MODELLING OF PNEUMATIC SYSTEM USING SYSTEM IDENTIFICATION APPROACH

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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 "Modelling of Pneumatic System Using System Identification Approach" is the result of my own work except for quotes as cited in the references.

Signature :

Author : Laila Nadhirah Binti Mohd Asri

Date : 25 Jun 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	:	25 Jun 2021……………………

DEDICATION

I wholeheartedly dedicated this thesis to my beloved parents, Mr Mohd Asri and Mrs Norsamalira that has always being my side, my family, to my supervisor Dr Siti Fatimah and family and friends that supports me through this journey and above all, our Almighty God, Allah SWT.

ABSTRACT

Nowadays, pneumatic system becomes complex since it integrates many components in a single pneumatic system. Basically, there are two ways to model the pneumatic system which are theoretical and empirical approach. This study proposed modelling of pneumatic system using empirical approach (or called as system identification technique in control system engineering). In this study, experimental setup for pneumatic system modelling was first designed. Then, a mathematical model that represent pneumatic system based on Auto-Regressive Exogenous Input (ARX), Auto-Regressive Moving Average with Exogenous input (ARMAX), Box-Jenkins (BJ) and Output-Error (OE) model structures using system identification were determined. Then, the identified ARX, ARMAX, BJ and OE model structures were validated based on system identification criteria and these models were then compared. For comparison, second-order for all model structures (ARX, ARMAX, BJ and OE) are eligible to represent the pneumatic system used in this study. Lastly, the performance of each second-order model structures as a plant model for Proportional-integral-Derivative (PID) controller (to control pneumatic positioning system) was evaluated based on simulation test. The simulation result using MATLAB Simulink revealed that second-order ARMAX model gives the best performance (in terms of transient response) in controlling the pneumatic positioning system compared to other models.

ABSTRAK

Pada masa kini, sistem pneumatik telah menjadi sulit kerana telah mengabungkan pelbagai komponen ke dalam satu sistem pneumatik. Pada asasnya, terdapat dua cara untuk memodelkan sistem pneumatik iaitu menerusi cara teori dan cara eksperimen. Kajian ini mencadangkan memodelkan sistem pneumatik dengan menggunakan cara eksperimen (atau dikenali sebagai Pengenalanan Sistem di dalam kejuruteraan kawalan). Di dalam kajian ini, ketetapan eksperimen memodelkan sistem pneumatik telah direka terlebih dahulu. Kemudian, model matematik untuk mewakili sistem pneumatik berdasarkan Input Auto-Regresif (ARX), Auto-Regresif dengan Input Purata Bergerak (ARMAX), Kotak Jenkins (BJ) dan Ralat Output (OE) struktur model dikenalpasti menggunakan pengenalpastian sistem. Kemudian, model yang telah dikenalpasti ARX, ARMAX, BJ dan OE disahkan berdasarkan kriteria pengenalpastian sistem dan model-model ini dibandingkan. Setelah perbandingan, urutan kedua bagi semua struktur model (ARX, ARMAX, BJ dan OE) layak untuk mewakili sistem pneumatik di dalam kajian ini. Akhir sekali, prestasi, setiap urutan kedua struktur model sebagai model loji untuk pengawal Derivative-Berkadar-Integral (PID) (untuk mengawal kedudukan sistem penumatik) dinilai berdasarkan ujian simulasi. Hasil keputusan simulasi menunjukkan urutan kedua model ARMAX memberi prestasi terbaik (berdasarkan tindak balas sementara) di dalam mengawal kedudukan sistem pneumatic dibandingkan dengan model lain.

ACKNOWLEDGEMENTS

First of all, I would like to thank to Allah for showering me blessing and has always guiding me to work on this project. With permission, this project was able to be completed within the timeframe.

My special thanks to my supervisor, Dr. Siti Fatimah Binti Sulaiman for supervising me throughout this project. Dr. Fatimah has taught me how to conduct the research and the concept related to pneumatic system. Her knowledge and expertise had helped me to understand the concept and able to grasp the knowledge to complete this project.

Next, I would love to express my gratitude to my parents, whom always supporting me and brought encouragement to me in completing this project. Their words always kept me moving forward and not give up.

Finally, I would like to thank to my classmates, assistant engineer and others who have willingly helped me and have well played their role to inspire me behind the certain.

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LIST OF SYMBOLS AND ABBREVIATIONS

ARX	:	Auto-Regressive with Exogenous Input
ARMAX	:	Auto-Regressive Moving Average with Exogenous Input
BJ	:	Box-Jenkins
OE	:	Output-Error
P	:	Proportional
PI	:	Proportional Integral
PID	:	Proportional-Integral-Derivative
PSoC	:	Programmable System on Chip
PWM	:	Pulse Width Modulation
DAQ	:	Data Acquisition
GUI	:	Graphical User Interface
FPE	:	Final Prediction Error
MSE	:	Mean Square Error
R&D	:	Research and Development

CHAPTER 1

INTRODUCTION

1.1 Background Study

Pneumatic system is a system that perform motion in linear or rotation by using compressed air. The history of pneumatic were started in 1600s when German physicist Otto von Guericke first invented a vacuum pump which utilized air pressure [1]. The pneumatics industry continues to evolve when leading names such as Alfred Beach, John Wanamaker and others continue to produce components that can improve efficiency, performance, and functionality. Nowadays, most of industries employed pneumatic system in their control operation [2].

There are two methods that can be adopted to model a pneumatic system. First method is through theoretical method and second method is through empirical method. The theoretical method is complex and requires a lot of time because it involves with the random non-linearities and unknown parameters within the system [3]. Alternatively, empirical method can be employed to model the pneumatic system. In control system engineering, modelling using an empirical approach is also called as system identification. System identification technique requires the information of dynamic characteristic of the system, which can be collected from real-time experiment. Auto-Regressive with Exogenous input (ARX), Auto-Regressive Moving Average with Exogenous input (ARMAX), Output-Error (OE) and Box-Jenkins (BJ) are the model structure which are commonly used to model the system using system identification technique. These model structures can be used to describes the characteristics or dynamics of the pneumatic system.

Previous researcher from Universiti Teknologi Malaysia (UTM), modelled the pneumatic system based on ARX model [1]. The researcher from University of Cairo, Egypt applied ARMAX to model pneumatic system [4]. Meanwhile, the researcher from Adana Science and Technology University, Turkey applied OE model to design adaptive estimator for closed-loop unstable linear of pneumatic system [5]. Subsequently, the researcher from Institute of Measurement and Control modelled the pneumatic system using Box-Jenkins [6].

Based on previous study conducted by researchers in [1], [4], [5] and [6] this study propose to model the pneumatic system using model structure of ARX, ARMAX, OE and BJ. The identified mathematical models were then compared based on system identification criteria to confirm the validity or accuracy of the model to represent the pneumatic system used in this study. In order to test the capability of the identified model to be used as a plant model for the controller (pneumatic positioning), the models were applied to basic Proportional-Integral-Derivative (PID) controller.

1.2 Problem Statement

The modern pneumatic are complex and intelligent compared to the conventional pneumatic system because the pneumatic system integrates various components in a single device [7]. However, this makes the modelling process of modern pneumatic system complicated. Modelling process is important as it represent the pneumatic system used in this study. Applying theoretical approach complicates the modelling process due to system complexities and unknown variable within the system components [3]. Improper modelling will result inaccurate positioning control of the pneumatic system [8]. Therefore, this study proposed the empirical approach using system identification for modelling of the pneumatic system.

1.3 Objectives

1. To design an experimental setup for the modelling and data validation of the pneumatic system.
2. To determine a mathematical model that represent the pneumatic system based on ARX, ARMAX, OE and BJ model structures using system identification technique.
3. To compare the validity of the identified ARX, ARMAX, OE and BJ model structures in terms of system identification criteria.
4. To evaluate the performance of of pneumatic positioning control using PID based on simulation test.

1.4 Scope of work

The scope and limitation of project were considered throughout this project, are presented as following:

1. The mathematical model of pneumatic system was determined using system identification technique. Only linear model structure such as ARX, ARMAX, OE and BJ were considered to represent the dynamic characteristics of pneumatic system.
2. The PID controller was adopted as the controller to control the pneumatic positioning system.
3. The parameter of PID controller was tuned by using Ziegler-Nichols method and heuristic tuning method.
4. The pressurized supply air was kept at constant (0.6 MPa) throughout the experiment.
5. The positioning control of pneumatic system was restricted to maximum distance of 200 mm.
6. The performance of the pneumatic positioning control using PID were analyzed based on stability and transient response.

1.5 Thesis Outline

Chapter 1 provides the background study, problem statement, objectives and the scope and limitation when conducting this study.

Chapter 2 reviews the related literature and previous studies conducted on the pneumatic system. This chapter begins with a brief introduction to the concept of pneumatic system. Then, the modelling of the pneumatic system was reviewed. Several review regarding control strategies for pneumatic positioning system were presented at the end of this chapter.

Chapter 3 describes the step-by-step methodology of this study. The process involves in modelling the pneumatic system using the system identification technique is described in detail in this chapter. The experimental process setup and the validation model process were also described in this chapter. Lastly, the procedures in designing a proposed control strategy (PID controller) were described at the end of this chapter.

Chapter 4 presents the result obtained from the modelling of the pneumatic system using system identification technique. The performance of the identified ARX, ARMAX, OE and BJ model structures based on system identification criteria were discussed. Subsequently, the performance of pneumatic positioning control using PID based on simulation test were described at the end of this chapter.

Chapter 5 concludes the overall studies and sum up the findings of the study based on objectives. Lastly, this chapter also suggest some recommendations and improvements that can be made for the future work, to improve the pneumatic system.

CHAPTER 2

LITERATURE REVIEW

This chapter view the previous studies related to pneumatic system. This chapter describes the pneumatic system based on its application, advantages and limitation. Apart from that, this chapter relate several methods adopted to model the pneumatic system and control the pneumatic system.

2.1 Overview of pneumatic system

Pneumatic system is a system that perform linear or rotary motion by using compressed air. The pneumatic system most often used because of its low cost and simplicity structure [9]. Pneumatic systems are extensively used in production and automation [10]. Apart from that, the pneumatic system has high speed response and capacity to withstand high temperature. Subsequently, pneumatic system is preferable compared to other system for control application [9].

The use of pneumatic system in the industrial application involves in such automotive [10], robotics [7] and medical application. Pneumatic system also reported used as a controller for temperature regulation in aeronautical industries [11]. Therefore, the Research and Development (R&D) on pneumatic system activities in university have significantly increased.

2.2 Modelling of Pneumatic System

Mathematical model represents the characteristic or the dynamic of the system. The characteristic of pneumatic system needs to be studied in order to apply the system for various tasks. Theoretical approach and empirical approach are two approaches which are always used for modelling the system [3].

Theoretical approach is based on the fundamental law of nature derived from the researcher and then applied the principles to demonstrate the ideas or obtain a result. In a contrary, the empirical approach is based on the observation and analysis through experiment. For this study, the empirical approach adopted to model the pneumatic system.

System identification build mathematical model based on the observation of input and output. In addition, system identification is considered as a practical approach since it can interface between control theory and real-time application [12]. Therefore, system identification is preferable to model the system. The theoretical method is compounded and protracted since it involves with unknown non-linearities and uncertainties parameters within the system [3].

2.2.1 Theoretical Approach for Modelling of Pneumatic System

Table 2.1 shows the summary of previous studies regarding the theoretical approach for modelling of pneumatic system.

Table 2.1 Summary of previous study regarding theoretical approach for modelling of pneumatic system

Author	Theoretical approach	Limitations
Nguyen *et al.*, 2015 [13]	Thermodynamic	The transfer of heat and temperature through all the pneumatic system are assumed to remained constant.
Shi *et al.*, 2015 [14]	-	The piston rod chamber of the pneumatic system is assumed to not having air leakage. The air entered into the piston rod is also assumed to follow all ideal gas law.
Saleem *et al.*, 2015 [15]	-	The mass flow rates in the pneumatic system and the effective flow passage area were assumed.
Setia *et al.*, 2016 [16]	Two layer-based model	The pressure drops for section of straight pipe straight and exit were assumed.
Khalili *et al.*, 2016 [17]	Bondgraph Method	The velocity and position of the pneumatic system were assumed zero at initial condition
Faham *et al.*, 2017 [18]	-	The final mathematical model complicated since it relies on θ value.
Badretdinov *et al.*, 2019 [19]	Two-phase model	The inertia of pneumatic system depends on the characteristics of the air flow in which it moves.

Table 2.1 summarized the theoretical approaches adopted by previous studies. From the Table 2.1, each of the theoretical approaches have their own limitation during the modelling of the pneumatic system process. As shown in the Table 2.1, the theoretical approach often assumes the characteristic of the pneumatic system such as the rate of air flow, air pressure entered into the piston rod and the position of the pneumatic system. Hence, the theoretical approach more challenging and time-consuming because the approach involved in unknown parameter and assumption [3]. From that, most studies apply the empirical approach for modelling of the pneumatic system.

