroke	200 mm
Diameter of Rod	16 mm
Maximum force (at 0.6 MPa)	120 N

In this study, the pneumatic actuator system integrates five main components into a single actuator. Each component serves a specific purpose in the pneumatic actuator control system. These components are: (1) optical encoder, (2) guide rod with stripe code, (3) pressure sensor, (4) valves, and (5) Programmable System on Chip (PSoC) microcontroller board.

1) Optical encoder (KOGANEI: ZMA1R): This type of sensor was installed at the top of the actuator, as illustrated in Figure 3.3. Its function was to identify the position of the cylinder stroke by reading the laser stripes secured to the actuator's guide rod. The reading indication was then transferred to the PSoC control board to be processed farther. This sensor has the potential to provide precision stroke readings with pitch as small as 0.01 mm. To accurately determine the position of the cylinder stroke, a specified spacing between the encoder and the laser stripes was ensured. The specifications of the parameters of this optical encoder is shown in Table 3.2.

Figure 3.3: Optical encoder at the top of actuator

Table 3.2: Specifications of optical encoder

Item	Specification
Voltage of power supply	24 VDC ± 5 %
Consumption current	100 mA (max)
Sensing method	Optical linear encoder
Minimum resolution	2.5 µm(4 × multiplication)
Accuracy	21 µm
Maximum response frequency	600 kHz
Mass	100 g (with cable)

2) Guide rod with stripe code: The pneumatic actuator system employed in this study used a tape type stripe code with a 0.01 mm pitch, as shown in Figure 3.4. The zoomed tape stripe code on a guide rod is also shown in Figure 3.4. The stripe codes were created by irradiating the tape with an Yttrium Aluminum Garnet (YAG) laser beam, which caused the tape surface to oxidize. An encoder was able to read the position of the pneumatic actuator stroke based on the tape on the guide rod. An encoder

can read a small pitch of 0.01 mm, resulting in improved positioning precision for the pneumatic actuator system.

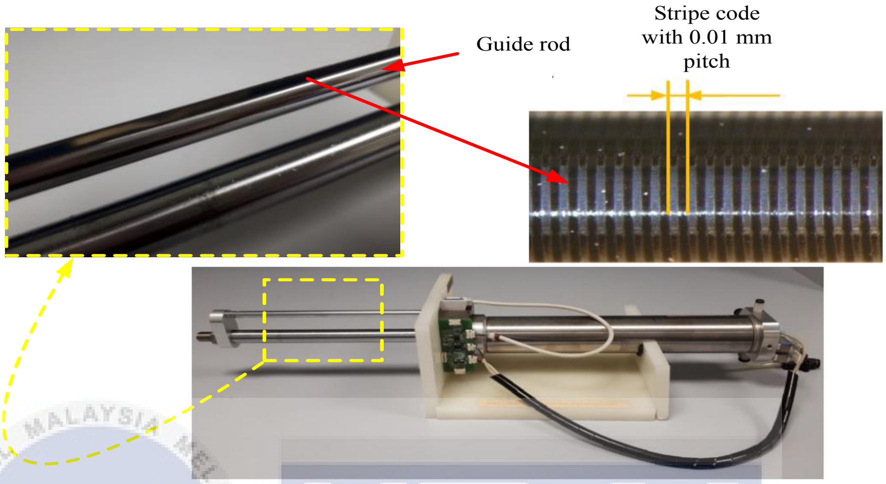


Figure 3.4: Tape stripe code on a guide rod

3) Pressure sensor: Table 3.3 shows the pressure sensor (KOGANEI: PSU-EM-S) and its specifications. Pressure sensor was employed in this study to identify the compulsion inside the cylinder chamber (Chamber 2). The signal from the pressure sensor was then transferred to the PSoC control board for further data processing and control. Figure 3.5 shows the position of the pressure sensor and valves on the actuator; where both components were attached at the end of cylinder body.

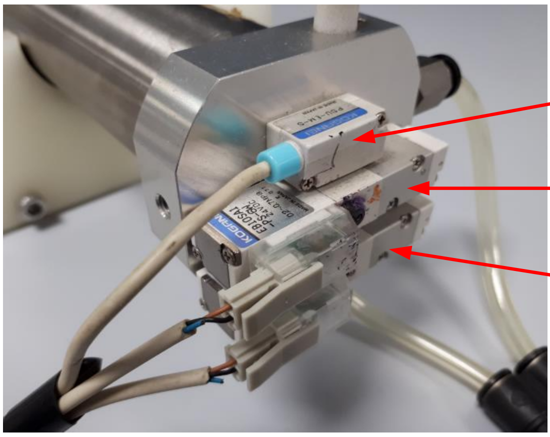


Figure 3.5: Pressure sensor and valves on the actuator

Table 3.3: Specification of pressure sensor

Item	Specification
Power supply (voltage)	24 VDC
Power supply (consumption current)	6 mA
Output voltage	1 ~ 5 V
Operating pressure range	-0.1 ~ 1.0 MPa
Mass	34 g (with cable)
Media	Air

4) Valves: The pneumatic system in this study uses two units of two-ports/two-position (2/2 valve) (KOGANEI: EB10SA1-PS-6W) type valves to drive the actuator. Table 3.4 shows the specifications for these valves. Both valves, which were secured at the cylinder's end, were used to control the cylinder's air inlet and air outlet (as shown in Figure 3.5). To drive the valves, the duty-cycle of the Pulse-Width Modulator (PWM) signal controlled the expansion and contraction of the cylinder stroke. In this

study, the cylinder stroke movements were controlled based on valves operating frequency at 20 Hz.

Table 3.4: Specification of valve

Item	Specification
Operating voltage	24 VDC
Operating pressure range	0.2 ~ 0.7 MPa
Response tie (ON/OFF)	6 or 7 ms (or below)
Maximum operating frequency	10 Hz
Media	Air
Operation type	Internal pilot type
Port size	M3 × 0.5

5) PSoC control board: PSoC control board is one of the most important elements of the pneumatic actuator system, since it is responsible for the actuator's control and communication. In this study, the PSoC control board was integrated on the cylinder and has connectors for communication, power, burning programme, sensors, and valves (see Figure 3.6). Besides, the PSoC control board also incorporates components such as PSoC chip, voltage regulator, Darlington pair, and Light Emitting Diode (LED) on the board. The components of the PSoC control board are listed in Table 3.5, together with the main functions of each component.

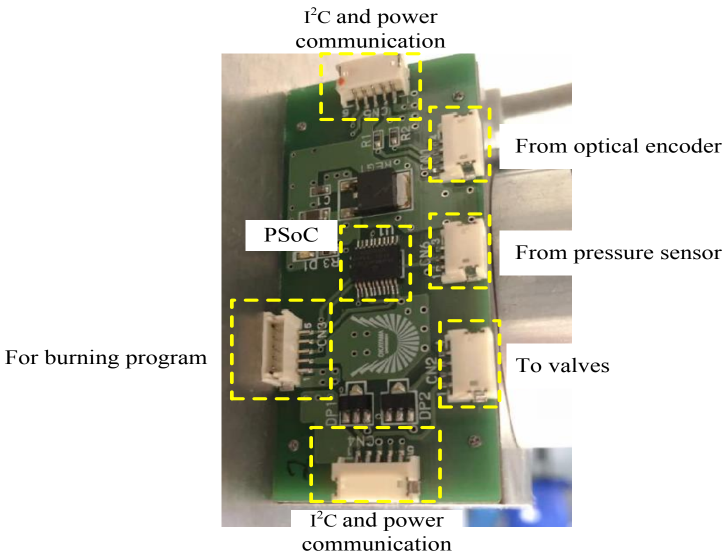


Figure 3.6: PSoC control board

Table 3.5: Components of PSoC control board and its functions

Component	Function
PSoC chip (CY8C27243)	Act as CPU, to control the input and output of the system
Voltage regulator	To supply stable 5 V to PSoC chip
Darlington pair	To drive the valves from PWM signal
LED	To indicate the state distinction

3.3 Modelling of Pneumatic Actuator System using System Identification Technique

In this study, systems identification technique is applied to determine the real-time mathematical model that represents the dynamics of the pneumatic actuator system used in this study. Figure 3.7 illustrates the steps used to model a pneumatic system using system identification techniques.

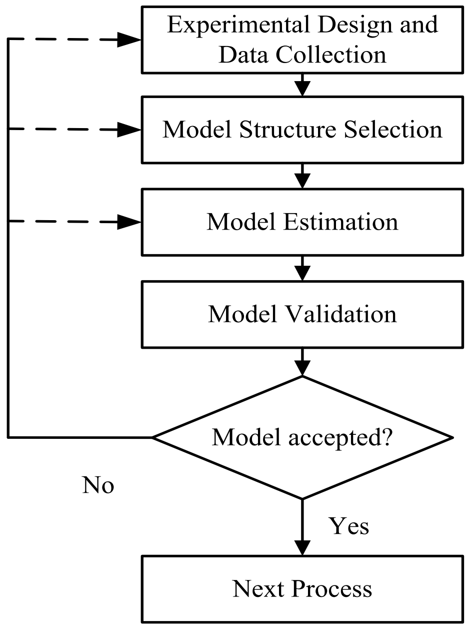


Figure 3.7: System Identification procedures

3.3.1 Experimental Design and Data Collection

Figure 3.8 shows the experimental setup of the pneumatic actuator positioning system. During the setup, the pressurized supply air was kept at constant (0.6 MPa) throughout the experiments. The overall system in Figure 3.8 comprised of:

1. Personal computer,
2. Data Acquisition (DAQ) system,
3. Air compressor system, and
4. Pneumatic actuator system.

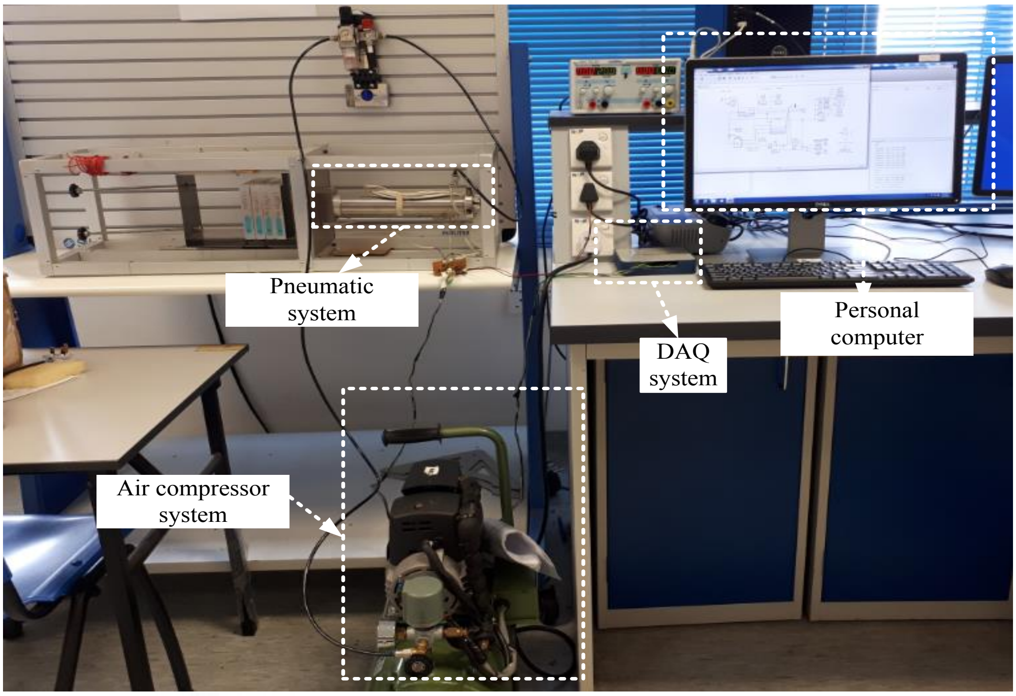


Figure 3.8: Experimental setup for pneumatic actuator system

The pneumatic system in this study uses compressed air in order to move its mechanical parts. The Hitachi Oil-Free Bebicon LE series air compressor system (model:0.4LE-8S5A) was employed in this study to compress air for the pneumatic actuator positioning system's operation. This type of air compressor can store up to 20 L of air and provide pressurized air at a maximum pressure of 0.8 MPa. In this study, the air supply pressure of the pneumatic positioning control system is an industrial pressure value of 0.6 MPa. Solid particles such as dust, dirt and rust are usually present in the compressed air produced by the compressor. If it is directly applied to a pneumatic system, it will damage the components of the pneumatic system, such as cylinders and valves. Therefore, before using compressed air in a pneumatic system, the compressed air must be cleaned first to remove any impurities. For this reason, Filter Regulator (FR) was used in this study, which filters the air and traps solid particles. In addition, the filter can separate liquids carried by compressed air, such as water and oil. In this research, a pressure regulator was used to control the pressure of compressed air because pressurized air of constant pressure (0.6 MPa) was required to activate the cylinder stroke of the pneumatic actuator system. Figure 3.9 illustrates the operations of a pneumatic actuator positioning system based on the experimental setup in Figure 3.8.