2.2.2 Empirical approach for Modelling of Pneumatic System

An empirical approach or system identification technique can be used to model the pneumatic system. System identification technique is considered as a practical approach it can interface between control theory and real-time application [12]. There are several parametric models that can be used to represent the overall system when using system identification technique, which are Auto-Regressive with Exogenous input (ARX), Auto-Regressive Moving Average with Exogenous input (ARMAX), Output-Error (OE) and Box-Jenkins (BJ).

Table 2.2 Summary of previous study regarding empirical approach for modelling of pneumatic system

Author	**Model Structure**	**Research Findings**
Izzuddin *et al.*, 2015 [20]	ARX Model	System identification (SI) approach is used to obtain the linear transfer function in discrete form. PFC is proposed to predict the future outputs of the actual plant.
Polyakov *et al.*, 2016 [21]	OE Model	This study presents robust recursive algorithm for identification of OE models of pneumatic system.
Piltan *et al.* 2017 [3]	ARX and ARMAX model	This study concluded ARMAX has better performance in terms of Final Prediction Error (FPE) compared to ARX model.
Jamian *et al.*, 2018 [22]	ARX and ARMAX model	This study presents the modeling of a single rod double acting pneumatic actuator system using system identification. This study concluded ARX has best fit of 77.90% which is better than ARMAX model.
Mahyudin *et al.*, 2018 [23]	ARX model	This research has presented development of Generalized Minimum Variance (GMV) algorithm in pneumatic system. The model using system identification plant model.
Abbasi *et al.*, 2020 [24]	ARX model	System identification approaches are used to model the behavior of the soft actuator, simulate time response, and design a suitable controller.

Table 2.2 summarize the empirical approach using system identification from previous studies. Based on the previous studies, the empirical approach using system identification approach has been implemented for modelling of pneumatic system. The empirical approach was selected due to the performance of the system identification itself. System identification produce accurate result and at the same time easier to use. System identification only requires the input and output data from real-time experiment of the pneumatic system. Thus, system identification approach was applied for this study to model pneumatic system.

Application of pneumatic system in the industries has been extensively applied due to the advantages of the pneumatic system itself. The high-speed response and precise positioning capabilities has given the pneumatic system advantage in the industries especially in control application [16]. In addition, wider applications of pneumatic system developed strategies that are pertinent [17]. There are various control strategies for the pneumatic system such as Proportional-Integral-Derivative (PID) control, Fuzzy logic control and others.

2.3 Control Strategies for Pneumatic System using Proportional-Integral-Derivatives (PID) controller

Proportional-Integral-Derivatives (PID) controller as a feedback for control system has been reported in several studies [25] and [26]. Heidari *et al.* [25] proposed the improvement of the pneumatic control valve using PID controller [25]. In this study, P and PI controller were also used to compare the performance of the pneumatic system based on the response characteristic of control valve. Heidari *et al.* [25] concluded the PID controller had the least overshoot and more robustness performance compared to P and PI controller. The PID controller had better response characteristic in a feedforward path [25].

Ibrahim *et al.* [26] proposed PID controller for low level control of soft pneumatic actuators [26]. The parameter of PID controller was tuned with the Ziegler-Nichols method [26]. The PID controller were employed through simulation testing and real-time experiment [26]. The designed PID controller has faster rise time and distinctive overshoot when tuning the parameter [26].

Apart from that, the combination of PID controller and other components to control the pneumatic actuator system was also reported in several studies [2] and [27]. Lai *et al.*, [2] modified the PID control with fuzzy control [2]. The combined fuzzy PD and fuzzy PI control schemes are applied to control a nonlinear pneumatic positioning system characterized with friction, unknown system model, and external disturbance [2].

Dhaifallah *et al*. [27] incorporated fuzzy-based fractional-order PID control to analyze the performance based robustness of load variation [27]. However, there are limitation in terms of performance of the conventional PID controller in terms of controlling resonant or integrating process. When the system is non-linear or having a certain constraint, the conventional PID controller tends to have inaccurate positioning control. Nevertheless, the PID remains relevant control strategy due to its simplicity.

2.4 Summary

This chapter reviewed the previous study on the modelling approaches which are theoretical approach and empirical approach for the pneumatic. This study considered to focus on the empirical approach which is system identification technique for the modelling of the pneumatic system. The theoretical approach is not recommended considering that there are certain system complexities and unknown parameters within the pneumatic system.

Besides that, this chapter also described the previous studies of control strategy using PID controller for pneumatic system. Based on the previous studies, the PID controller was used to control the pneumatic positioning system. There are also recent trend where there are combination PID controller with other system to improve the system performance. In this study, the transient response such as rise time, settling time and overshoot percentage were used to determine the performance of the pneumatic positioning system.

CHAPTER 3

METHODOLOGY

3.1 Methodology Flowchart

This study involves with four stages of activities. Figure 3.1 shows the methodology flowchart for this study.

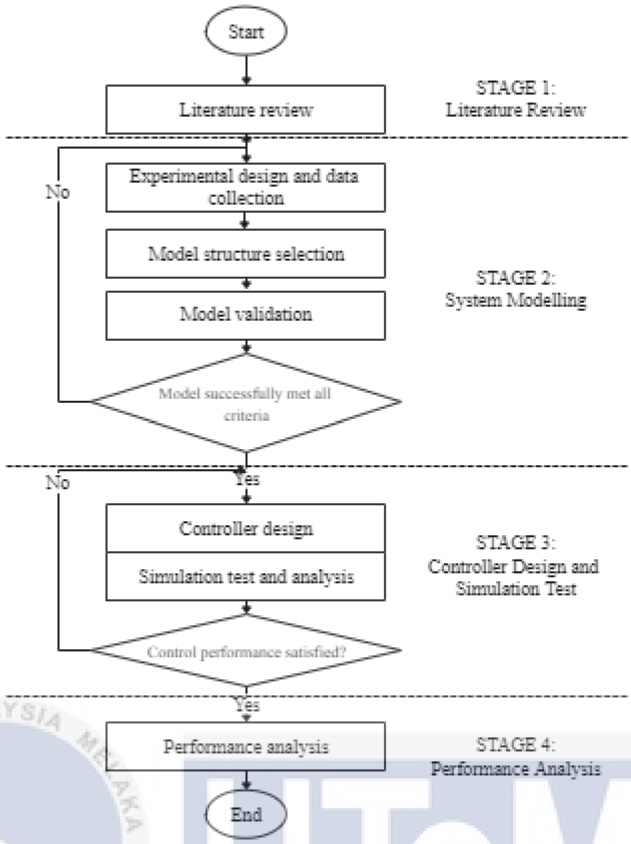


Figure 3.1 Flowchart of methodological framework

The first stage of this study is the literature review. The main objective of the stage is to highlight the main issues related to the method adopted to model the pneumatic system.

For the second stage which is system modelling stage, system identification technique was used to determine the mathematical model of the pneumatic system used in this study. The pneumatic system mathematical model was derived from data obtained from experimental work. In this study, the linear parametric models were selected as the model to represent the real pneumatic system used. The identified models were then be validated based on the system identification benchmark, in order to confirm its acceptance as a model that represents the pneumatic actuator system under study.

The third stage of the study is the controller design and simulation test. In this stage, the identified model was applied in the PID controller to control the pneumatic positioning system. MATLAB/Simulink were used to develop the PID controller. The performances of the pneumatic positioning system using PID controller will be accessed with respect of the transient response (i.e., rise time, settling time, overshoot and steady-state error) of the system.

In the final stage of this study, the pneumatic positioning system using Proportional-Integral-Derivative (PID) controller with several model structures were validated by performing simulation testing. The performances of pneumatic positioning control using Proportional-Integral-Derivative (PID) controller with several model structures were compared and analysed in terms of transient response based on rise time, settling time and others.

3.2 Pneumatic system component

The pneumatic system in this study was equipped with five main components, which were integrated into a single actuator. Each component has its own function in controlling the pneumatic system. Figure 3.2 shows the components of pneumatic actuator system. These components included (1) optical encoder, (2) stripe code on a guide rod, (3) pressure sensor, (4) valves, and Programmable System on Chip (PSoC) microcontroller board.

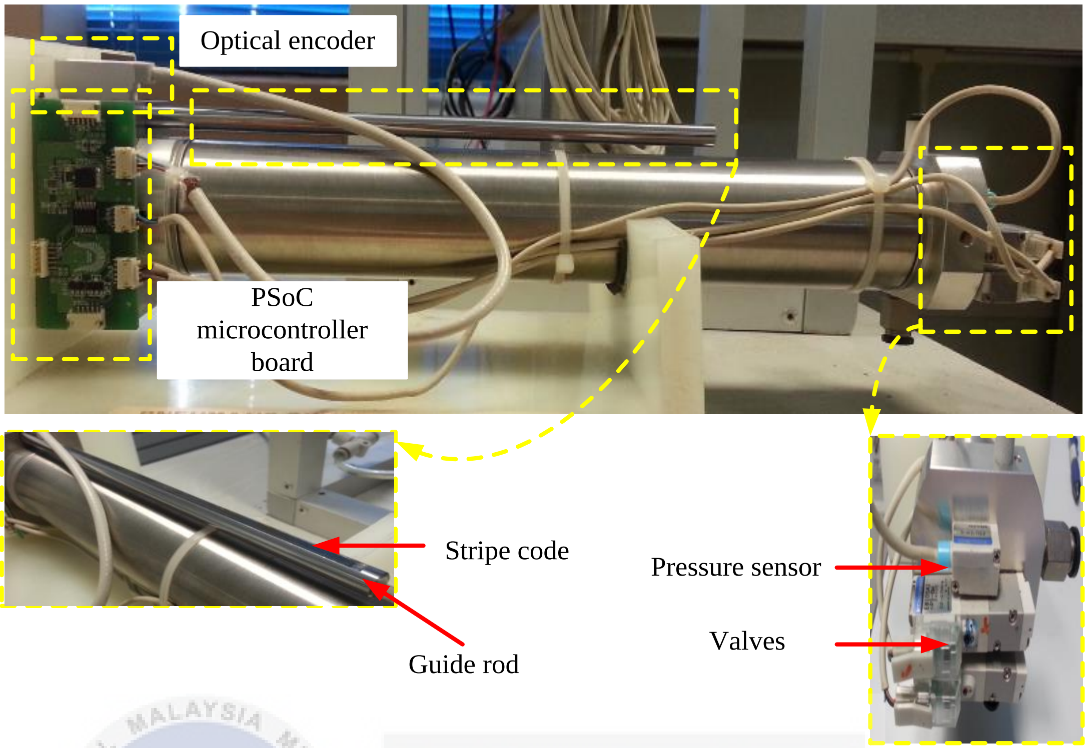


Figure 3.2 Components of pneumatic system

1) Optical encoder

The optical encoder was mounted as shown in the Figure 3.3. The optical encoder detects the linear displacement and position of cylinder stroke on the code stripe. This signal reading was sent to the Programmable System on Chip (PSoC) control board to process the data.

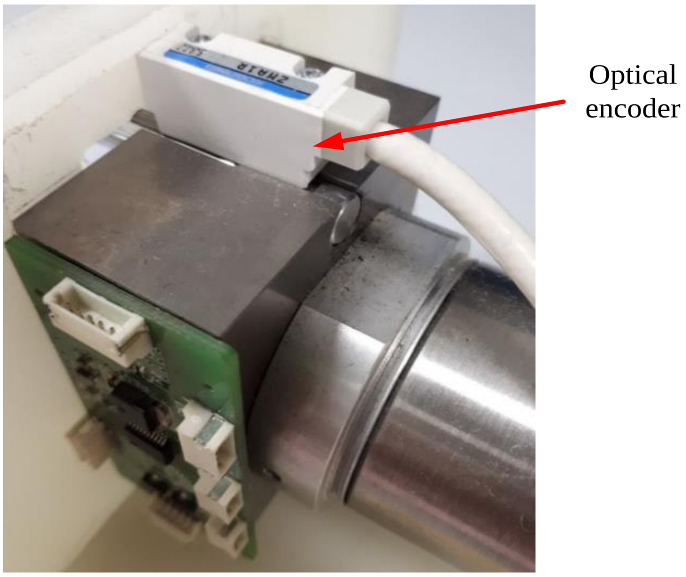


Figure 3.3 Optical encoder on top of actuator

2) Strip code

Strip code is the tape on the guide rod enabled the encoder to read the position of the pneumatic cylinder stroke. Figure 3.4 shows a strip code on the guide rod.

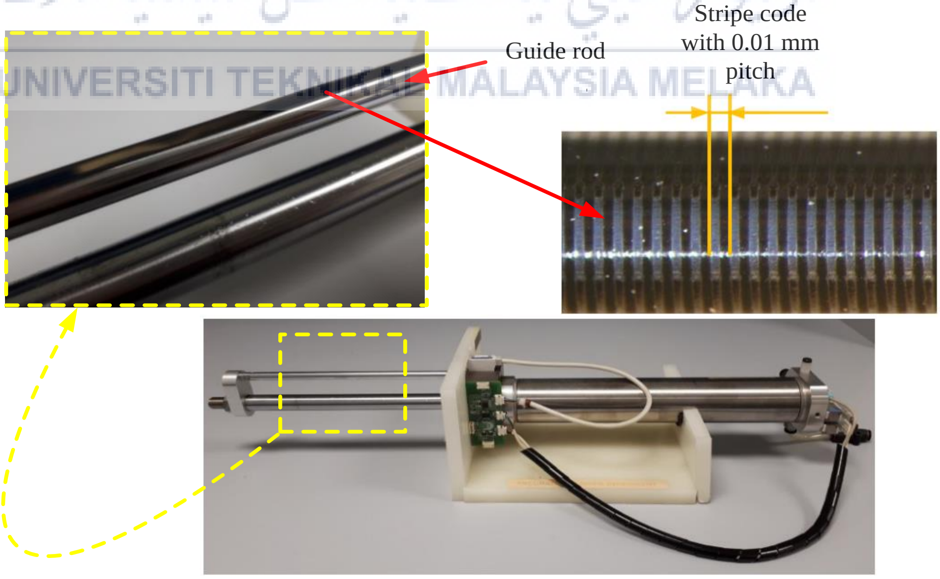


Figure 3.4 Strip code on guide rod

3) Pressure sensor

The pressure sensor read the pressure inside the cylinder chamber and sent the pressure reading to the Programmable System on Chip (PSoC) circuit board. Then, the Programmable System on Chip (PSoC) circuit board processed the data and conducted action. Figure 3.5 shows the pressure sensor and valves. The valves located at the bottom of the pressure sensor. Both pressure sensor and valves were attached at the end of the pneumatic cylinder.

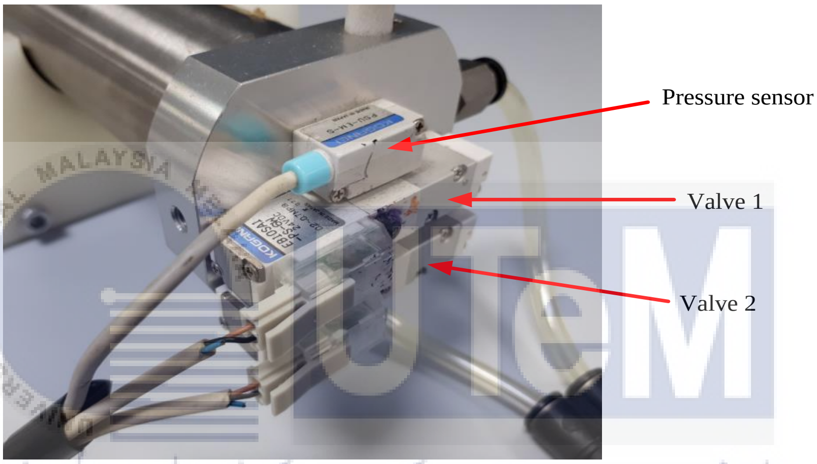


Figure 3.5 Pressure sensor and valves

4) Valves

There are two valves located at the end of the pneumatic cylinder: Valve 1 and Valve 2. The valves controlled the air inlet and air outlet of pneumatic cylinder. The extension of cylinder rod was controlled using Valve 1, meanwhile, the retraction of cylinder rod was controlled by Valve 2.

5) PSoC circuit board

Programmable System on a Chip (PSoC) integrated microcontroller in embedded system. PSoC acts as central unit where it handled I^2C communication, input and output data, and Pulse Width Modulation (PWM) duty-cycle. Figure 3.6 shows the Programmable System on Chip (PSoC) circuit board.

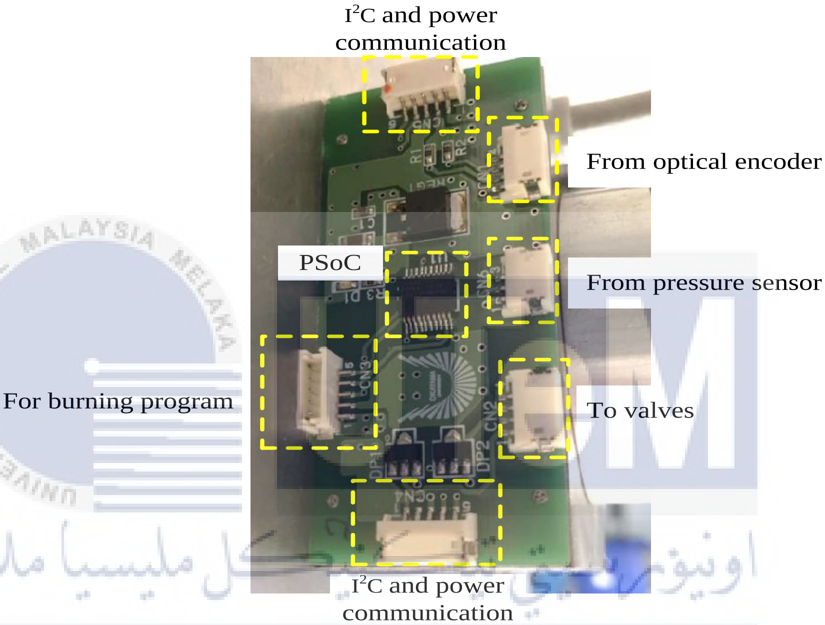


Figure 3.6 Programmable system on chip (PSoC) circuit board

3.3 Modelling of Pneumatic System Using System Identification Technique

There are four steps to model the pneumatic system using system identification technique. The first step is experimental design and data collection. The second step to select the model structure. The model structure was selected in order to represent the pneumatic system. The third step is to estimate the model. The last step is to validate the model.

3.3.1 Experimental Design and Data Collection

Figure 3.7 displays the experimental setup of the pneumatic positioning system. In this study, the pressurised supply air was kept at constant (0.6 MPa) throughout these experiments. The overall system comprised of:

1. Computer
2. Data Acquistion (DAQ) system
3. Air compressor
4. Pneumatic system

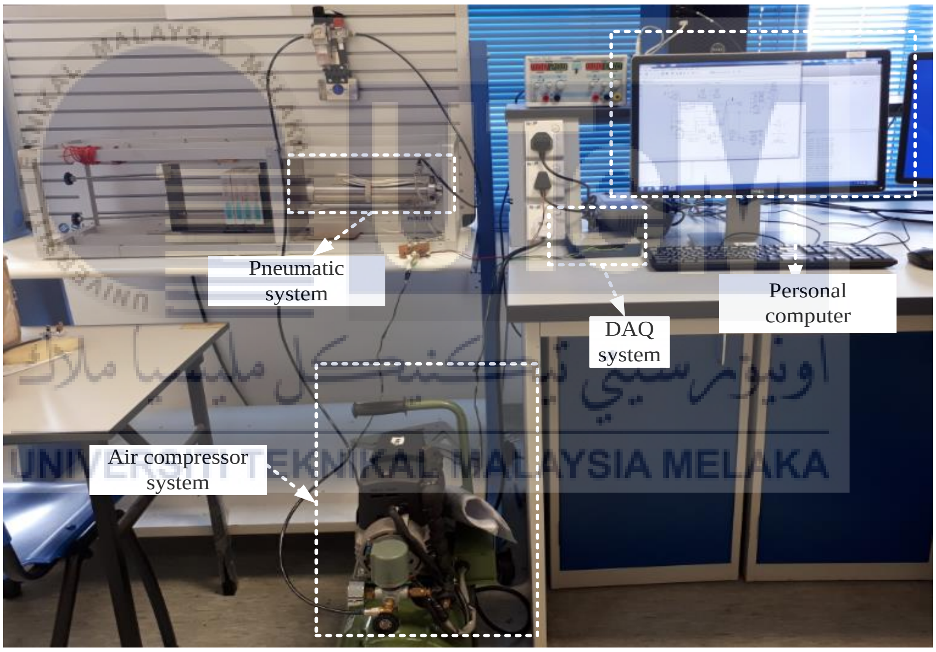


Figure 3.7 Experimental setup

Figure 3.8 shows the schematic diagram for pneumatic system. The air compressor supplied pressure of 0.6 MPa to the pneumatic system.

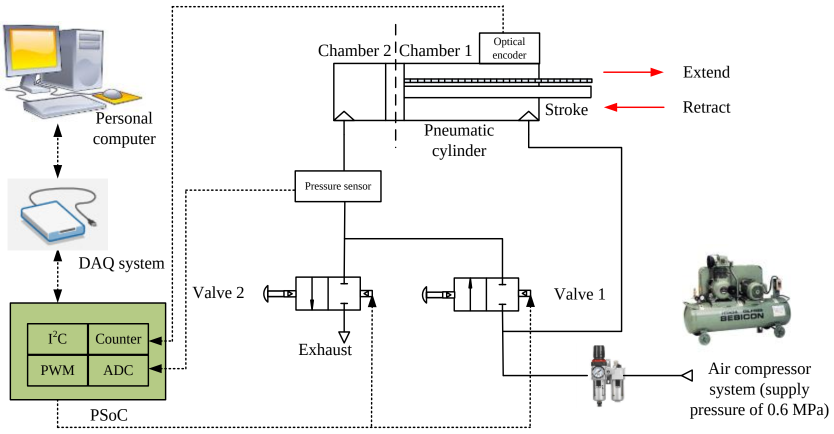
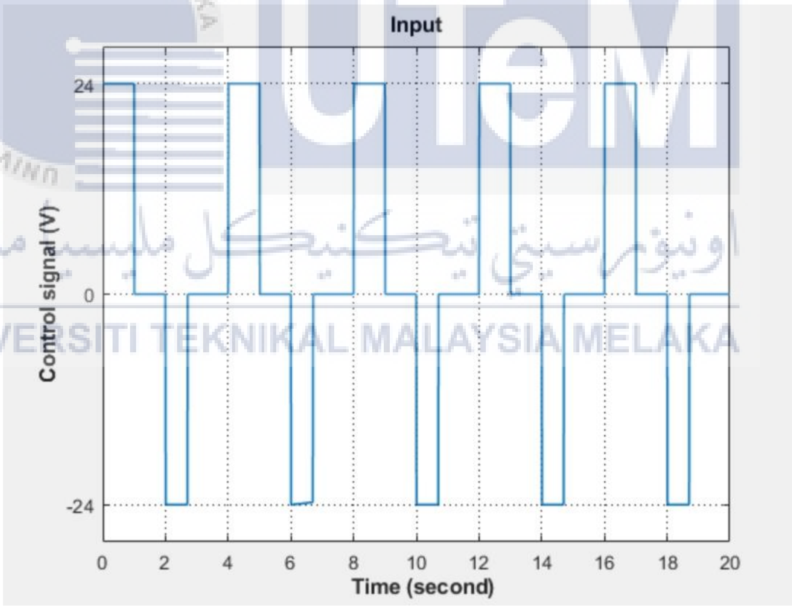
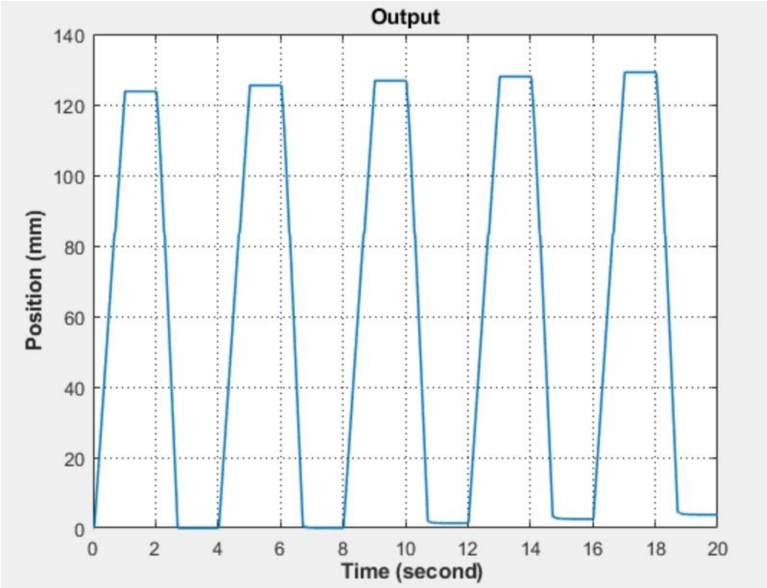


Figure 3.8 Schematic diagram for pneumatic system



(a)



(b)

Figure 3.9 (a) Input signal and (b) Output signal

Figure 3.9 shows the plot of measured input and output data obtained from the real-time experiment shown in Figure 3.7. The applied input signal as shown in Figure 3.9 (a) was injected as excitation signal and subsequently, the output of the system (shown in the Figure 3.9 (b)) was recorded. For the pneumatic system used in this study, the extension of cylinder rod was controlled using Valve 1, meanwhile, the retraction of cylinder rod was controlled by Valve 2. The output signal of pneumatic system as shown in the Figure 3.9 (b) was from the cylinder rod stroke position. From the Figure 3.9 (b) also, it can be seen that the cylinder rod took longer time to extend rather than to retract.

2000 measurements of input and output data were collected from the real-time experiment. The input data was from the continuous step input signal applied to the input valves (Valve 1 and Valve 2) of the pneumatic system. Meanwhile, the output data was collected from the measured position of cylinder stroke. To model the data using system identification technique, the input and output data were divided into two sets: one set for estimation process and one set for validation process. Figure 3.10 shows the estimation and validation processes of the measured input and output data conducted using System Identification Tool.