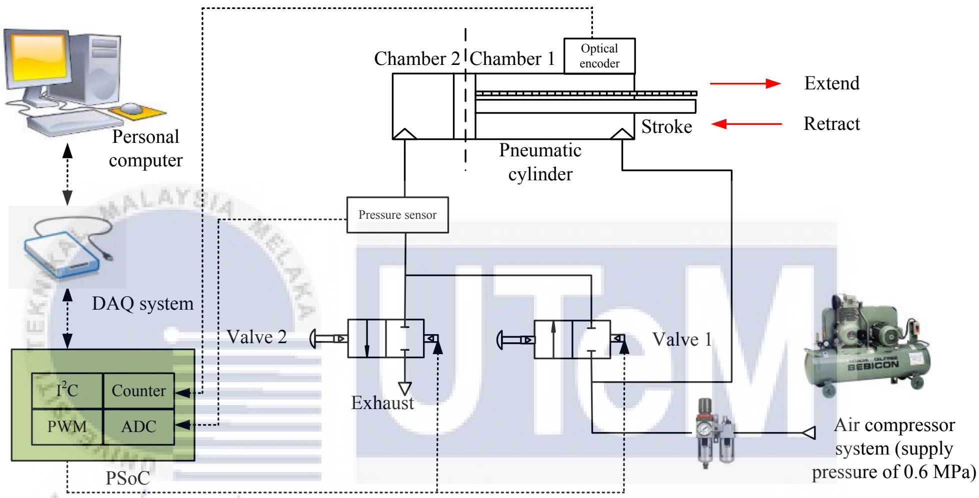


Figure 3.9: Schematic diagram of pneumatic actuator system

In this study, the expansion (right movement) and refraction (left movement) of the cylinder stroke were operate by the duty cycle of PWM signal to navigate the valves in controlling the pressure in Chamber 2. The PWM module provided a precision of 8-bit; where the value of amplitude signal sent to module range between +255 and -255 (2n – 1 = 255; n=8). The opening and closing of valves were realized through PWM signal. Furthermore, amplitude signal of +255 and -255 corresponded to 100% opening (full opening) of Valve 1 and Valve 2, respectively. Therefore, the control signal, u (from the controller) was initially converted into PWM signal for each valve in order to operate these valves. Table 3.6 summarizes the movements of cylinder stroke based on the operation of valves.

Table 3.6: Movements of cylinder stroke based on the operations of valves

Valve condition		**Cylinder stroke condition**
Valve 1	**Valve 2**	
Off	Off	No operation
On	Off	Extend (moves right direction)
Off	On	Retract (moves left direction)
On	On	No operation

When the PWM module receives a positive signal from the controller, it transforms it to an equivalent PWM signal and transmits it to Valve 1 (Valve 1 On, Valve 2 Off) to execute extension, as shown in Table 3.6. The model delivers the signal to Valve 2 when the PWM module receives a negative signal. (Valve 1 Off, Valve 2 On) to perform retraction. However, the cylinder stroke will not perform any operations either extension or retraction when both valves (Valve 1 and Valve 2) receives the same signals from the PWM module.

A personal computer with MATLAB software was equipped in the study and Simulink was employed as the platform. MATLAB Real-Time Windows Target (RTWT) is coded as an interface in this connection. It should be noted that the Input/ Output (I/O) signals of the personal computer are in digital form, while the I/O signals of the pneumatic actuator system are in analogue form. Therefore, this study adopted the DAQ system for the conversion of digital signal into analogue signal and vice versa to control the pneumatic actuator positioning system and to acquire experimental data. Figure 3.10 displays the configuration between personal computer (software) and pneumatic actuator system (hardware) via DAQ system.

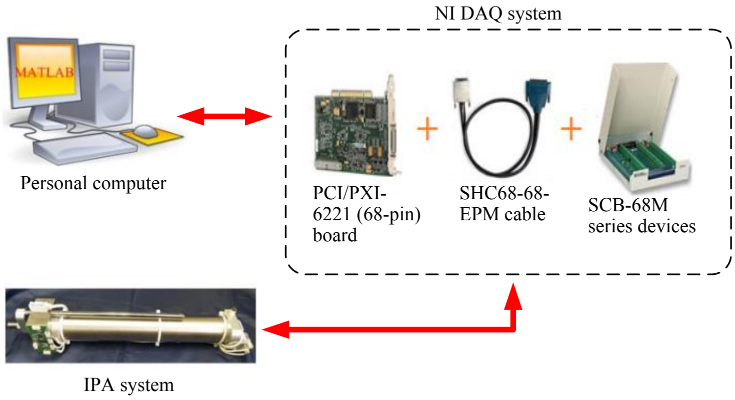


Figure 3.10: Configuration between personal computer and pneumatic actuator system via DAQ

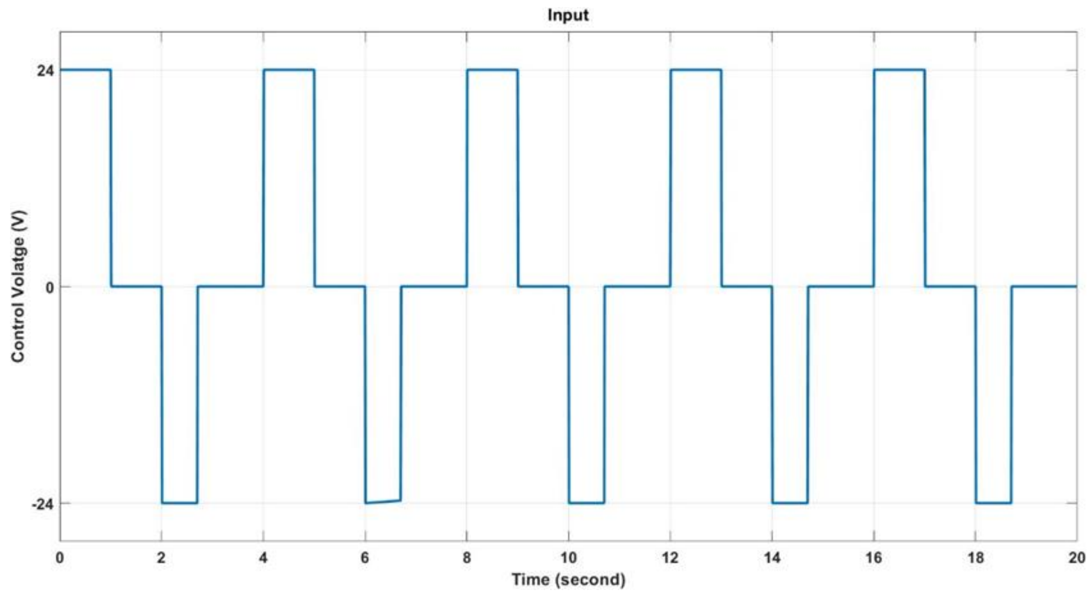
Basically, the DAQ system, which was manufactured by National Instruments Inc., consists of three main parts: (1) PCI/PXI-6221 (68-pin) board, (2) SHC68-68-EPM cable, and (3) SCB-68M series device. The PCI/PXI-6221 (68-pin) board was installed in Peripheral Component Interconnect (PCI) slots that are available on the PC motherboard, while SCB-68M series device was connected to the components of the pneumatic actuator system in order to gather signals (i.e. position, pressure, and force) from the measurement and digitize these signals for the purposes of analysis, storage, and presentation on personal computer. Meanwhile, SHC68-68-EPM cable was used to connect both devices (PCI board and DAQ device) to 68-pin accessories. Table 3.7 describes the general specification of the DAQ device.

Table 3.7: NI-DAQ device specification

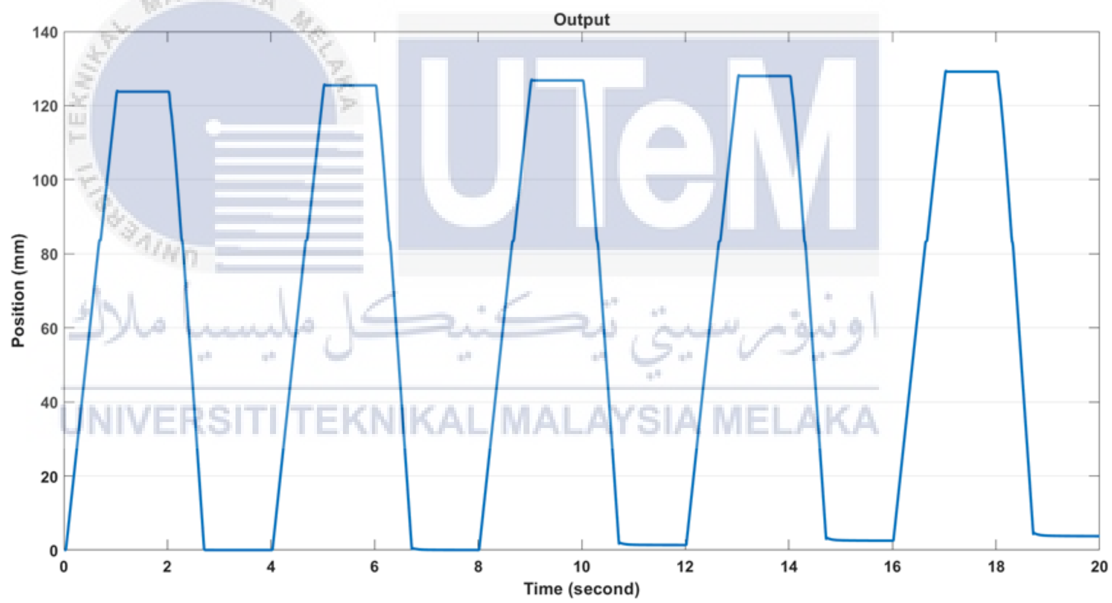
Item	Specification
Power supply	10 V
Resolution	16 bits
Max sampling rate	250 kHz
Analogue input, output	16 channels, 2 channels
Digital input/output	24 channels

As mentioned earlier, the first process for modeling a pneumatic drive system using system identification techniques is experimental design and data collection (refer Figure 3.7). The main objective of this procedure is to collect experimental input and output data in real time, to define a mathematical model representing the dynamics of a pneumatic drive system based on excitation signals and answer. With that, it was clear that the input stimulus signal, used for the identification process, is affecting the identified model.

Figure 3.11 illustrates the plot of data of measured input and output acquired from real-time experiment. The input signal (shown in Figure 3.11(a)) was injected as excitation signal and the output of this system (shown in Figure 3.11(b)) was recorded.



(a)

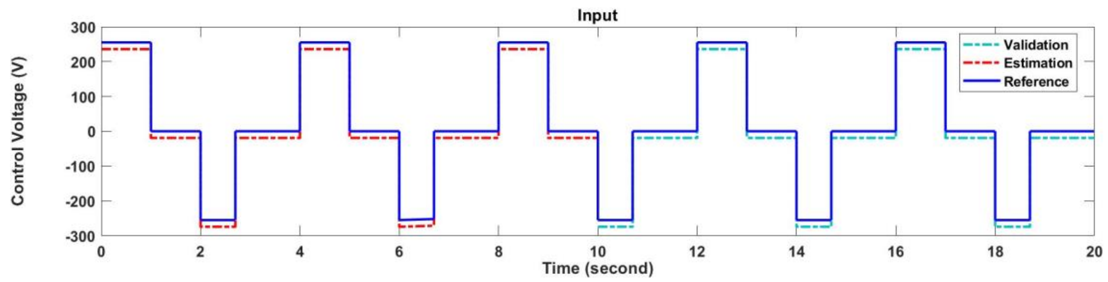


(b)

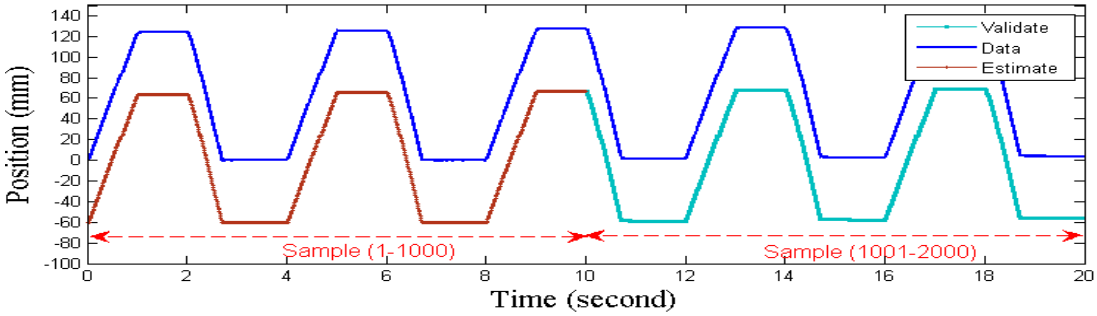
Figure 3.11: Plot of measured data: (a) input and (b) output

Specifically, Figure 3.11(a) shows the applied input signal to the valves of the pneumatic actuator system. As described earlier in this section, Valve 1 controlled the air inlet of the cylinder to perform extension, while Valve 2 controlled the air outlet (exhaust) of the cylinder to perform retraction. Both valves were operated at 24 V. In order to convert an analogue signal from both valves (24 V valve operating voltage) into signals that can be read by PWM module, ADC was used. The positive amplitude signal (0 to +255) is then sent to the PWM module to activate valve 1 (to perform expansion), while the negative amplitude signal (0 to -255) is then sent to the PWM for activate valve 2 (to retract). Figure 3.11 (b) shows the recorded output response of the system (cylinder rod stroke position). Referring to Figure 3.11 (b), it is clearly shown that the response time due to displacement of the outgoing rod is longer than the response time to retraction

In this study, 2000 measurements of input and output data were collected from an open-loop test; the input data consisted of a continuous step input signal applied to the on/off valves of the pneumatic positioning system, while the output data was the measured position of the cylinder stroke. The data of input and output were divided into two sets for modelling using the system identification approach: one set for training (estimation) and the other set for validation of the identified model. Figure 3.12 shows the estimation and validation process using the MATLAB System Identification Tool.



(a)



(b)

Figure 3.12: Plots of estimation and validation process of measured data using MATLAB System Identification Tool: (a) input and (b) output

According to the plots in Figure 3.12, 50 % of the first data set (1000 data points of input and output; sample 1-1000) from the real-time experiment was used for model training (estimation), while the remaining 50 % of the second data set (1000 data points of input and output; sample 1001-2000) was used for model validation.

3.3.2 Model Structure Selection

There are several parametric model structures that can be used to model or represent the system using system identification technique, such as Auto-Regressive with eXogenous input (ARX), Auto-Regressive Moving Average with eXogenous input (ARMAX), Output Error (OE), and Box-Jenkins (BJ) model. However, this study only considered to employ the ARX as the model structure to represent the pneumatic system used in this study.

Figure 3.13 illustrates the block diagram of ARX model structure, meanwhile Equation (3.1) expresses the transfer function of ARX using backshift interpretation of q^{-1}.

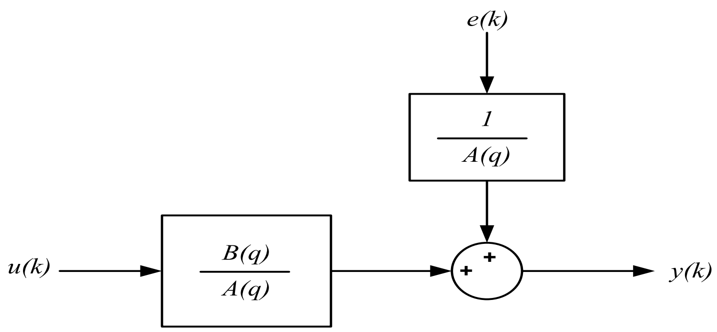


Figure 3.13: Block diagram of the ARX model structure

$$\boldsymbol{y(k)} = \frac{\boldsymbol{B(q)}}{\boldsymbol{A(q)}}\boldsymbol{u(k)} + \frac{\boldsymbol{1}}{\boldsymbol{A(q)}}\boldsymbol{e(k)} \qquad \textbf{(3.1)}$$

where

$A(q) = 1 + a_1q^{-1} + \cdots + a_{n_a}q^{-n_a}$,

$B(q) = b_1q^{-1} + \cdots + b_{n_b}q^{-n_b}$,

n_a is the number of poles,

n_b is the number of zeros,

$y(k)$ is the output,

$u(k)$ is the input,

$e(k)$ is the white-noise error,

q^{-1} is the backshift operator, and

$n_a \geq n_b$

3.3.3 Model Estimation

Following the selection of ARX as a model structure for the pneumatic system, the next identification procedure is to estimate the ARX model's coefficients or parameters. The coefficients or parameters of the ARX model were estimated using the least-squares method using MATLAB System Identification Tool in this study. Figure 3.14 shows the Graphical User Interface (GUI) of the System Identification Tool, which was used to model a pneumatic system.

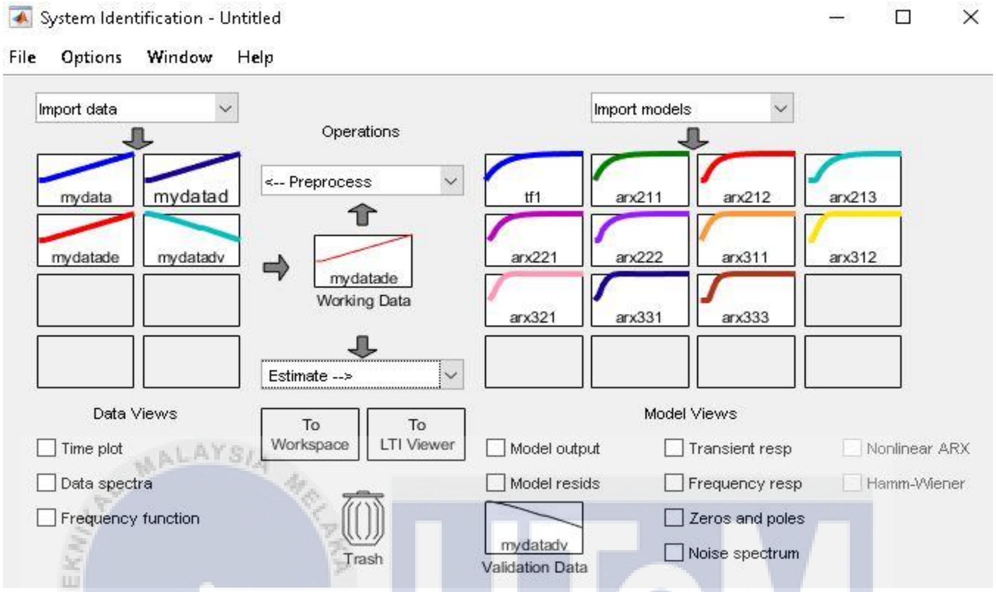


Figure 3.14: GUI of MATLAB System Identification Tool

Based on the measured input and output data from the experiment, this tool generates a mathematical model of the pneumatic system. As previously described in Subsection 3.3.1, the first data set (1000 data points of input and output, sample 1-1000) from the real-time experiment was used for model estimation, while the second data set (1000 data points of input and output, sample 1001-2000) was used for model validation. Subsequently, all of these data were imported into the MATLAB System Identification Tool, allowing the tool to evaluate the model parameters. The model parameters were estimated by minimizing the error between the simulated and measured models using the least-squares method.

In this study, ARX with a second-order system was chosen as the pneumatic system model structure. Higher-order models (i.e., third-order, fourth-order, and fifth-order) were not considered in this study because they do not always warrant higher pneumatic system accuracy. In addition, by increasing the model's complexity typically increases the uncertainties in parameter estimation. However, in order to validate the suitability of the second-order model as a model for the pneumatic system used in this study, the performances of the ARX with second-order system were also examined and compared with the ARX model with different model order (third-order).

Equation (3.2) expresses the discrete-time transfer function of pneumatic system dynamics based on second-order ARX model structure, which was estimated using MATLAB System Identification Tool. Equation (3.3) represents Equation (3.2) in the form of state-space.

$$G(z^{-1}) = \frac{0.001662z^{-1}}{1 - 1.716z^{-1} + 0.7164z^{-2}} \tag{3.2}$$

$$A = \begin{bmatrix} 1.7160 & -0.7164 \\ 1.0000 & 0 \end{bmatrix},\quad B = \begin{bmatrix} 0.0313 \\ 0 \end{bmatrix}, C = \begin{bmatrix} 0.0532 & 0 \end{bmatrix},\quad D = [0] \tag{3.3}$$

where $A, B, C,$ and D are the pneumatic system matrices with dimension, $n = 2$.

Another important aspect to consider in a control system is the controllability and observability of the system. The estimated model is said capable in controlling and interacting with the particular system if it manages to fulfil the controllability and observability tests; thus, indicating that the identified model is controllable and observable. Equation (3.4) and Equation (3.5) measure the controllable and observable ability of the simulated model of pneumatic system in Equation (3.3), respectively.

$$controllability = [B \quad AB \quad \cdots \quad A^{n-1} \quad B] \tag{3.4}$$

$$observability = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{bmatrix} \tag{3.5}$$

In this study, the identified model in Equation (3.3) is considered controllable if the controllability matrix in Equation (3.4) has full row rank $(n = 2)$, and the simulated model is considered observable if the observability matrix in Equation (3.5) has full column rank $(n = 2)$. Following that, the controllability and observability matrices of the estimated model of pneumatic positioning system in Equation (3.3) can be described as Equation (3.6) and Equation (3.7), respectively.

$$controllability = [B \ AB \ A^2 \ B] \tag{3.6}$$

$$controllability = \begin{bmatrix} 0.0313 & 0.0536 \\ 0 & 0.0313 \end{bmatrix}, \text{has full row rank } (n = 2)$$

$$observability = \begin{bmatrix} C \\ CA \\ CA^2 \end{bmatrix} \tag{3.7}$$

$$observability = \begin{bmatrix} 0.0532 & 0 \\ 0.0913 & -0.0381 \end{bmatrix}, \text{has full column rank } (n = 2)$$

Thus, the identified model in Equation (3.3) guarantees its ability to control and interact with the pneumatic positioning system since it complies with the requirement of controllability and observability test; to provide full row rank and full column rank.

3.3.4 Model Validation

The final step in using system identification technique to obtain the mathematical model of the pneumatic positioning system is model validation. The purpose of this procedure is to verify the validity between the measured data and the simulated data in accordance with certain verification requirements; to verify if the identified model adequately represents the considered process. In this study, the first 50 % of the data set (sample 1-1000) collected from real-time experiments is used for training (estimation), and the remaining 50 % of the data set (sample 1001-2000) is used for testing (validation) . Validate the identified mathematical model based on the best fit and the Final Prediction Error percentage (FPE), where the decision is made to accept or reject the identified model based on these criteria.

In this study, the best fit criteria were used to validate the identified ARX model. Equation (3.8) calculates the percentage of fitness between measured and simulated model output. In particular, 100 % denotes a perfect fit, whereas 0 % denotes that the fit is no better than approximate the output to be a constant ($\hat{y} = \bar{y}$). The identified model will be contemplated accurate to the real model, and if its fitness exceeds 90 %, it is acceptable.

$$Best\ fit\ (\%) = \left(1 - \frac{|y - \hat{y}|}{|y - \bar{y}|}\right) \times 100 \tag{3.8}$$

where y is the measured output, $\hat{y}$ is the simulated or predicted model output, and $\bar{y}$ is the mean of the measured output.