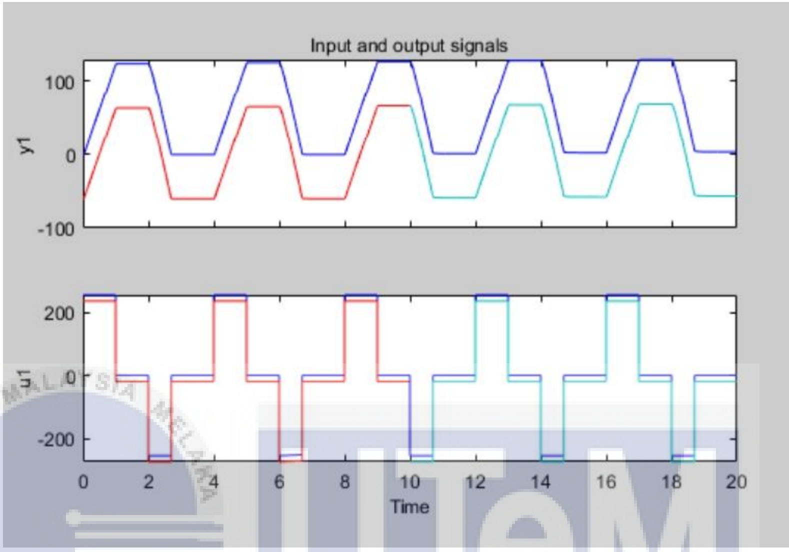


Figure 3.10 Estimation and validation processes

Based on the plots in Figure 3.10, the first data set contained 1000 input and output data were (red) used for estimation, while another 1000 input and output data (turquoise) were used for validation process.

3.3.2 Model Structure Selection

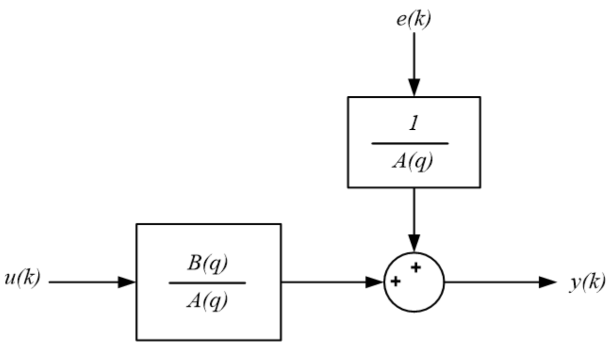


Figure 3.11 Block diagram of the ARX model structure

For this study, the linear parametric model structure was chosen to represent the dynamic characteristic of the pneumatic system used. The structures used are Auto-Regressive with Exogenous input (ARX), Auto-Regressive Moving Average with Exogenous input (ARMAX), Output Error (OE), and Box-Jenkins (BJ). Figure 3.11 shows the block diagram of ARX model structure, meanwhile Equation (3.1) is the

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

where,

$$A(q) = 1 + a_1q^{-1} + \cdots + a_{n_a}q^{-n^a} \tag{3.2}$$

$$B(q) = b_1q^{-1} + \cdots + b_{n_a}q^{-n^a} \tag{3.3}$$

where,

n_a is the number of poles

n_b is the number of zeroes

$y(k)$ is the output

$u(k)$ is the input

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

q^{-1} is the backshift operator w hen $n_a \geq n_b$

ARX model is the simplest model among other models. Apart from that, the estimation of the ARX model is the most efficient of the polynomial estimation methods because it is the result of solving linear regression equations in analytic form. Therefore, the ARX model is always preferable, especially to model high order system.

Figure 3.12 shows the block diagram of ARMAX model, meanwhile Equation 3.4 is the equation of the ARMAX model.

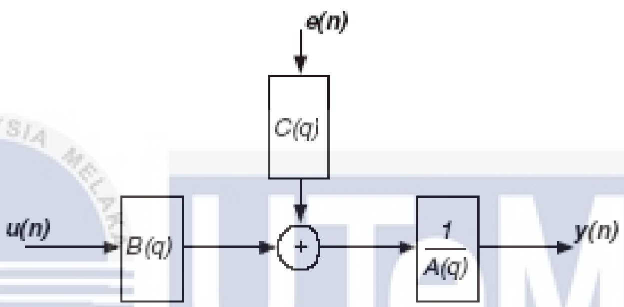


Figure 3.12 Block diagram of ARMAX model structure

Compared to ARX, ARMAX model includes stochastic dynamics. When there is disturbance at input, ARMAX models are useful to overcome that limitation. The ARMAX model has more flexibility than the ARX model in handling models that contain disturbances.

$$y(k) = \frac{B(q)}{A(q)}u(k) + C(q)e(k) \tag{3.4}$$

Figure 3.13 shows the block diagram of Output-Error (OE) model, meanwhile Equation (3.5) is the equation of the OE model.

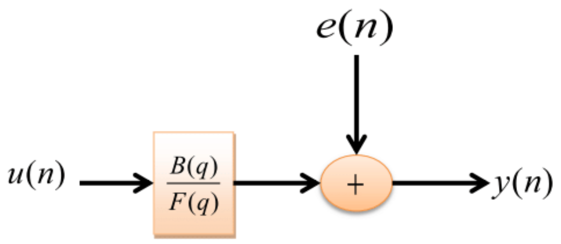


Figure 3.13 Block diagram of OE model structure

$$y(k) = \frac{B(q)}{F(q)}u(k) + e(k) \tag{3.5}$$

The Output-Error (OE) model structure is a special configuration of polynomial models, having only two active polynomials B and F. OE models represent conventional transfer functions that relate measured inputs to outputs while also including white noise as an additive output disturbance.

Figure 3.14 shows the block diagram of Box-Jenkins (BJ) model, meanwhile Equation (3.5) is the equation of the BJ model. Box-Jenkin model is mathematical model that developed data from specified time based on input.

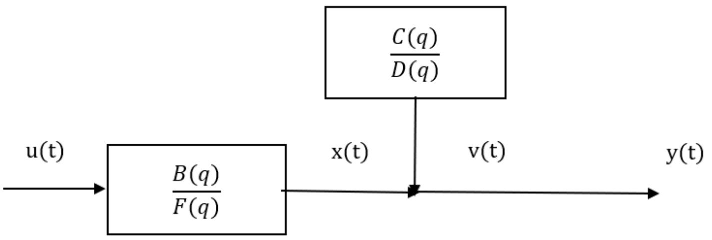


Figure 3.14 Block diagram of BJ model

$$y(k) = \frac{B(q)}{F(q)}u(k) + \frac{C(q)}{D(q)}e(k) \tag{3.6}$$

3.3.3 Model Estimation

In this study, a model estimation is used to estimate the coefficients and parameters for Auto-Regressive with Exogenous input (ARX), Auto-Regressive Moving Average with Exogenous input (ARMAX), Output Error (OE), and BJ model. Figure 3.15 shows the Graphical User Interface (GUI) of System Identification Tool for the modelling of pneumatic system.

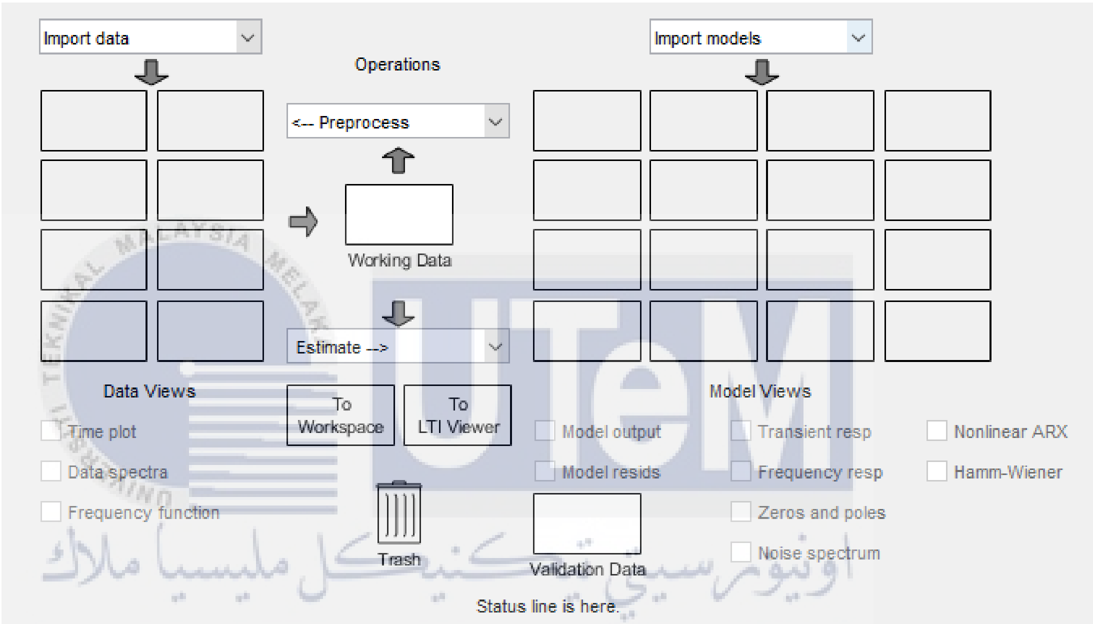


Figure 3.15 Graphical user interface (GUI) of System Identification Tool

The MATLAB System Identification Tool provided the mathematical model of the pneumatic system based on the input and output data collected during real-time experiment. The input and output data were imported into System Identification Tool to estimate the parameter of this models. The estimation of the model parameters was performed by minimizing the error between simulated model and measured model using least-squared model. In this study, ARX, ARMAX, OE and BJ were chosen as a model structure to model the pneumatic system used in this study. The performance of these models was then compared and analyzed based on different model orders (first-, second-, third-, fourth-, fifth order). This is important in order to select which model structure provides the best performance in terms of system identification criteria. Figure 3.16 shows the estimation process between model structures. The estimation process was generated from least square error (LSE) of the data.

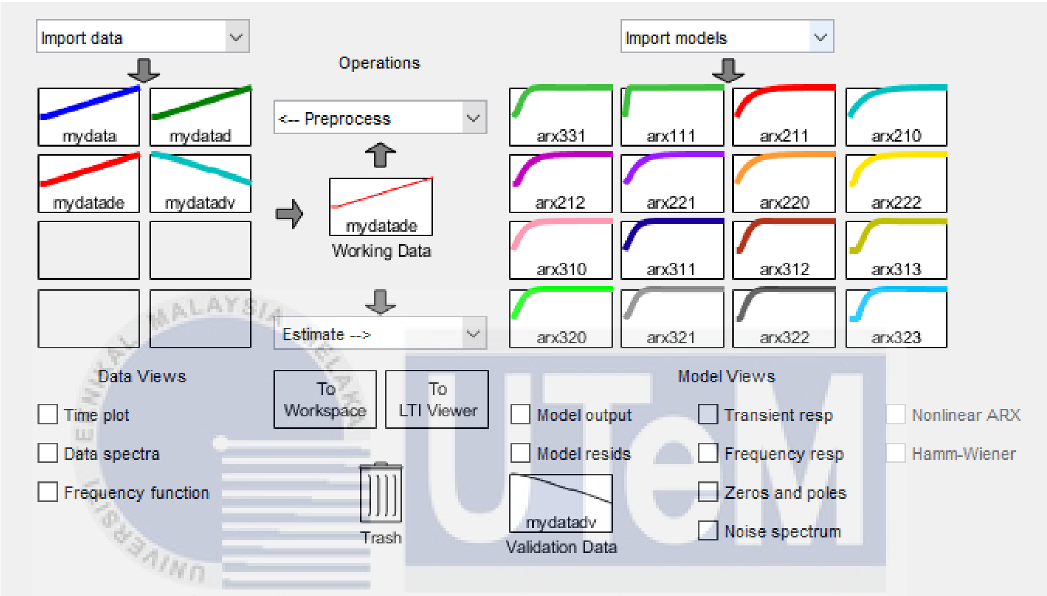


Figure 3.16 Estimation process between models

3.3.4 Model Validation

Best fit, final prediction error (FPE), mean square error (MSE) and pole-zero plot are the criteria used in the system identification technique in order to validate the identified model.

Best fit percentage is the percentage of fitness between the measured model and simulated model. The identified model will be identified as the precise when if the fitness is exceed 90% [2].

$$Best\ fit = \left(1 - \frac{|y - \hat{y}|}{|y - \bar{y}|}\right) \times 100 \tag{3.7}$$

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.

Akaike's Final Prediction Error (FPE) as describes in Equation (3.8) is used to measure the quality of the measured model.

$$FPE = V\left(\frac{1 + \frac{d}{N}}{1 - \frac{d}{N}}\right) \tag{3.8}$$

where d is the number of approximated parameters that represents the model complexity and N denotes the number of the sample. The term V indicates the loss function, as expressed in Equation (3.9). $e(k)$ in Equation (3.9) is the error vector,

$$V = \frac{e^2(k)}{N} = \frac{e^T(k).e(k)}{N} \tag{3.9}$$

where the value of FPE must be low in order to accept the model. Lower FPE value shows that the model is accurate. Apart from that, the stability of the model was also observed in this study. The stability of the model is based on the pole-zero plot to accept the model for pneumatic system. The system is stable when the magnitude of the pole must be less than 1 (<1). This mean that all the poles were inside the unit circle. Subsequently, if one or more poles were equal or greater than zero, the system is considered to be unstable due to one or more poles were located outside of the unit circle.