Equation (3.9) define Final Prediction Error (FPE) to measure the quality of the identified model.

$$FPE = V\left(\frac{1+\frac{d}{N}}{1-\frac{d}{N}}\right) \tag{3.9}$$

where d is the number of approximated parameters that represents the model complexity and N denotes the number of sample. The term V indicates the loss function, as expressed in Equation (3.10). $e(k)$ in Equation (3.10) is the error vector, which is represented as $e(k) = [e_k \quad e_{k-1} \quad \cdots \quad e_{k-N}]^T$.

$$V = \frac{e^2(k)}{N} = \frac{e^T(k).e(k)}{N} \tag{3.10}$$

The identified model of the pneumatic positioning system in Equation (3.3) is considered acceptable if it produces low FPE and low Mean Square Error (MSE) values, indicating that the identified model is accurate. The stability of the identified model was observed in this study using a zero-pole plot to validate its acceptance as a model that represents the pneumatic system.Specifically, for stable discrete-time model, all poles of the identified model must be inside the unit circle. Table 3.8 shows the validation results of ARX second-order model, meanwhile Table 3.9 summarizes the stability, controllability, and observability of the ARX second-order model in Table 3.8.

Table 3.8: Validation results of second-order ARX model

ARX model	Discrete-time transfer function	Best fit (%)	FPE	MSE
ARX 211	$G(z^{-1}) = \frac{0.001662z^{-1}}{1 - 1.716z^{-1} + 0.7164z^{-2}}$	91.69	0.02318	0.02295
ARX 212	$G(z^{-1}) = \frac{0.001829z^{-2}}{1 - 1.686z^{-1} + 0.6858z^{-2}}$	91.74	0.0235	0.02326
ARX 213	$G(z^{-1}) = \frac{0.001526z^{-3}}{1 - 1.733z^{-1} + 0.7331z^{-2}}$	91.49	0.02653	0.02626
ARX 221	$G(z^{-1}) = \frac{0.001031z^{-1} + 0.0008063z^{-2}}{1 - 1.6872z^{-1} + 0.6866z^{-2}}$	91.70	0.02293	0.02266
ARX 222	$G(z^{-1}) = \frac{0.002258z^{-1} - 0.0005759z^{-3}}{1 - 1.71z^{-1} + 0.7106z^{-2}}$	91.26	0.02338	0.02310

Table 3.9: Stability, controllability, and observability of the ARX second-order model

Model	Stability	Controllable	Observable
ARX 211	Stable	Yes	Yes
ARX 212	Unstable	Yes	Yes
ARX 213	Stable	Yes	Yes
ARX 221	Unstable	Yes	Yes
ARX 222	Stable	Yes	Yes

Table 3.10 shows the validation results of ARX third-order model, meanwhile Table 3.11 summarizes the stability, controllability, and observability of the ARX third-order model in Table 3.10.

Table 3.10: Validation results of third-order ARX model

ARX model	Discrete-time transfer function	Best fit (%)	FPE	MSE
ARX311	$G(z^{-1}) = \frac{0.001759z^{-1}}{1 - 1.953z^{-1} + 1.209z^{-2} - 0.2562z^{-3}}$	91.26	0.02114	0.02085
ARX312	$G(z^{-1}) = \frac{0.001962z^{-2}}{1 - 1.921z^{-1} + 1.183z^{-2} - 0.2617z^{-3}}$	91.36	0.02134	0.02104
ARX321	$G(z^{-1}) = \frac{0.001023z^{-1} + 0.0009468z^{-2}}{1 - 1.922z^{-1} + 1.183z^{-2} - 0.2612z^{-3}}$	91.34	0.02077	0.02044
ARX331	$G(z^{-1}) = \frac{0.001027z^{-1} + 0.001228z^{-2} - 0.0003766z^{-3}}{1 - 1.928z^{-1} + 1.179z^{-2} - 0.2516z^{-3}}$	91.31	0.02075	0.02038
ARX333	$G(z^{-1}) = \frac{0.002307z^{-3} - 0.0003658z^{-4} - 0.0004067z^{-5}}{1 - 1.962z^{-1} + 1.197z^{-2} - 0.2349z^{-3}}$	90.72	0.02387	0.02344

Table 3.11: Stability, controllability, and observability of the ARX third-order model

Model	Stability	Controllable	Observable
ARX311	Unstable	Yes	Yes
ARX312	Stable	Yes	Yes
ARX321	Unstable	Yes	Yes
ARX331	Unstable	Yes	Yes
ARX333	Stable	Yes	Yes

3.4 Controller Design

Different control strategies, such as PID controller, pole-placement controller, predictive controller and fuzzy-logic controller were proposed for controlling the pneumatic positioning system was reported. However, in this study, the focused are only on positioning control using pole-placement controller and PID controller.

3.4.1 Pole-Placement Controller

The main controller for the pneumatic positioning system in this study was proposed as a pole-placement. The pole-placement controller was selected due to its ability to provide stable and accurate positioning control of pneumatic system. The main objective of this study is to make the output of the controller (actual stroke position) to track the reference input (target position). Figure 3.15 illustrates the open-loop block diagram of the pneumatic system (without controller).

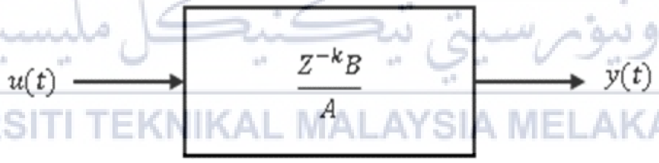


Figure 3.15: Open-loop block diagram of the pneumatic system (without controller)

Equation (3.11) expressed the open-loop pneumatic system equation in Figure 3.15.

$$y(t) = \frac{z^{-k}B}{A}\, u(t) \tag{3.11}$$

where,

$A = 1 + a_1 z^{-1} + \cdots a_{na} z^{-na}$, $B = b_0 + b_1 z^{-1} + \cdots b_{nb} z^{-nb}$

Figure 3.16 illustrates the closed-loop block diagram of the pneumatic positioning system when the pole-placement controller is considered.

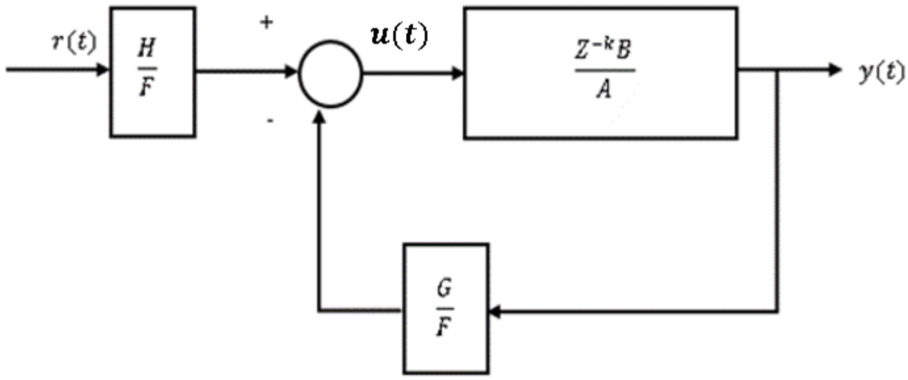


Figure 3.16: Closed loop pole-placement control block diagram

The closed-loop response in Figure 3.16 is therefore given by Equation 3.12.

$$u(t) = \frac{H}{F}\, r\,(t) - \frac{G}{F}\, y(t) \tag{3.12}$$

where,

$H = h_0 + h_1 z^{-1} + \cdots + h_{nh} z^{-nh}$

$G = g_0 + g_1 z^{-1} + \cdots + g_{ng} z^{-ng}$

$F = 1 + f_1 z^{-1} + \cdots + f_{nf} z^{-nf}$

Substitution of Equation (3.12) into Equation (3.11) gives Equation (3.13).

$$y(t) = \frac{z^{-k}B}{A}\left[\frac{H}{F}\, r(t) - \frac{G}{F}\, y(t)\right]$$

$$y(t) = \frac{z^{-k}B}{A}\left[\frac{H\, r(t) - G\, y(t)}{F}\right]$$

$$y(t) = \frac{z^{-k}B\,H\,r(t) - z^{-k}B\,G\,y(t)}{AF}$$

$$AF\,y(t) = z^{-k}B\,H\,r(t) - z^{-k}B\,G\,y(t)$$

$$y(t)[AF + z^{-k}B\,G\,] = z^{-k}B\,H\,r(t)$$

$$y(t) = \frac{z^{-k}B\,H}{AF + z^{-k}B\,G}r(t) \tag{3.13}$$

The closed-loop poles can be described as:

$$AF + z^{-k}B\,G = 0 \tag{3.14}$$

Let $T = 1 + t_1 z^{-1} + \cdots + t_{nt}z^{-nt}$, therefore, the desired closed-loop characteristics equation is:

$$AF + z^{-k}B\,G = \mathrm{T} \tag{3.15}$$

Substitution of Equation (3.15) into Equation (3.14) gives Equation (3.16).

$$y(t) = \frac{z^{-k}B\,H}{T}\,r(t) \tag{3.16}$$

Followings are the conditions need to be checked when designing the pole-placement controller:

1) A and B have no common zeroes
2) $nf = nb + k - 1$
3) $ng = na - 1$
4) $nt \leq na + nab + k - 1$

For $y(\theta),\ r = (t)$ at steady state. Therefore,

$$H = \frac{T(1)}{B(1)} \tag{3.17}$$

Based on the validation procedure in Sub-section 3.3.4, this study decided to select ARX211 as the model to represent the real pneumatic system used in this study. ARX211 was selected since it fulfils all the criteria as outline in the system identification; best fit >90 %, low FPE, low MSE, stable, controllable, and observable. Moreover, ARX211 was also selected due to its simple structure (have only two poles, one zeros, and one delay).

Figure 3.17 to Figure 3.20 illustrates the closed-loop block diagram of the pneumatic positioning system controlled using pole-placement when pole located at $+0.01, +0.1, +0.5$, and $+0.9$, respectively.

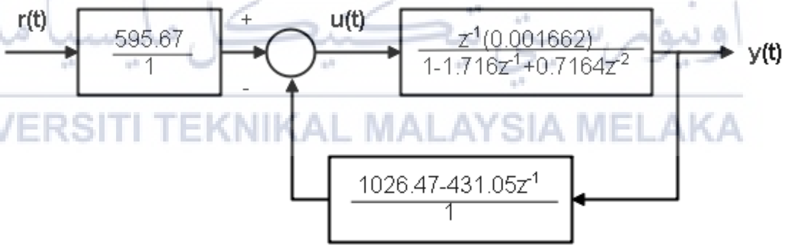


Figure 3.17: The closed-loop block diagram of the pneumatic positioning system controlled using pole-placement when pole located at $+0.01$

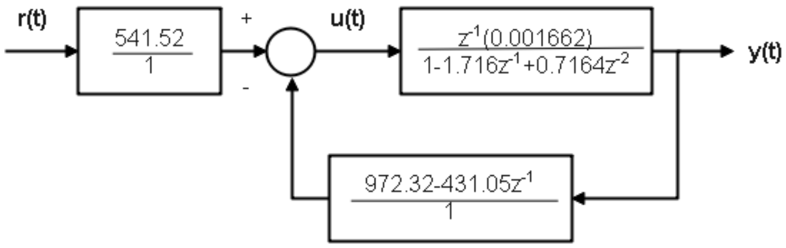


Figure 3.18: The closed-loop block diagram of the pneumatic positioning system controlled using pole-placement when pole located at $+0.1$

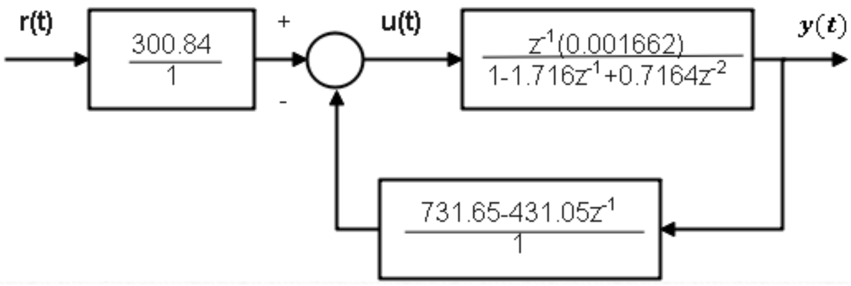


Figure 3.19: The closed-loop block diagram of the pneumatic positioning system controlled using pole-placement when pole located at $+0.5$

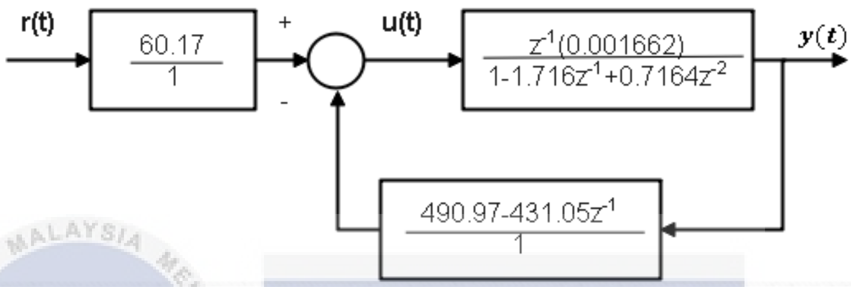


Figure 3.20: The closed-loop block diagram of the pneumatic positioning system controlled using pole-placement when pole located at $+0.9$

The detail procedure and calculation in developing the controller shown in Figure 3.17 to Figure 3.20 are presented in Appendix section.