3.4 Proportional-Integral-Derivative (PID) Controller Design

Proportional-Integral-Derivative (PID) controller was widely used in industrial control application. PID controller is simple, effective and commonly used to control the pneumatic positioning system. This study considered PID as the controller to control the pneumatic positioning system. Figure 3.16 shows the basic block diagram of PID controller.

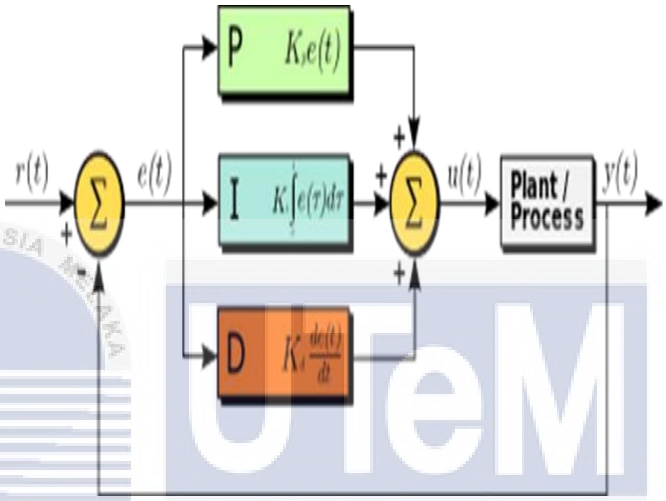


Figure 3.17 Basic block diagram of PID controller

As shown in the Figure 3.17, PID controller works in the closed loop system. The error signal (e) is fed to the PID controller and the controller computes derivative and integral of the error signal respect to time. The control signal (u) is fed to the plant and the output is obtained. The new output then fed into the reference to find new error signal (e). The controller takes new error signal and update the control input. This process continues until the controller effected. Equation 3.10 describes the PID controller signal output equation, calculated in the time domain from the feedback error:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)dt + K_p \frac{de}{dt} \tag{3.10}$$

where K_p = proportional gain, K_i = integral gain, K_d = derivative gain.

Each term in PID controller has its own function. When K_p increased, the error signal increased proportionally at the same level of error. Apart from that, increasing K_p will reduce the steady-state error. The drawback of increasing K_p is it tend to overshoot since the closed-loop system react quickly. When K_i increased, the control signal increased while the error signal reduced due to the integrator keep building. Also, increasing K_i reduced the steady state error. In a contrary, it will make the system complicated and take time the integrator to unwind. The addition of K_d, the control signal increased same goes to the error signal. Moreover, the addition of K_d, tends to add damping to the system. Hence, the overshoot decreased.

In this study, Ziegler-Nichols method was used to tune the parameter value of PID controller. Table 3.1 Shows the Ziegler-Nichols parameter tuning table used to tune the PID controller parameters (K_p, K_i, K_d).

Table 3.1 Ziegler-Nichols parameter tuning method

Controller	K_P	$T_i = \frac{K_p}{K_i}$	$T_d = \frac{K_d}{K_p}$
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$\frac{L}{3}$	0
PID	$1.2\frac{T}{L}$	$2L$	$0.5L$

In this study, the PID controller is used to control the pneumatic positioning system. In this regard, the transient response performance of pneumatic positioning system when controlling using PID controller based on different model structure were presented and evaluated at the end of this study.

3.5 Summary

This chapter reviews the methodology process of this study. The methodology process involved with two important stages which are system modelling and controller design, System modelling process consists of experimental design and data validation, model structure selection, model estimation and model validation. These processes were conducted by using System Identification Tool in the MATLAB software.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Pneumatic System Model Identification

This section presents the results of modelling the pneumatic system using Auto-Regressive Exogenous Input (ARX), Auto-Regressive Moving Average with Exogenous input (ARMAX), Box-Jenkins (BJ) and Output-Error (OE) models based on system identification technique. All models order from first-order until fifth-order model using four different model structures were presented. MATLAB System Identification Tool was used to validate the models based on the criteria as outlined in the system identification technique, such as the percentage of best fit, Final Prediction Error (FPE), Mean Square Error (MSE) and pole-zero plot.

4.1.1 Pneumatic System Model Identification based on Auto- Regressive Exogenous Input Model (ARX)

Table 4.1 tabulates the results of linear ARX model validation based on system identification criteria.

Table 4.1 Performance of a linear ARX model based on different model orders

Criteria	ARX Models				
	1st Order (ARX111)	2nd Order (ARX212)	3rd Order (ARX312)	4th Order (ARX412)	5th Order (ARX511)
Best Fit	89.1	91.74	91.36	91.7	91.64
Final Prediction Error (FPE)	0.07099	0.0235	0.02134	0.02034	0.01951
Mean Square Error (MSE)	0.07057	0.02326	0.02104	0.01998	0.01908
Stability	No	Yes	Yes	Yes	Yes

From Table 4.1 the percentage of best fit for all ARX model orders are above 90 % except for first-order model where it was 89.1 %. The highest percentage is 91.74 %, which obtained from second-order model. The model is accepted to represent the system if the best fit obtained is exceed 90 %. Thus, from the result, first-order ARX model are rejected due to the best fit percentage is below 90 %. Besides, the final prediction error and mean square error also were recorded as indicators to accept or reject the identified model. If the final prediction error and mean square error are small, the model is acceptable to represent the system. This is because lower error indicates higher accuracy of the system. As shown in the Table 4.1, all ARX model orders have low final prediction error and mean square error.

Apart from that, the stability of each model orders is one of crucial factor to determine the best model to represent the pneumatic system. The stability of the ARX model orders were developed based on the input and output data form an open-loop real-time experiment. Then, each pole-zero plot were generated by using pzmap command in the MATLAB. The poles in the pole-zero plot were observed whether within the unit circle or not. The system is said to be stable if all the poles are within the unit circle.

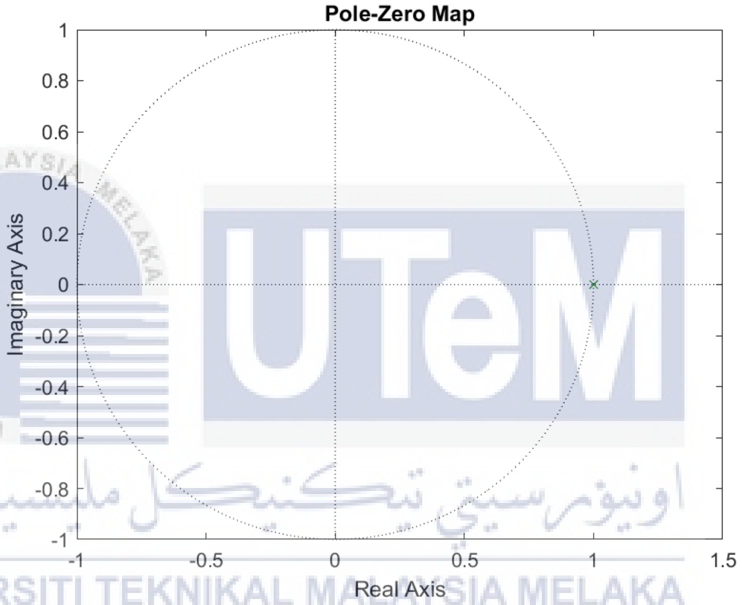


Figure 4.1 Pole-zero plot for the first-order ARX model

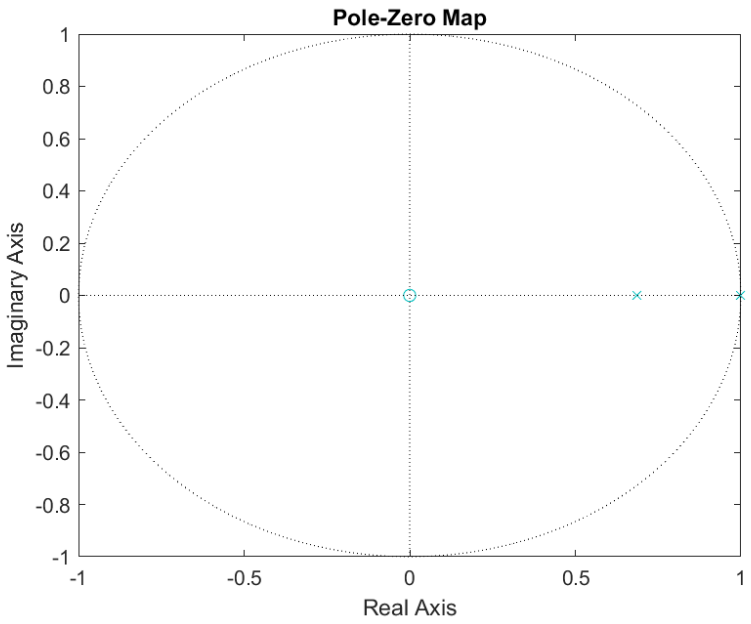


Figure 4.2 Pole-zero plot for the second-order ARX model

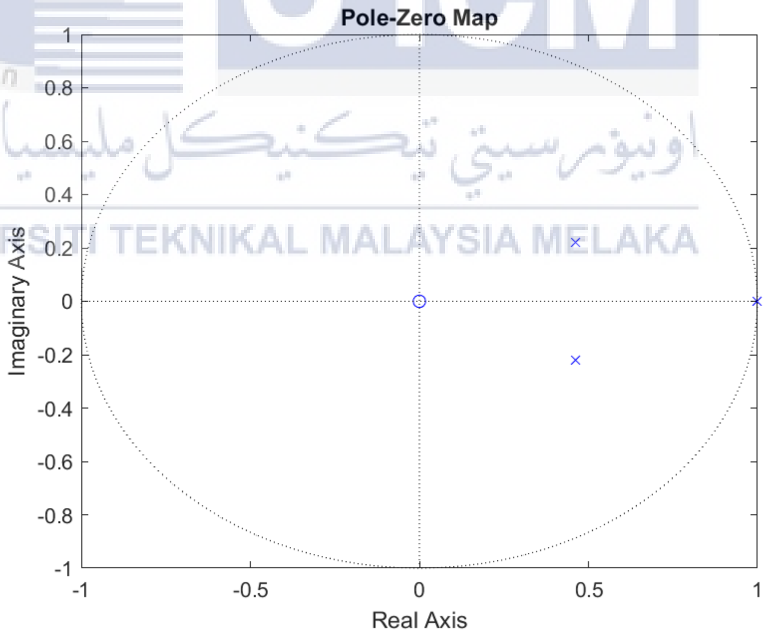


Figure 4.3 Pole-zero plot for the third-order ARX model

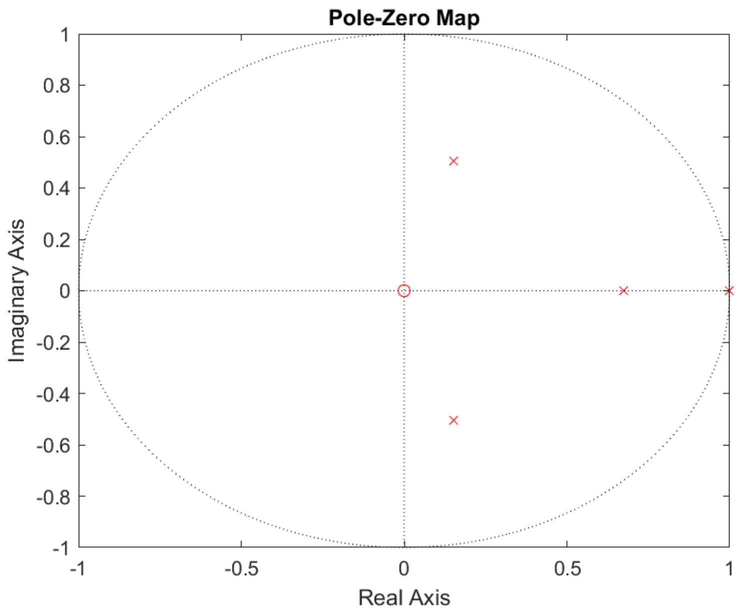


Figure 4.4 Pole-zero plot for the fourth-order ARX model

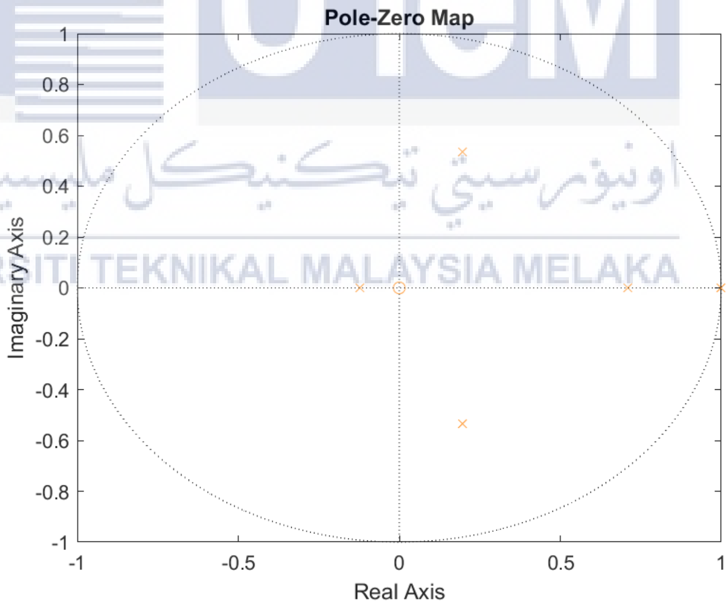


Figure 4.5 Pole-zero plot for the fifth-order ARX model

Figure 4.1 shows the pole-zero plot for ARX111 model. The pole-zero plot was recorded based on the obtained input and output data from open-loop real-time experiment. The ARX111 model is not stable because the system's pole is located outside the unit circle (1.0009) (refer to Figure 4.1).

Figure 4.2 shows the pole-zero plot for ARX212 model. The ARX212 model is stable because the system's pole is successfully located inside the unit circle (0.9995, 0.686, 0) (refer to Figure 4.2).

Figure 4.3 shows the pole-zero plot for ARX312 model. The ARX312 model is stable because the system's pole is successfully located inside the unit circle (0.9999, 0.4607, 0.4607) (refer to Figure 4.3).

Figure 4.4 shows the pole-zero plot for ARX412 model. The ARX412 model is stable because the system's pole is successfully located inside the unit circle (0.9997, 0.6746, 0.1525, 0.1525) (refer to Figure 4.4).

Figure 4.5 shows the pole-zero plot for ARX511 model. The ARX511 model is stable because the system's pole is successfully located inside the unit circle (0.9996, 0.7105, 0.1966, 0.1966, -0.1222) (refer to Figure 4.5). From the result shown, the ARX second-, third-, fourth- and fifth-order models are considered to represent the pneumatic system utilized in this study.

4.1.2 Pneumatic System Model Identification based Auto-Regressive Moving Average with Exogenous Input Model (ARMAX)

Table 4.2 Performance of a linear ARMAX model based on different model orders

Criteria	ARMAX Models				
	1st Order (AMX1111)	2nd Order (AMX2111)	3rd Order (AMX3111)	4th Order (AMX4111)	5th Order (AMX5111)
Best Fit (%)	90	91.34	91.26	91.71	91.64
Final Prediction Error (FPE)	0.04504	0.02131	0.02109	0.01998	0.01952
Mean Square Error (MSE)	0.04468	0.02106	0.02076	0.01959	0.01906
Stability	No	Yes	No	Yes	Yes

From Table 4.2 the percentage of best fit for all ARMAX model orders are above 90 %. The highest percentage is 91.7 %, which obtained from fourth-order model. Thus, from the result, all ARMAX model are accepted in terms of best fit criteria due to the best fit percentage is above 90 %. For the final prediction error and mean square error, all model has low final prediction error and mean square error as shown in Table 4.2. Lower final prediction error and mean square error indicates the identified model is accurate

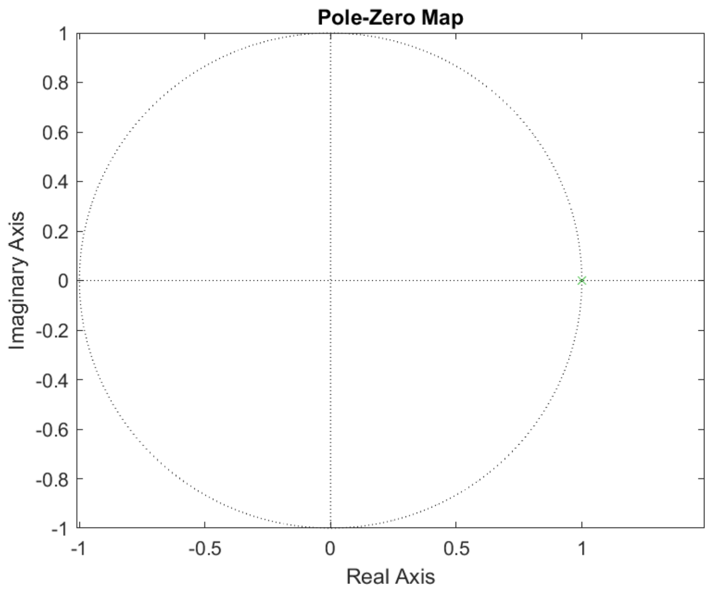


Figure 4.6 Pole-zero plot for the first-order ARMAX model

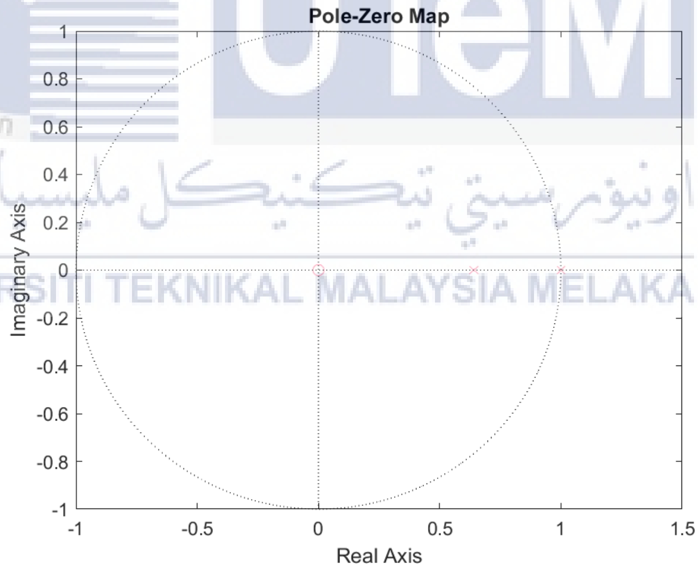


Figure 4.7 Pole-zero plot for the second-order ARMAX model

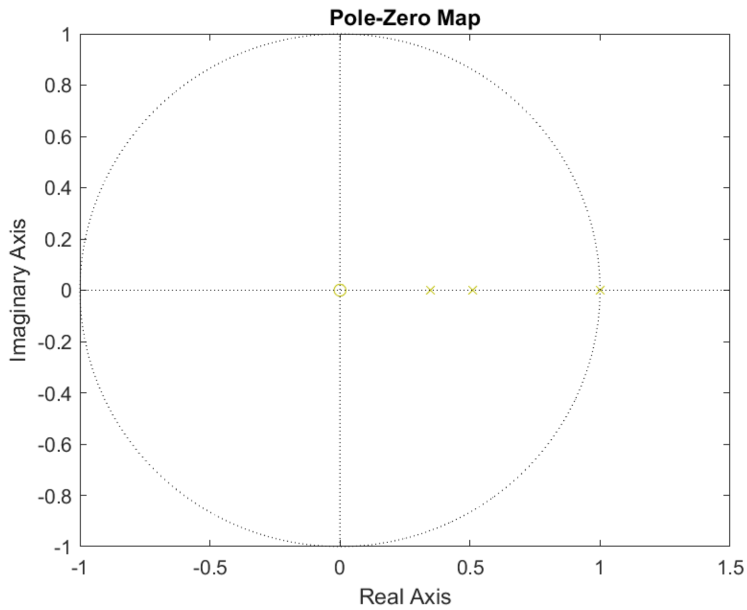


Figure 4.8 Pole-zero plot for the third-order ARMAX model

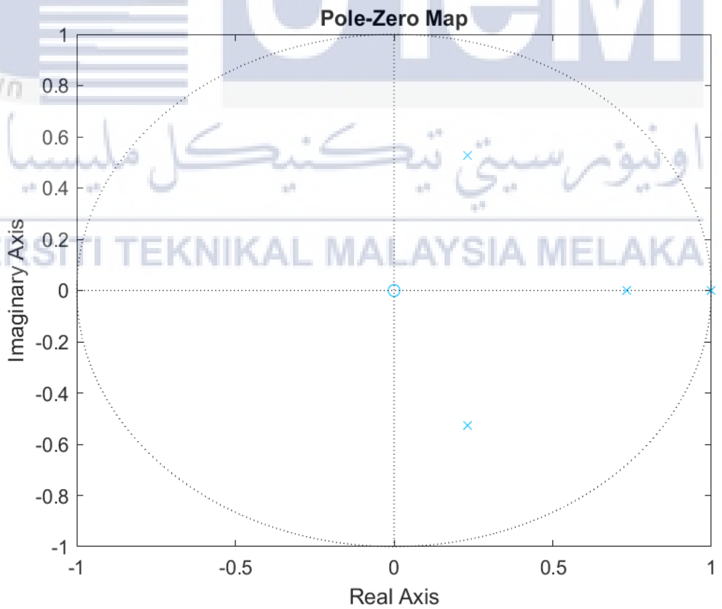


Figure 4.9 Pole-zero plot for the fourth-order ARMAX model

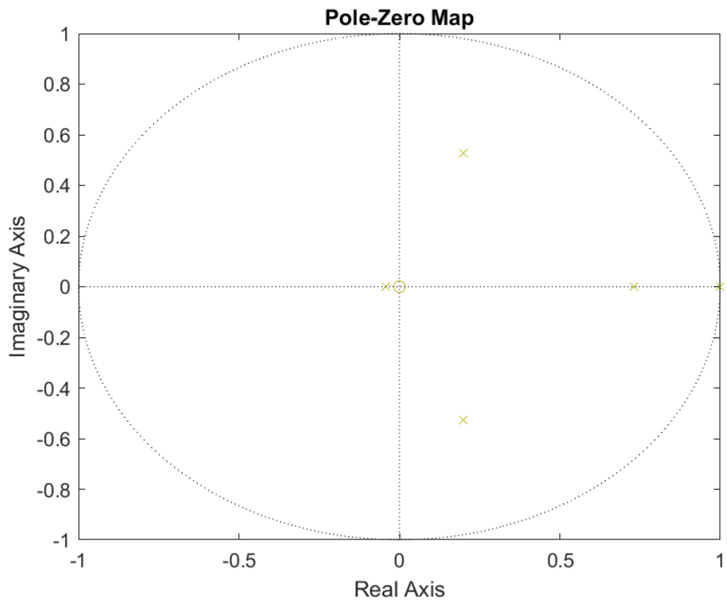


Figure 4.10 Pole-zero plot for the fifth-order ARMAX model

Figure 4.6 shows the pole-zero plot for ARMAX1111 model. The pole-zero plot was recorded based on the obtained input and output data from open-loop real-time experiment. The ARMAX1111 model is not stable because the system's poles are located outside the unit circle (1.0006) (refer to Figure 4.6).

Figure 4.7 shows the pole-zero plot for ARMAX2111 model. The ARMAX2111 model is stable because the system's pole is successfully located inside the unit circle (0.9995, 0.6377) (refer to Figure 4.7).

Figure 4.8 shows the pole-zero plot for ARMAX3111 model. The ARMAX3111 model is not stable because the system's poles are located outside the unit circle (1.0002, 0.5097, 0.3485) (refer to Figure 4.8).

Figure 4.9 shows the pole-zero plot for ARMAX4111 model. The ARMAX4111 model is stable because the system's pole is successfully located inside the unit circle (0.9998, 0.7317, 0.2323, 0.2323) (refer to Figure 4.9).

Figure 4.10 shows the pole-zero plot for ARMAX5111 model. The ARMAX5111 model is stable because the system's pole is successfully located inside the unit circle (0.9999, 0.7315, 0.1988, 0.1988, -0.0432) (refer to Figure 4.10). From the result shown, the ARMAX second-, fourth- and fifth-order models are considered to represent the pneumatic system utilized in this study.

4.1.3 Pneumatic System Model Identification using Box-Jenkins Model (BJ)

Table 4.3 Performance of a linear BJ model based on different model orders

Criteria	BJ Models				
	1st Order (BJ11111)	2nd Order (BJ22222)	3rd Order (BJ32221)	4th Order (BJ42221)	5th Order (BJ51111)
Best Fit (%)	87.1	91.61	90.97	92.05	90.98
Final Prediction Error (FPE)	0.04316	0.02032	0.021	0.02137	0.03888
Mean Square Error (MSE)	0.04364	0.02984	0.02042	0.0207	0.03787
Stability	Yes	Yes	No	No	No

From Table 4.3 the percentage of best fit for all Box Jenkins model (BJ) orders are above 90 % except for first-order model where it was 87.1 %. The highest percentage is 92.05 %, which obtained from second-order model. The model is accepted to represent the system if the best fit obtained is exceed 90 %. Thus, from the result, first-order BJ model are rejected due to the best fit percentage is below 90 %. Besides, the final prediction error and mean square error also were recorded as indicators to accept or reject the identified model. The final prediction error and mean square error are small, the model is acceptable to represent the system. This is because lower error means the identified model is accurate. As shown in the Table 4.3, all BJ model orders have low final prediction error and mean square error.