3.4.2 Proportional-Integral-Derivative (PID) Controller

One of the linear controller which is commonly used to control the pneumatic positioning system is the Proportional-Integral-Derivative (PID) controller. In order to evaluate the performance of pneumatic positioning system controlled using pole-placement strategy, this study used PID controller for comparison. The basic block diagram of PID controller is shown in Figure 3.21.

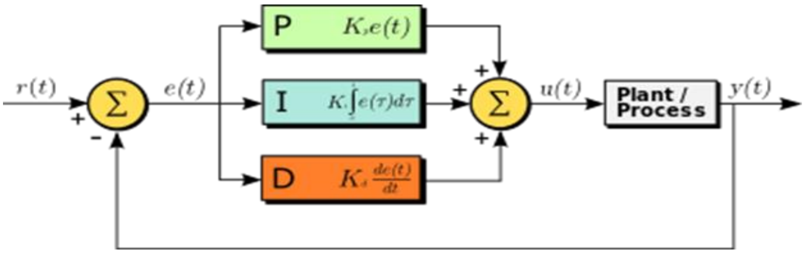


Figure 3.21: Basic block diagram of PID controller

Based on Figure 3.21, PID controller consist of three gains; Proportional (K_p), Integral (K_i), and Derivative (K_d). The input signal to the PID controller comes from the error signal and the output signal from the PID controller ($u(t)$) will be the input signal of the plant/process. In general, the control devices used to manage the various processes in industry are the final control equipment, such as the actuators, the control valves and other control devices. The process variables like pressure, speed, temperature, flow, etc. are also manipulated by the PID.

In this study, the Ziegler-Nichols tuning method was used in order to determine the values of PID parameters (K_p, K_i, K_d). In order to determine the PID parameter values using Ziegler-Nichols method, the open-loop model of the pneumatic system must be first obtained. Equation (3.18) presents the general transfer function of an open-loop process model, meanwhile, Equation (3.19) presents an open-loop model of the pneumatic system used in this study, which obtained from MATLAB System Identification Tool.

$$G(s) = \frac{Ke^{-sL}}{Ts+1} \tag{3.18}$$

$$G(s) = \frac{10.665e^{-0.03126s}}{18.621s+1} \tag{3.19}$$

By comparing Equation (3.18) with Equation (3.19),

$$K = 10.665$$

$$L = 0.03126$$

$$T = 18.621$$

Table 3.12 summarized the PID parameter values based on Ziegler-Nichols tuning method.

Table 3.12: PID parameter values based on Ziegler-Nichols tuning method

Controller type	K_p	$T_i = \frac{K_p}{K_i}$	$T_d = \frac{K_d}{K_p}$
P	$\frac{T}{L} = 595.681$	∞	0
PI	$0.9\frac{T}{L} = 536.113$	$\frac{L}{0.3} = 0.1042$ $\therefore K_i = 5145.038$	0
PID	$1.2\frac{T}{L} = 714.818$	$2L = 0.06252$ $\therefore K_i = 11433.429$	$0.5L = 0.01563$ $\therefore K_d = 11.173$

The value of PID parameters as indicated in Table 3.12 were then applied in the PID controller designing in MATLAB Simulink.

3.5 Summary

This section describes all the processes and procedures in this study, especially in the modelling and control of the pneumatic system. At the beginning of this chapter, step-by-step methods of modelling the pneumatic system using system identification techniques were presented. The data accumulation of input and output for system modelling was performed by conducting an open-loop experimental test to the pneumatic positioning system. The ARX model was selected as the model structure to represent the linear dynamics of pneumatic actuator system used in this study. The System Identification Tool was readily available in MATLAB and was used to estimate the parameters of the ARX model. When the determined model is confirmed to be accepted, the model is used for the development of the pole-placement controller, which is the main controller that controls the pneumatic positioning system. The design methodology of the pole-placement controller, including its mathematical formulas, was described at the end of this chapter. The stability of the closed-loop pneumatic positioning system is also taken into account in the design of the controller.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the results of modelling and controlling the pneumatic positioning system. This chapter also demonstrates capability of the proposed pole-placement controller to control the position of the pneumatic system. The simulation results regarding the capability of the proposed pole-placement controller compared with the PID controller was presented at the end of this chapter.

4.1 System Modelling

In this study, system identification technique was selected for the modelling purpose of pneumatic system. The Auto-Regressive with eXogenous input (ARX) model has been chosen as the model structure to represent the real pneumatic system in this study. However, in this study, the system modelling based on the ARX model was only tested using second-order and third-order model.

4.1.1 Modelling of Pneumatic System based on Second-order ARX Model

Table 4.1 shows the summarizes the validation performance of the ARX based on second-order model.

Table 4.1: Performance of second-order ARX model

Validation criteria	ARX 2nd-order				
	ARX211	ARX212	ARX213	ARX221	ARX222
Best fit (%)	91.69	91.74	91.49	91.70	91.70
FPE	0.02318	0.02350	0.02653	0.02293	0.02338
MSE	0.02295	0.02326	0.02626	0.02266	0.02266
Stability	Stable	Not stable	Stable	Not stable	Stable
Controllable	✓	✓	✓	✓	✓
Observable	✓	✓	✓	✓	✓

Table 4.1 shows that the percentage of best fit for all second-order models is greater than 90 %, with ARX212 having the highest percentage of 91.74 %. The table also proves that none of the identified model fit the actual pneumatic system 100 %, due to the nonlinearity and uncertainty issues in pneumatic system itself. However, in this case, all the identified models are considered acceptable to represent the pneumatic system used in this study, since it provides fitness >90 %. In addition to the percentage of best fit, the acceptance or rejection of the identified model was verified based on the value of the Final Prediction Error (FPE). If the determined model produces a small FPE value, the model was considered to be a model representing the actual pneumatic system. Therefore, based on the results in Table 4.1, the FPE for all second-order

models are small; thus, indicating that the identified model was accurate. In this study, the acceptance or rejection of the identified model was also made based on the stability of the system (observed using pole-zero plot of the unit circle). Figure 4.1(a)-(e) illustrates the plot of pole-zero location for the second-order ARX in Table 4.1.

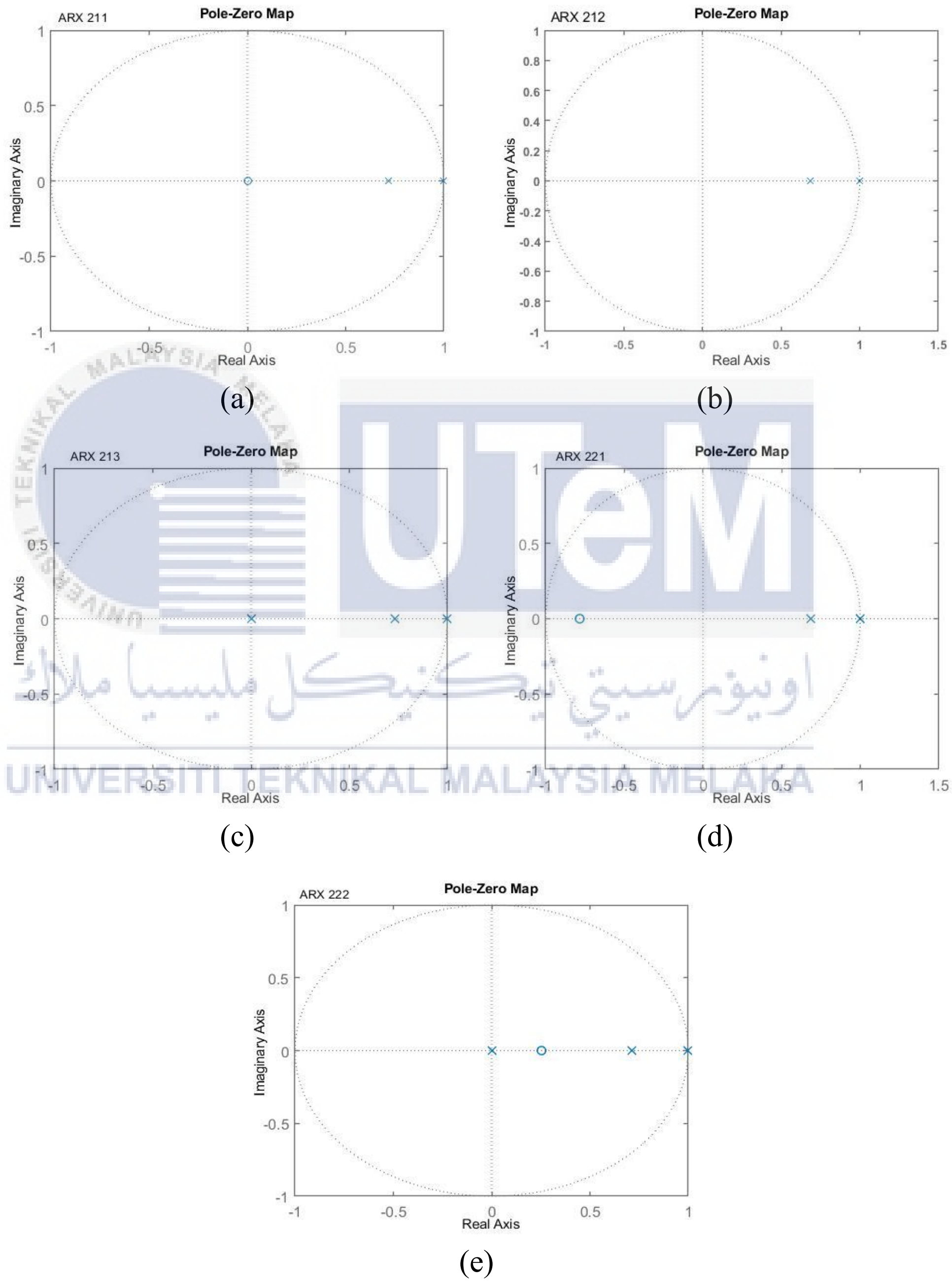


Figure 4.1: The pole-zero plot for second-order ARX model

From Table 4.1 and Figure 4.1, only three models are stable; ARX211, ARX213, and ARX222.

4.1.2 Modelling of Pneumatic System based on Third-order ARX Model

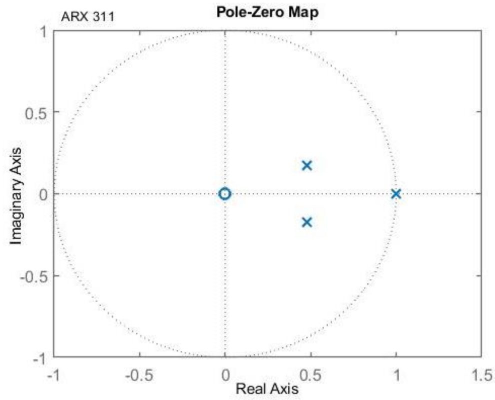
Table 4.2 shows the summarizes the validation performance of the ARX based on third-order model.

Table 4.2: Performance of a third-order ARX model

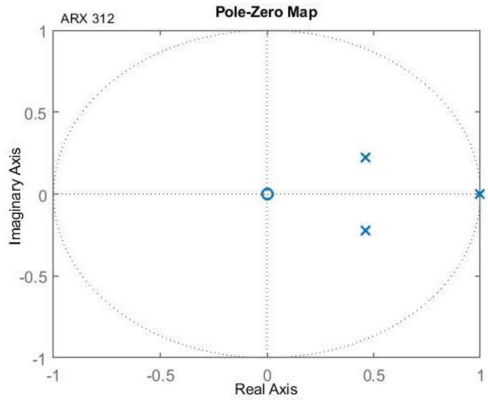
Validation criteria	ARX 3rd-order				
	ARX311	ARX312	ARX321	ARX331	ARX333
Best fit (%)	91.26	91.36	91.34	91.31	90.72
FPE	0.02114	0.02134	0.02075	0.02075	0.02387
MSE	0.02085	0.02104	0.02044	0.02038	0.02344
Stability	Not stable	Stable	Not stable	Not stable	Stable
Controllable	✓	✓	✓	✓	✓
Observable	✓	✓	✓	✓	✓

Table 4.2 shows the performance of ARX third-order model. From the table, It can be shown that all third-order models have a percentage of best fit greater than 90 %, with ARX312 having the greatest percentage at 91.36 %. Like in Table 4.1, this table also proves that none of the identified model fit the actual pneumatic system 100 %, due to the nonlinearity and uncertainty issues in pneumatic system itself. However, in this case, all the identified models are considered acceptable to represent the pneumatic system used in this study, since it provides fitness >90 %. In addition, all the identified models were considered acceptable as a model to represent the real pneumatic system since it produces a small FPE value. Therefore, based on the results in Table 4.2, the FPE for all third-order models are small; thus, indicating that the

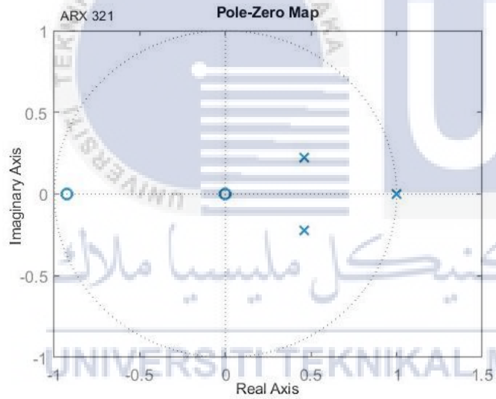
identified model was accurate. Figure 4.2(a)-(e) illustrates the plot of pole-zero location for the third-order ARX in Table 4.2.



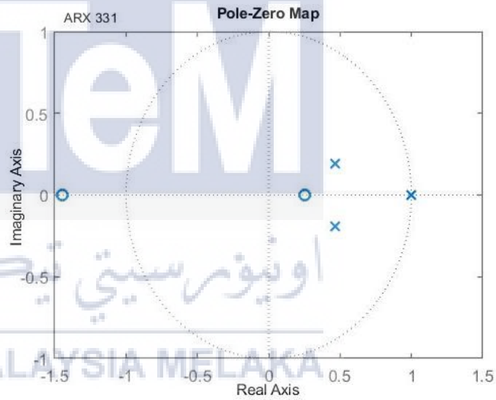
(a)



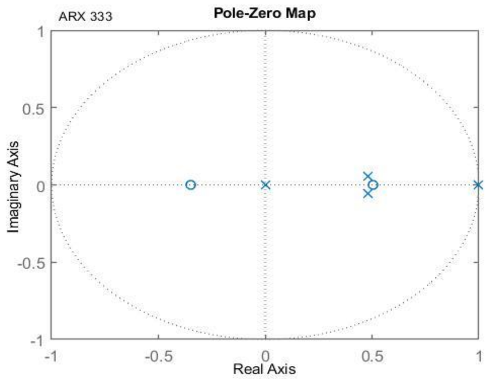
(b)



(c)



(d)



(e)

Figure 4.2: The pole-zero plot for third-order ARX model

From Table 4.2 and Figure 4.2, only two models are stable; ARX312 and ARX333. However, by considering the simplicity of the model, this study opted to focus only on the use of ARX211 when designing the controller. In addition, ARX211 also contributed the highest percentage of best fit compared to the third-order ARX model (ARX312 and ARX333).

4.2 Controller Design for Pneumatic Positioning System

In this study, pole-placement controller was proposed as a strategy to control the pneumatic positioning system. As mentioned in Sub-section 2.3.2, pole-placement controller was designed based on the pole assigned in the controller algorithm. Figure 4.3 shows the performance of pneumatic positioning system using pole-placement controller based on the ARX211 model and Figure 4.4 shows the performance of pneumatic positioning system using a pole-placement controller based on the ARX312 model. Both controllers assigned the pole to be located at +0.9, and both controllers also aiming for reference positioning distance of 100 mm.

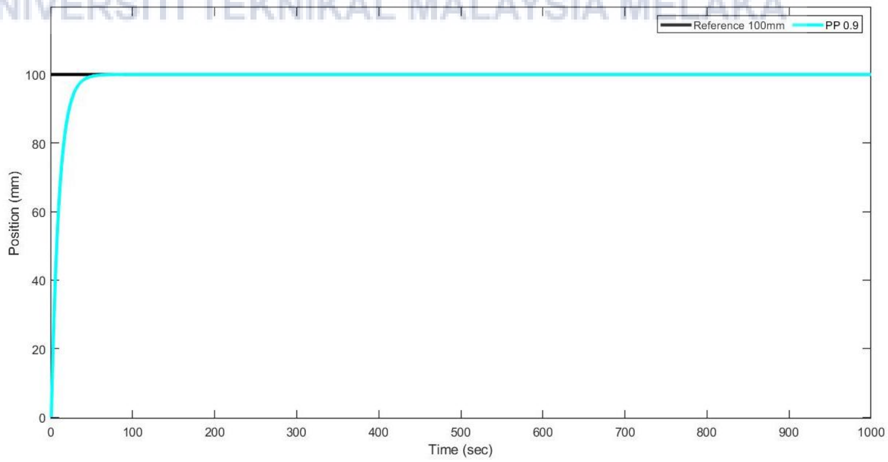


Figure 4.3: Transient response performance of pole-placement controller based on ARX211

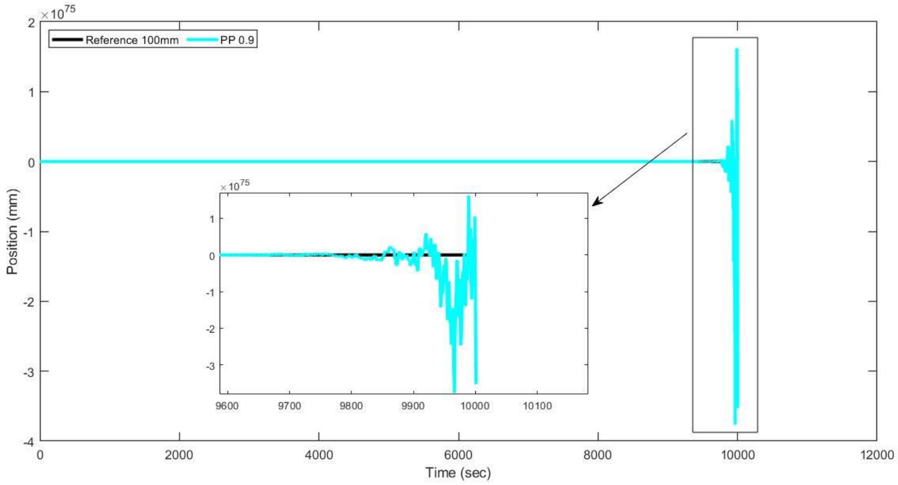


Figure 4.4: Transient response performance of pole-placement controller based on ARX312

Table 4.3 summarize the transient performance of pole-placement controller based on ARX211 and ARX312.

Table 4.3: The transient performance of pole-placement control at distance 100 mm

Transient performance	Model	
	ARX211 (2nd-order)	ARX312 (3rd-order)
t_r (s)	0.2086	invalid
t_s (s)	0.3714	invalid
OS (%)	≈ 0	invalid
e_{ss} (mm)	0.0155	invalid

Based on Table 4.3, it can be seen that the third-order ARX model (ARX312) was incapable to control the pneumatic positioning system. Controlling the pneumatic positioning system using pole-placement controller based on the second-order ARX model (ARX211) provided 0.2086 s of rise time (t_r) and 0.3714 s of settling time (t_s). The simulation results in Figure 4.4. also shows that there is no overshoot was produced when controlling the pneumatic positioning system using pole-placement controller based on ARX211. The recorded steady-state error (e_{ss}) for pole-placement controller based on ARX211 is only 0.0155 mm, thus showing that, the control strategy using pole-placement based on ARX211 was capable to provide high accuracy of pneumatic positioning system.

For the purpose of analyzing the effect of pole location on the positioning control performance of a pneumatic system, therefore, several poles locations (i.e., +0.01, +0.1, +0.5, +0.9) were used in this study when designing the pole-placement controller. Figure 4.5 to Figure 4.7 shows a comparison of the position control performance of a pneumatic system at three different positions (i.e., 50 mm, 100 mm, and 150 mm) using two types of control strategy, namely pole-placement controller and PID controller based on Ziegler-Nichols tuning method. Controlling using pole-placement controller, four different poles location were used for the purpose of analyzing in detail the effect of pole location on the position control performance of pneumatic system. Table 4.4 summarizes the transient response performance of the pneumatic positioning control system in Figure 4.5 to Figure 4.7.

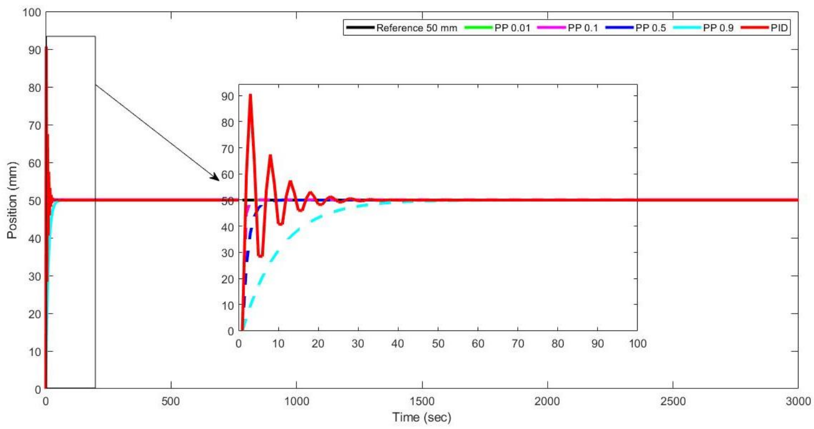


Figure 4.5: Performance of pole-placement controller and PID controller at position distance 50 mm

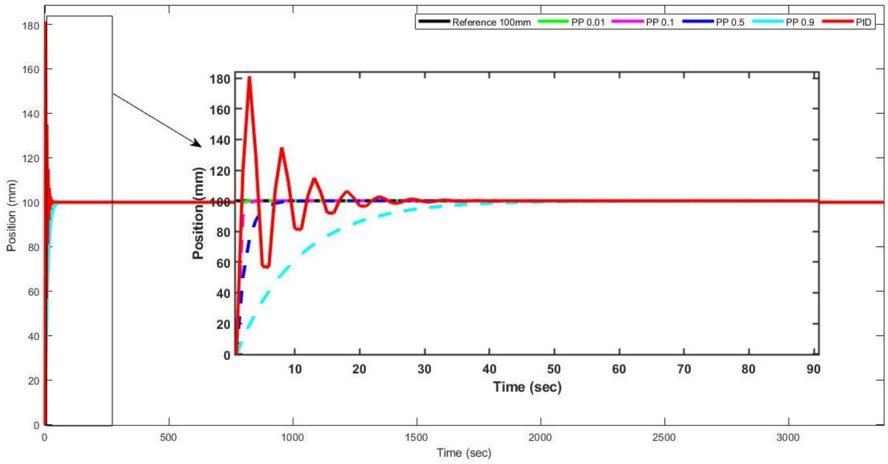


Figure 4.6: Performance of pole-placement controller and PID controller at position distance 100 mm