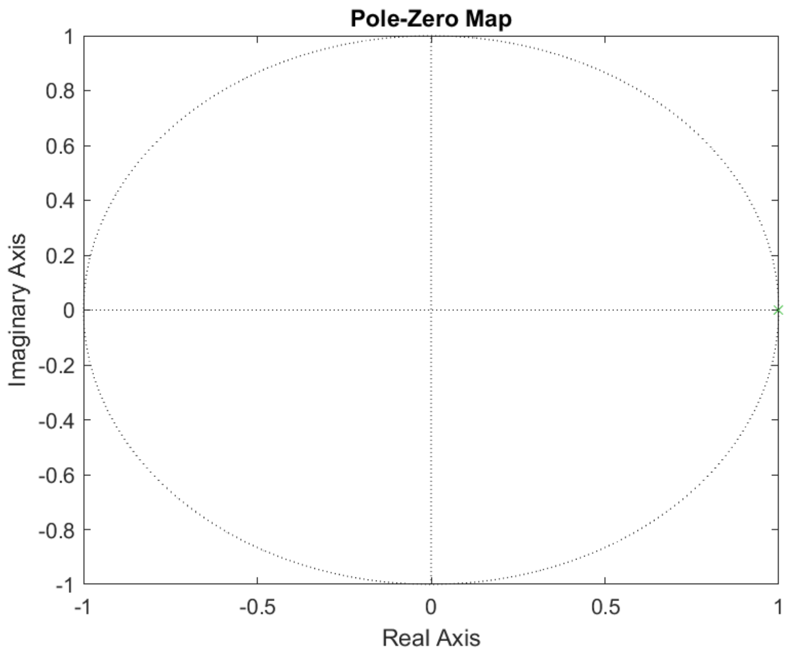


Figure 4.11 Pole-zero plot for the first-order BJ model

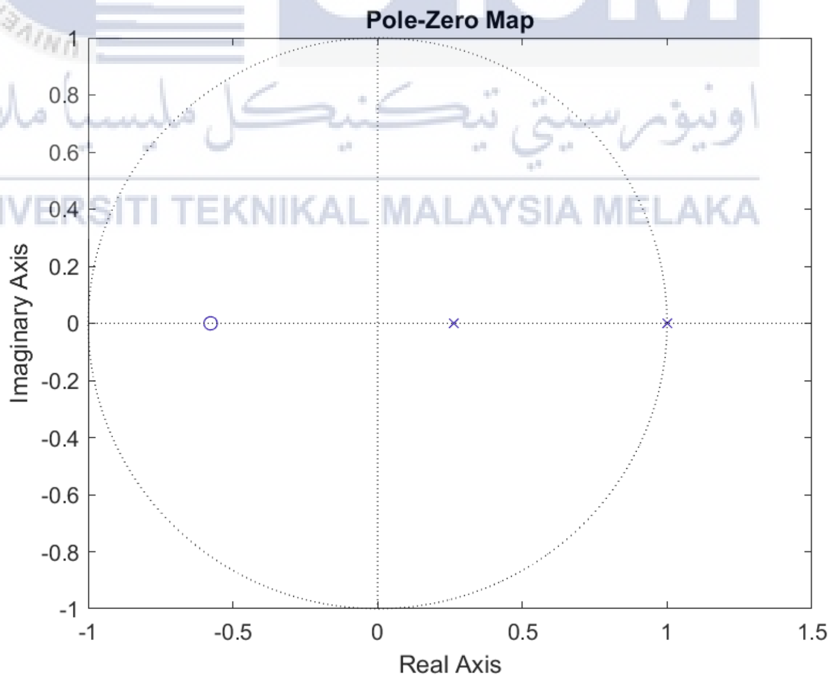


Figure 4.12 Pole-zero plot for the second-order BJ model

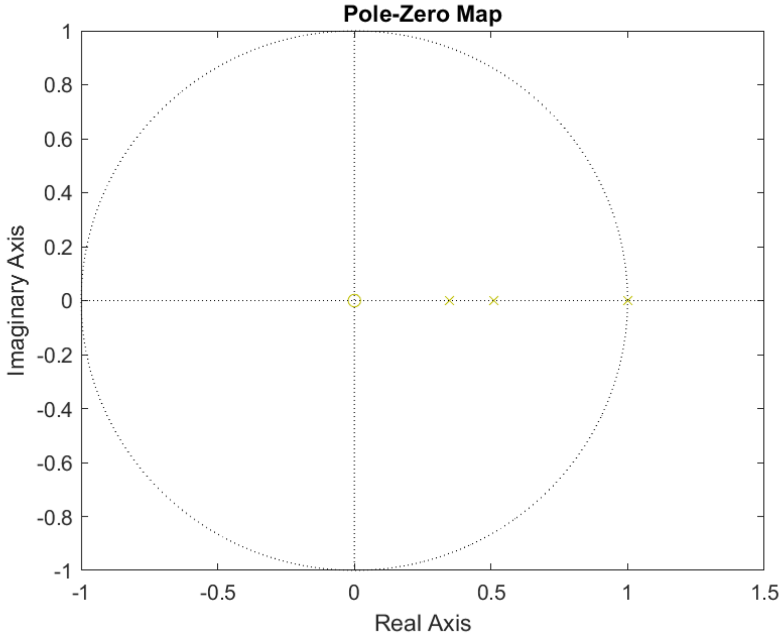


Figure 4.13 Pole-zero plot for the third-order BJ model

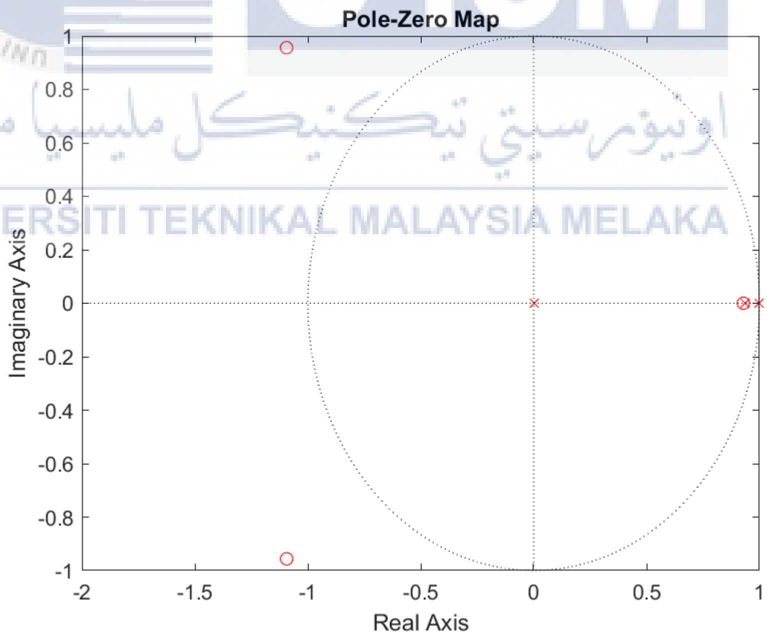


Figure 4.14 Pole-zero plot for the fourth-order BJ model

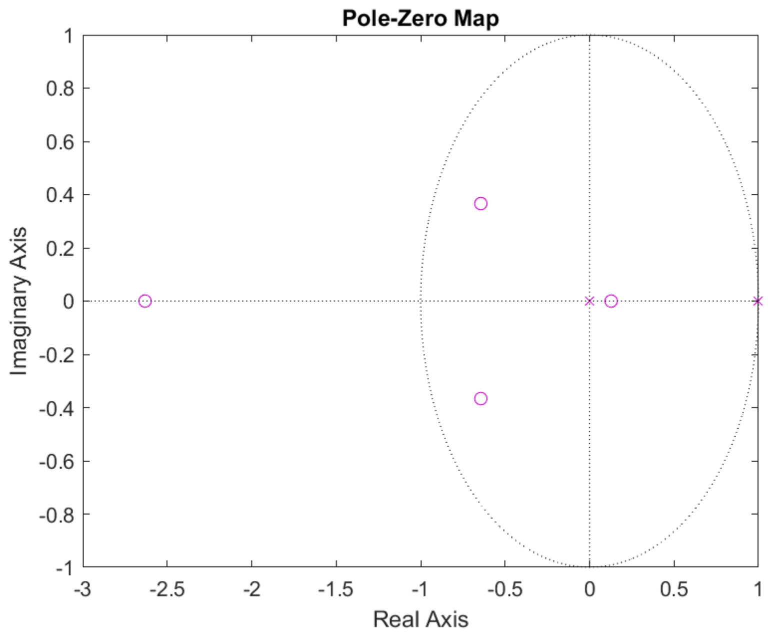


Figure 4.15 Pole-zero plot for the fifth-order BJ model

Figure 4.11 shows the pole-zero plot for BJ11111 model. The pole-zero plot was recorded based on the obtained input and output data from open-loop real-time experiment. The BJ11111 model is stable because the system's pole is successfully located inside the unit circle (0.9995) (refer to Figure 4.11).

Figure 4.12 shows the pole-zero plot for BJ22222 model. The BJ22222 model is stable because the system's pole is successfully located inside the unit circle (1.0000, 0.2616, -0.5769) (refer to Figure 4.12).

Figure 4.13 shows the pole-zero plot for BJ32221 model. The BJ32221 model is not stable because the system's pole is are located outside the unit circle (0.1002, 0.4322, 0) (refer to Figure 4.13).

Figure 4.14 shows the pole-zero plot for BJ42221 model. The BJ42221 model is not stable because the system's poles are located outside the unit circle (1.0005, 0.9361, 0) (refer to Figure 4.14).

Figure 4.15 shows the pole-zero plot for BJ51111 model. The BJ51111 is stable because the system's pole is successfully located inside the unit circle (1.0000, 0) (refer to Figure 4.15). From that, the BJ first-, second- and fifth-order models are considered to represent the pneumatic system utilized in this study.

4.1.4 Pneumatic System Model Identification based on Output-Error Model (OE)

Table 4.4 Performance of a linear OE model based on different model orders

Criteria	1st Order (OE111)	2nd Order (OE220)	3rd Order (OE311)	4th Order (OE410)	5th Order (OE510)
Best Fit	89.8	91.8	91.76	91.77	91.78
Final Prediction Error (FPE)	28.57	19.36	19.33	19.37	19.35
Mean Square Error (MSE)	28.4	19.13	19.06	19.06	18.96
Stability	Yes	Yes	No	No	No

From Table 4.4 the percentage of best fit for all Output-Error model orders (OE) are above 90 % except for first-order model where it was 89.8 %. The highest percentage is 91.78 %, which obtained from fifth-order model. The model is accepted to represent the system if the best fit obtained is exceed 90 %. Thus, from the result, first-order OE model are rejected due to the best fit percentage is below 90 %. Besides, the final prediction error and mean square error also were recorded as indicators to accept or reject the identified model. If the final prediction error and mean square error are small, the model is acceptable to represent the system. This is because lower error means the identified model is accurate. As shown in the Table 4.4, all OE model orders have high final prediction error and mean square error. Therefore, OE model are not accepted to represent the pneumatic system.