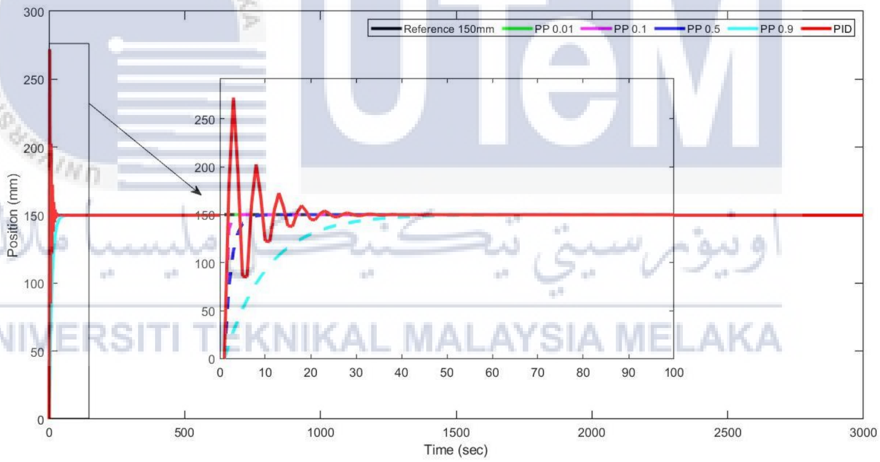


Figure 4.7: Performance of pole-placement controller and PID controller at position distance 150 mm

Table 4.4: Summary of the pneumatic positioning control system using pole-placement controller and PID controller for position distance of 50 mm, 100 mm, and 150 mm

Distance	Transient performance	CONTROL STRATEGY				
		PP (0.01)	PP (0.1)	PP (0.5)	PP (0.9)	PID
50 mm	t_r (s)	0.0081	0.0091	0.0320	0.2086	0.0067
	t_s (s)	0.0099	0.0191	0.0572	0.3714	0.2246
	OS (%)	0	0	0	0	81.4158
	e_{ss} (mm)	0.0008	0.0934	0.0001	0.0078	0.0167
100 mm	t_r (s)	0.0081	0.0089	0.0320	0.2086	0.0067
	t_s (s)	0.0099	0.0189	0.0572	0.3714	0.2246
	OS (%)	0	0	0	0	81.4158
	e_{ss} (mm)	0.0016	0.0017	0.0002	0.0155	0.0333
150 mm	t_r (s)	0.0081	0.0089	0.0320	0.2086	0.0067
	t_s (s)	0.0099	0.0189	0.0572	0.3714	0.2246
	OS (%)	0	0	0	0	81.4158
	e_{ss} (mm)	0.0023	0.0026	0.0003	0.0233	0.0500

Note: PP refers to the pole-placement controller

From Table 4.4, it can be seen that the pole location affected the transient response performance of the pole-placement controller. From Table 4.4, it was found that the larger the pole value (i.e. the pole is closer to the unit circle), the larger the t_r and t_s values. Thus, it can be concluded that, cylinder stroke was take longer to reach the target distance (i.e., 50 mm, 100 mm, and 150 mm) when large pole values were used in the pole-placement controller algorithm. PID controller was seen to take a short time to reach the target distance. However, position control using PID was unstable compared to control using pole-placement controller. From Figure 4.5 to Figure 4.7, it was clearly shown that the PID controller produces an output that constantly oscillates until the simulation test was completed.

In terms of steady-state error, it was found that pole-placement controller with pole value 0.5 managed to provide the most accurate position control, compared to pole-placement controller with pole value 0.01, 0.1, and 0.9. However, position control using PID controller and pole-placement with pole values of 0.01, 0.1, and 0.9 was still considered good since e_{ss} is still within ± 2 % of the final value.

From Table 4.4, it was found that all pole-placement controllers are able to control the pneumatic positioning system without produce any overshoot during the simulation test. In contrast to the PID controller, the PID controller produces an overshoot > 80 % for each position control.

Overall, the comparison of pneumatic positioning control system performance using pole-placement and PID control strategy confirms that pole-placement controller based on second-order ARX model was able to control pneumatic positioning system well compared to PID controller. Controlling the positioning control system using pole-placement was able to provide an accurate position control, fast response, and stable.

4.3 Summary

The results of modelling and controlling the pneumatic positioning system was presented in this chapter. The pneumatic system used in this study was shown as a second-order ARX model based on the system identification technique as it meets all the criteria outlined in system identification. Besides that, the capability of the proposed pole-placement controller to control the pneumatic positioning system was also presented in this chapter. From the simulation test that was conducted, it was found that pole location affected the performance of pole-placement controller. The speed response of the pneumatic positioning system will be faster if a small pole value (pole near the origin) was used in the pole-placement controller algorithm. Comparison of the performance with PID controller shows that pole-placement controller based on second-order ARX model was able to control the pneumatic positioning system well compared to PID controller. Pneumatic positioning control system using pole-placement was also proving that can provide an accurate position control, fast response, and stable.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

This chapter concludes the overall findings, especially the improvements that have been made by the proposed controller. Subsequently, the future improvement which can be taken to improve the pneumatic positioning control system has been suggested. At the end of this chapter, the marketability opportunities of the proposed controller are presented.

5.1 Conclusions

A new control strategy for controlling pneumatic positioning systems, namely the pole-placement controller, has been proposed. The purpose of the proposed controller is to improve the transient response of the pneumatic position control system; so that the system will deliver accurate, fast, and stable closed-loop transient response performance. In order to achieve the goal (i.e., to develop a pole-placement controller), a mathematical model that can represent the pneumatics system used in this study shall be produced. Since the pneumatic system used is complex and most of the component's information is not available, hence, this study suggests the use of an experimental approach to model this pneumatic system.

System modelling based on experimental approach (i.e., system identification technique) need to go through four main procedures, before the proposed controller can be developed. These procedures are: 1) experimental design and data collection, 2) model structure selection, 3) model estimation, and 4) model validation. Therefore, an experimental setup for the modelling and data validation of the pneumatic system has been designed. A comprehensive study throughout the conduction of this study found that the linear second-order Auto-Regressive with eXogenous input (ARX) is very suitable to be used as a structure of the model to represent the dynamic of the pneumatic system used in this study. This is because, the validation of the model based on the system identification criteria shows that the identified model successfully meets all the criteria that have been set.

Once the mathematical model has been identified, the next process is to develop a pole-placement controller as a control technique to control the pneumatic positioning system. A pole-placement controller algorithm (refer Chapter 3) was used to develop the pole-placement controller, and MATLAB Simulink was used as a platform. Since pole-placement controller was designed based on pole location (to ensure its closed-loop stability), therefore, four different poles (i.e., 0.01, 0.1, 0.5, and 0.9) were used for comparison purpose. Other linear controller, which is Proportional-Integral-Derivative (PID) controller is also used for comparison.

The last stage of this study is to make an analysis regarding pneumatic positioning control performance using pole-placement controller and PID controller. In this study, the analysis is based on transient response performance and the aim is the proposed controller will provide accurate, fast, and stable closed-loop transient response performance of pneumatic positioning system. Simulation result shows that the proposed pole-placement is capable to control the positioning of the pneumatic system used in this study. Comparison with PID controller based on simulation testing also proves that the proposed controller successfully provides an accurate, fast, and stable transient response during controlling the pneumatic positioning system.

5.2 Recommendation

There are few improvements that can be made for the future work; to improve the pneumatic positioning system in terms of modelling and controlling part. Therefore, it is recommended to:

i. Propose the new algorithm to automatic tune the pole-placement controller.
ii. Design another type of controller that can provide more accurate, fast, and stable pneumatic positioning control system.

5.3 Commercialization Relevancy

The proposed pole-placement control has a potential to be commercialized due its capability to provide pneumatic positioning control system with good transient response performances. Thus, the proposed pole-placement controller can be used to control any applications that requires fast, accurate, and stable positioning response in its operation. Previous studies have also reported that the pole-placement controller is still relevant to be used in the industries due to its simple structure.

REFERENCES

[1] S. Jamian *et al.*, “Review on controller design in pneumatic actuator drive system,” *Telkomnika (Telecommunication Comput. Electron. Control.*, vol. 18, no. 1, pp. 332–342, 2020, doi: 10.12928/TELKOMNIKA.V18I1.12626.

[2] I. Engineering, U. Teknikal, H. T. Jaya, and D. Tunggal, “Review on Modeling and Controller Design,” vol. 4, no. 4, pp. 630–661, 2011.

[3] W. K. Lai, M. F. Rahmat, and N. A. Wahab, “Modeling and controller design of pneumatic actuator system with control valve,” *Int. J. Smart Sens. Intell. Syst.*, vol. 5, no. 3, pp. 624–644, 2012, doi: 10.21307/ijssis-2017-499.

[4] D. Saravanakumar, B. Mohan, and T. Muthuramalingam, “A review on recent research trends in servo pneumatic positioning systems,” *Precis. Eng.*, vol. 49, pp. 481–492, 2017, doi: 10.1016/j.precisioneng.2017.01.014.

[5] Z. Wang, K. Or, and S. Hirai, “A dual-mode soft gripper for food packaging,” *Rob. Auton. Syst.*, vol. 125, p. 103427, 2020, doi: 10.1016/j.robot.2020.103427.

[6] S. Yu, J. Bai, S. Xiong, and R. Han, “A new iterative learning controller for electro-pneumatic servo system,” *Proc. - 8th Int. Conf. Intell. Syst. Des. Appl.*

ISDA 2008, vol. 3, pp. 101–105, 2008, doi: 10.1109/ISDA.2008.226.

[7] A. A. M. Faudzi, K. Suzumori, and S. Wakimoto, "Design and control of new intelligent pneumatic cylinder for intelligent chair tool application," *IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM*, pp. 1909–1914, 2009, doi: 10.1109/AIM.2009.5229768.

[8] S. E. Song *et al.*, "Development of a pneumatic robot for MRI-guided transperineal prostate biopsy and brachytherapy: New approaches," *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 2580–2585, 2010, doi: 10.1109/ROBOT.2010.5509710.

[9] M. Önkol and C. Kasnakoğlu, "Adaptive model predictive control of a two-wheeled robot manipulator with varying mass," *Meas. Control (United Kingdom)*, vol. 51, no. 1–2, pp. 38–56, 2018, doi: 10.1177/0020294018758527.

[10] E. Dincel and M. T. Söylemez, "Digital PI-PD controller design for arbitrary order systems: Dominant pole placement approach," *ISA Trans.*, vol. 79, pp. 189–201, 2018, doi: 10.1016/j.isatra.2018.04.009.

[11] K. Zabet, J. A. Rossiter, R. Haber, and M. Abdullah, "Pole-placement Predictive Functional Control for under-damped systems with real numbers algebra," *ISA Trans.*, vol. 71, pp. 403–414, 2017, doi: 10.1016/j.isatra.2017.08.002.

[12] S. F. Sulaiman, M. F. Rahmat, A. A. M. Faudzi, and K. Osman, "A new technique to reduce overshoot in pneumatic positioning system," *Telkomnika (Telecommunication Comput. Electron. Control.*, vol. 17, no. 5, pp. 2607–2616,

2019, doi: 10.12928/TELKOMNIKA.v17i5.12807.

[13] A. W. N. Husna *et al.*, "Critical Review: Adaptive Pole Assignment PID Controller on DC-DC Converters," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 767, no. 1, 2020, doi: 10.1088/1757-899X/767/1/012039.

[14] N. Nevaranta, P. Jaatinen, J. Vuojolainen, T. Sillanpää, and O. Pyrhönen, "Adaptive MIMO pole placement control for commissioning of a rotor system with active magnetic bearings," *Mechatronics*, vol. 65, no. May 2019, p. 102313, 2020, doi: 10.1016/j.mechatronics.2019.102313.

[15] N. Sun, Di. Liang, Y. Wu, Y. Chen, Y. Qin, and Y. Fang, "Adaptive Control for Pneumatic Artificial Muscle Systems with Parametric Uncertainties and Unidirectional Input Constraints," *IEEE Trans. Ind. Informatics*, vol. 16, no. 2, pp. 969–979, 2020, doi: 10.1109/TII.2019.2923715.

[16] P. Perz, I. Malujda, D. Wilczyński, and P. Tarkowski, "Methods of Controlling a Hybrid Positioning System Using LabVIEW," *Procedia Eng.*, vol. 177, pp. 339–346, 2017, doi: 10.1016/j.proeng.2017.02.235.

[17] S. Davis, "Pneumatic actuators," *High-Throughput*, vol. 7, no. 3, pp. 5–7, 2018, doi: 10.3390/act7030062.

[18] A. Khalid, P. Kirisci, Z. H. Khan, Z. Ghrairi, K. D. Thoben, and J. Pannek, "Security framework for industrial collaborative robotic cyber-physical systems," *Comput. Ind.*, vol. 97, pp. 132–145, 2018, doi: 10.1016/j.compind.2018.02.009.

[19] K. Osman, A. N. Ahmad Sukri, S. F. Sulaiman, A. R. Azira, and M. F. Faujan,

"Predictive controller with Kalman filter for Intelligence Pneumatic Actuator (IPA)," *J. Adv. Manuf. Technol.*, vol. 13, no. Special Issue 2, pp. 1–10, 2019.

[20] L. Zhao, Y. Xia, Y. Yang, and Z. Liu, "Multicontroller Positioning Strategy for a Pneumatic Servo System Via Pressure Feedback," *IEEE Trans. Ind. Electron.*, vol. 64, no. 6, pp. 4800–4809, 2017, doi: 10.1109/TIE.2017.2674605.

[21] S. Wakimoto, K. Suzumori, and T. Kanda, "Development of intelligent McKibben actuator," *2005 IEEE/RSJ Int. Conf. Intell. Robot. Syst. IROS*, pp. 487–492, 2005, doi: 10.1109/IROS.2005.1545315.

[22] N. Arx, M. For, I. Pneumatic, and A. Systems, "Jurnal Teknologi LINEAR AND NONLINEAR ARX MODEL FOR," vol. 6, pp. 21–28, 2016.

[23] H. I. Ali, S. B. B. M. Noor, S. M. Bashi, and M. H. Marhaban, "A review of pneumatic actuators (modeling and control)," *Aust. J. Basic Appl. Sci.*, vol. 3, no. 2, pp. 440–454, 2009.

[24] M. A. Azman, A. A. M. Faudzi, M. O. Elnimair, O. F. Hikmat, K. Osman, and C. C. Kai, "P-Adaptive Neuro-Fuzzy and PD-Fuzzy controller design for position control of a modified single acting pneumatic cylinder," *2013 IEEE/ASME Int. Conf. Adv. Intell. Mechatronics Mechatronics Hum. Wellbeing, AIM 2013*, pp. 176–181, 2013, doi: 10.1109/AIM.2013.6584088.

[25] "View of Integrating Servo-Pneumatic Actuator with Ball Beam System based on Intelligent Position Control.pdf" .

[26] A. A. A. Emhemed, R. Bin Mamat, and A. A. M. Faudzi, "A new predictive control technique for force control of pneumatic actuator plant," *2015 10th*

Asian Control Conf. Emerg. Control Tech. a Sustain. World, ASCC 2015, 2015, doi: 10.1109/ASCC.2015.7244883.

[27] H. Asif, A. Nasir, U. T. Shami, S. T. H. Rizvi, and M. M. Gulzar, "Design and comparison of linear feedback control laws for inverse Kinematics based robotic arm," *Proc. - 2017 13th Int. Conf. Emerg. Technol. ICET2017*, vol. 2018-January, pp. 1–6, 2018, doi: 10.1109/ICET.2017.8281705.

LIST OF PAPERS PRESENTED

1. **Nur Ain Mohd Jomli** and Siti Fatimah Sulaiman (2021). Pole-placement control for pneumatic positioning. In *Virtual Innovation and Technology Competition (INOTEK) 2021*.

APPENDICES

Pole-Placement Controller Design

<u>Pole-placement controller when pole located at +0.01:</u>

$$G(z^{-1}) = \frac{0.001662z^{-1}}{1 - 1.716z^{-1} + 0.7164z^{-2}}$$

$\therefore A = 1 - 1.716z^{-1} + 0.7164z^{-2}$
$na = 2$
$z^{-1}B = 0.001662z^{-1}$
$= z^{-1}(0.001662)$
$k = 1$
$nb = 0$

Let, closed-loop pole at +0.01. Therefore, $T = 1 - 0.01z^{-1}$
$nt = 1$

Checking conditions:

1) A and B are have no common zeros
2) $nf = nb + k - 1 = 0$
3) $ng = na - 1 = 1$
4) $nt \leq na + nb + k - 1 = 1 \leq 2$

Therefore,
$F = 1$
$G = g_0 + g_1z^{-1}$
$H = ?$

The desired close loop equation: $AF + Z^{-1}BG = 1$

Substitute,
$(1 - 1.716z^{-1} + 0.7164z^{-2})(1) + z^{-1}(0.001662)(g_0 + g_1z^{-1}) = 1 - 0.01z^{-1}$
$(1 - 1.716z^{-1} + 0.7164z^{-2}) + 0.001662g_0z^{-1} + 0.001662g_1z^{-2}$
$= 1 - 0.01z^{-1}$
$1 - (1.716 + 0.001662g_0)z^{-1} + (0.7164 + 0.001662g_1)z^{-2} = 1 - 0.01z^{-1}$

Equating both sides,

$-1.716 + 0.001662\, g_0 = -0.01$
$0.001662\, g_0 = -0.01 + 1.716$
$0.001662 g_0 = 1.706$
$\boldsymbol{g_0 = 1026.47}$

$0.7164 + 0.001662\, g_1 = 0$
$0.001662\, g_1 = -0.7164$
$\boldsymbol{g_1 = -431.05}$
$\therefore F = 1$
$G = g_0 + g_1 Z^{-1} = 1026.47 - 431.05 Z^{-1}$

For $y(t) = r(t)$ at steady-state.

$$H = \frac{T(1)}{B(1)} = \frac{1 - 0.01z^{-1}}{0.001662z^{-1}} |Z = 1$$

$$H = \frac{0.99}{0.001662}$$

$\boldsymbol{H = 595.67}$

Pole-placement controller when pole located at +0.1:

$$G(z^{-1}) = \frac{0.001662z^{-1}}{1 - 1.716z^{-1} + 0.7164z^{-2}}$$

$\therefore A = 1 - 1.716z^{-1} + 0.7164z^{-2}$
$na = 2$
$z^{-1}B = 0.001662z^{-1}$
$= z^{-1}(0.001662)$
$k = 1$
$nb = 0$

Let, closed-loop pole at $z = +0.1$. Therefore, $T = 1 - 0.1z^{-1}$
$nt = 1$

Checking conditions:
1) A and B are have no common zeros
2) $nf = nb + k - 1 = 0$
3) $ng = na - 1 = 1$
4) $nt \leq na + nb + k - 1 = 1 \leq 2$

Therefore,
$F = 1$
$G = g_0 + g_1 z^{-1}$
$H = ?$

The desired close loop equation: $AF + Z^{-1}BG = 1$

Substitute,

$$(1-1.716z^{-1}+0.7164z^{-2})(1)+z^{-1}(0.001662)(g_0+g_1z^{-1})=1-0.1z^{-1}$$
$$(1-1.716z^{-1}+0.7164z^{-2})+0.001662g_0z^{-1}+0.001662g_1z^{-2}=1-0.1z^{-1}$$
$$1-(1.716+0.001662g_0)z^{-1}+(0.7164+0.001662g_1)z^{-2}=1-0.1z^{-1}$$

Equating both sides,

$$-1.716+0.001662\,g_0=-0.1$$
$$0.001662\,g_0=-0.1+1.716$$
$$0.001662g_0=1.616$$
$$\boldsymbol{g_0=972.32}$$

$$0.7164+0.001662\,g_1=0$$
$$0.001662\,g_1=-0.7164$$
$$\boldsymbol{g_1=-431.05}$$

$\therefore F=1$

$G=g_0+g_1Z^{-1}=972.32-431.05Z^{-1}$

For $y(t)=r(t)$ at steady-state.

$$H=\frac{T(1)}{B(1)}=\frac{1-0.1z^{-1}}{0.001662z^{-1}}|Z=1$$

$$H=\frac{0.9}{0.001662}$$

$\boldsymbol{H=541.52}$

Pole-placement controller when pole located at +0.5:

$$G(z^{-1})=\frac{0.001662z^{-1}}{1-1.716z^{-1}+0.7164z^{-2}}$$

$\therefore A=1-1.716z^{-1}+0.7164z^{-2}$

$na=2$

$z^{-1}B=0.001662z^{-1}$

$=z^{-1}(0.001662)$

$k=1$

$nb=0$

Let, closed-loop pole at $z=+0.5$. Therefore, $T=1-0.5z^{-1}$

$nt=1$

Checking conditions:

1) A and B are have no common zeros
2) $nf=nb+k-1=0$
3) $ng=na-1=1$
4) $nt\le na+nb+k-1=1\le 2$

Therefore,

$F=1$

$G=g_0+g_1z^{-1}$

$H = ?$

The desired close loop equation: $AF + Z^{-1}BG = 1$

Substitute,
$(1 - 1.716z^{-1} + 0.7164z^{-2})(1) + z^{-1}(0.001662)(g_0 + g_1z^{-1}) = 1 - 0.5z^{-1}$
$(1 - 1.716z^{-1} + 0.7164z^{-2}) + 0.001662g_0z^{-1} + 0.001662g_1z^{-2} = 1 - 0.5z^{-1}$
$1 - (1.716 + 0.001662g_0)z^{-1} + (0.7164 + 0.001662g_1)z^{-2} = 1 - 0.5z^{-1}$

Equating both sides,
$-1.716 + 0.001662\, g_0 = -0.5$
$0.001662\, g_0 = -0.5 + 1.716$
$0.001662g_0 = 1.216$
$\boldsymbol{g_0 = 731.65}$

$0.7164 + 0.001662\, g_1 = 0$
$0.001662\, g_1 = -0.7164$
$\boldsymbol{g_1 = -431.05}$

$\therefore F = 1$
$G = g_0 + g_1z^{-1} = 731.65 - 431.05Z^{-1}$
For $y(t) = r(t)$ at steady-state.
$H = \frac{T(1)}{B(1)} = \frac{1 - 0.5z^{-1}}{0.001662z^{-1}} |Z = 1$
$H = \frac{0.5}{0.001662}$
$\boldsymbol{H = 300.84}$

Pole-placement controller when pole located at +0.9:

$$G(z^{-1}) = \frac{0.001662z^{-1}}{1 - 1.716z^{-1} + 0.7164z^{-2}}$$

$\therefore A = 1 - 1.716z^{-1} + 0.7164z^{-2}$
$na = 2$
$z^{-1}B = 0.001662z^{-1}$
$= z^{-1}(0.001662)$
$k = 1$
$nb = 0$

Let, closed-loop pole at $z = +0.9$. Therefore, $T = 1 - 0.9z^{-1}$
$nt = 1$

Checking conditions:
1) A and B are have no common zeros
2) $nf = nb + k - 1 = 0$
3) $ng = na - 1 = 1$

4) $nt \leq na + nb + k - 1 = 1 \leq 2$

Therefore,
$F = 1$
$G = g_0 + g_1 z^{-1}$
$H = ?$

The desired close loop equation: $AF + Z^{-1}BG = 1$

Substitude
$(1 - 1.716z^{-1} + 0.7164z^{-2})(1) + z^{-1}(0.001662)(g_0 + g_1 z^{-1}) = 1 - 0.9z^{-1}$
$(1 - 1.716z^{-1} + 0.7164z^{-2}) + 0.001662g_0 z^{-1} + 0.001662g_1 z^{-2} = 1 - 0.9z^{-1}$
$1 - (1.716 + 0.001662g_0)z^{-1} + (0.7164 + 0.001662g_1)z^{-2} = 1 - 0.9z^{-1}$

Equating both sides,
$-1.716 + 0.001662\, g_0 = -0.9$
$0.001662\, g_0 = -0.9 + 1.716$
$0.001662 g_0 = 0.816$
$\boldsymbol{g_0 = 490.97}$

$0.7164 + 0.001662\, g_1 = 0$
$0.001662\, g_1 = -0.7164$
$\boldsymbol{g_1 = -431.05}$

$\therefore F = 1$
$G = g_0 + g_1 z^{-1} = 490.97 - 431.05Z^{-1}$
For $y(t) = r(t)$ at steady-state.
$H = \frac{T(1)}{B(1)} = \frac{1 - 0.9z^{-1}}{0.001662z^{-1}} | Z = 1$
$H = \frac{0.1}{0.001662}$
$\boldsymbol{H = 60.17}$