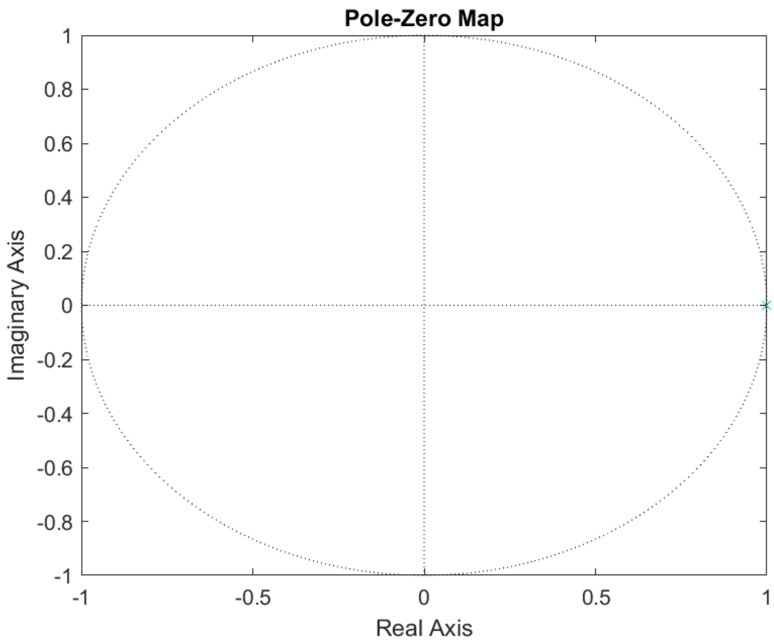


Figure 4.16 The zero-pole plot for the first-order OE model

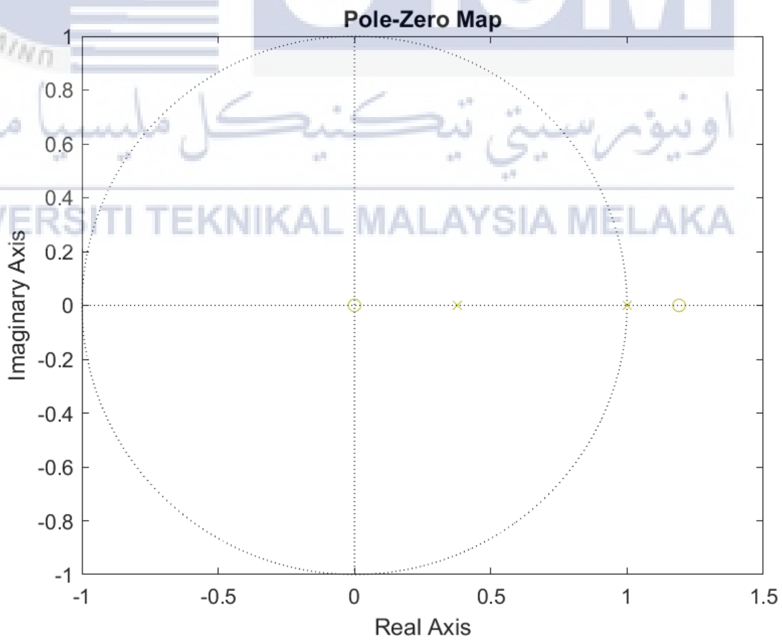


Figure 4.17 The zero-pole plot for the second-order OE model

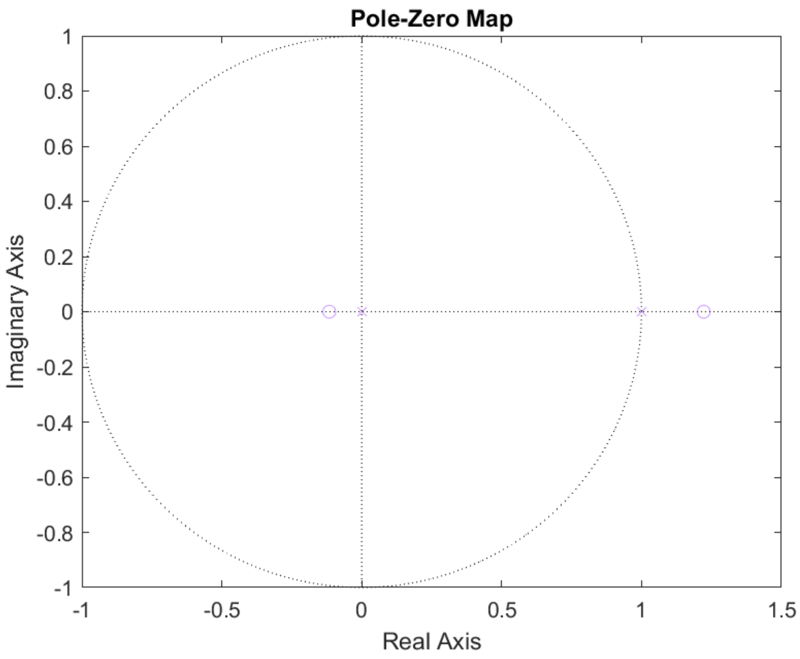


Figure 4.18 The zero-pole plot for the third-order OE model

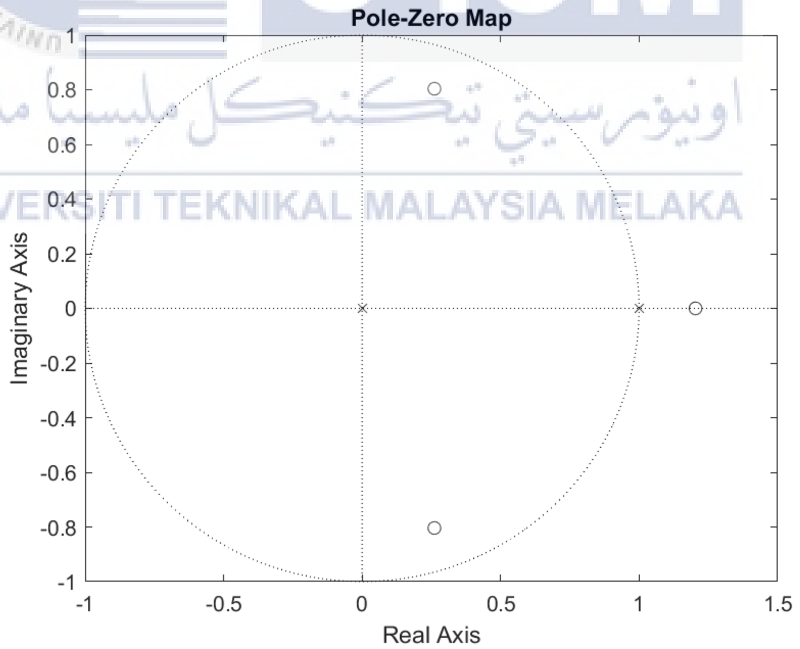


Figure 4.19 The zero-pole plot for the fourth-order OE model

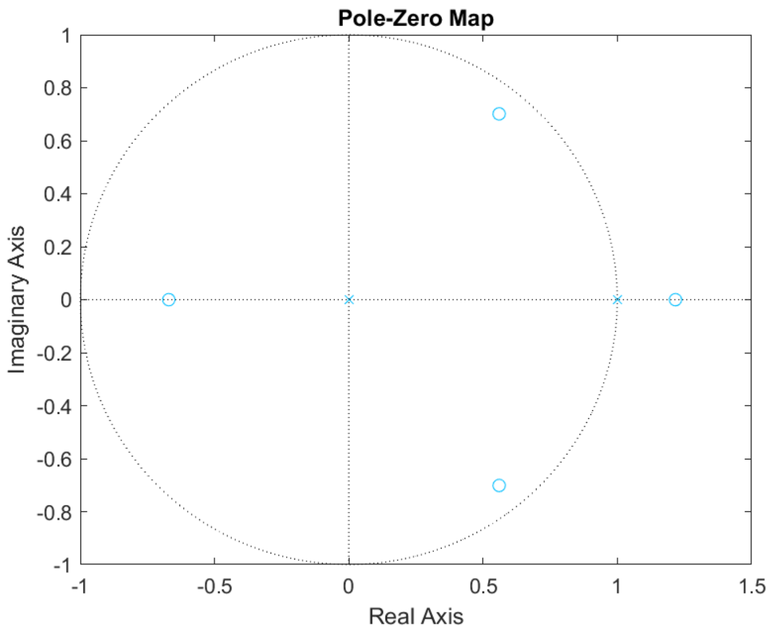


Figure 4.20 The zero-pole plot for the fifth-order OE model

Figure 4.16 shows the pole-zero plot for OE111 model. The pole-zero plot was recorded based on the obtained input and output data from open-loop real-time experiment. The OE111 is stable because the system's pole is successfully located inside the unit circle (0.9994) (refer to Figure 4.16).

Figure 4.17 shows the pole-zero plot for OE220 model. The OE220 is stable because the system's pole is successfully located inside the unit circle (0.9986, 0.3782) (refer to Figure 4.17).

Figure 4.18 shows the pole-zero plot for OE311 model. The OE311 is stable because the system's pole is successfully located inside the unit circuit (0.9986, 0) (refer to Figure 4.18).

Figure 4.19 shows the pole-zero plot for OE410 model. The OE410 is stable because the system's pole is successfully located inside the unit circle (0.9985, 0) (refer to Figure 4.19).

Figure 4.20 shows the pole-zero plot for OE510 model. The OE510 is stable because the system's pole is successfully located inside the unit circle (0.9985, 0) (refer to Figure 4.20). From the result shown all OE model orders are considered to represent the pneumatic system utilized in this study.

4.1.5 Summary of Pneumatic System Model Identification

From the system model identification result, all second-order model for ARX, ARMAX, BJ and OE are qualified to represent the pneumatic system used in this study. This is because all second-order models fulfilled the system identification criteria such as best fit percentage, low FPE, low MSE and stable according to pole-zero plot.

4.2 Simulation Test Performance of Pneumatic Positioning System and Discussion

This section describes the simulation test performance of pneumatic positioning system using Proportional-Integral-Derivative (PID) controller. The identified models which are all second-order models were applied to the Proportional-Integral-Derivative (PID) controller. The simulation tests were conducted by using Simulink in the MATLAB software. The transient response performance (i.e., rise time, settling time, overshoot, steady state error) of pneumatic positioning system of each model was compared.

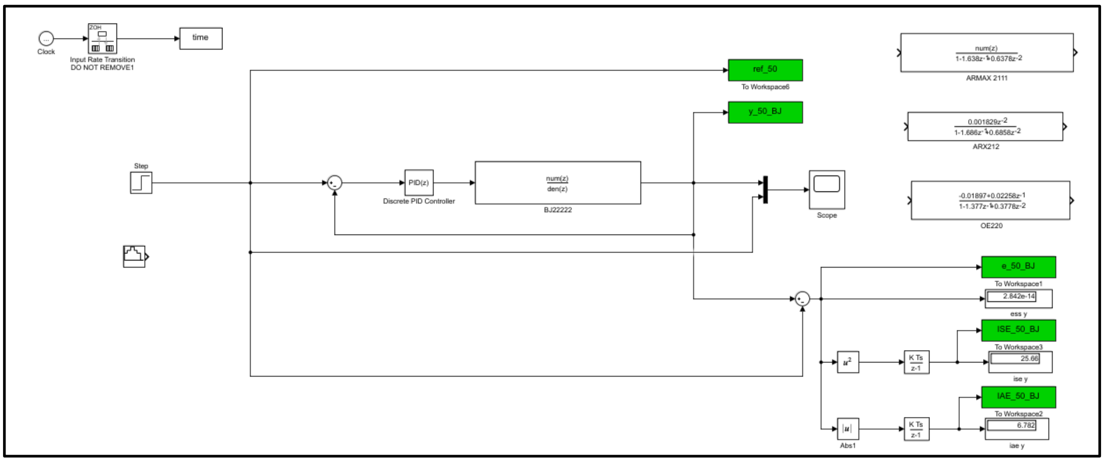


Figure 4.21 Components of PID controller in Simulink

Figure 4.21 illustrate the components of PID controller in Simulink. In this study, there are two methods applied to obtain the PID parameter such K_P, K_i and K_d. The first method applied is the Ziegler-Nichols method, where the next method applied was the heuristic method.

4.2.1 Simulation Test Performance of Pneumatic Positioning System using PID Controller based on Ziegler-Nichols Tuning Method

In this study, Ziegler-Nichols tuning method was applied to optimize the PID controller values K_P, K_i and K_d. K_P in PID controller represents proportional gain, K_i represents integral gain and K_d represents derivative gain. In order to use Ziegler-Nichols table (refer Chapter 3), the open-loop transfer function of the process model must be first known. Figure 4.22 shows the process of obtaining an open-loop transfer function of the process model using System Identification Tool, and Figure 4.23 shows an open-loop transfer function of the process model generates by System Identification Tool.

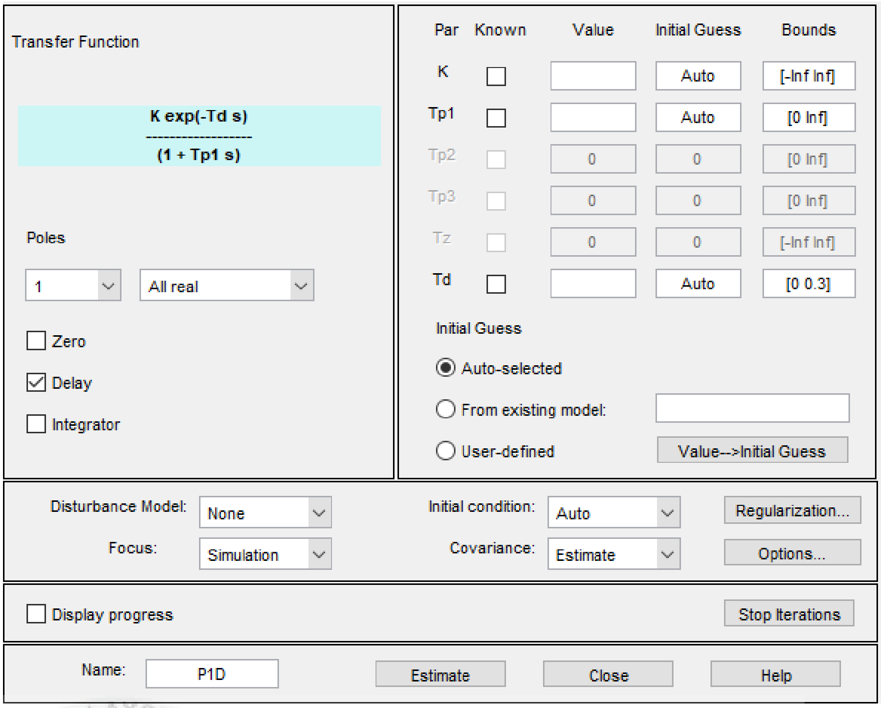


Figure 4.22 Process model in System Identification Tool

```
Process model with transfer function:
             Kp
  G(s) = ---------- * exp(-Td*s)
          1+Tp1*s

        Kp = 10.665
       Tp1 = 18.621
        Td = 0.03126

Name: P1D
```

Figure 4.23 An open-loop transfer function of the process model generated by System Identification Tool

Then, the parameter values of an open-loop transfer as shown in Figure 4.23 were applied in the Ziegler-Nichols tuning table in order to get the PID controller parameter values. Table 4.5 tabulates PID controller parameter values based on Ziegler-Nichols tuning method.

Table 4.5 PID controller parameter values based on Ziegler-Nichols tuning method

Controller	K_P	$T_i = \frac{K_p}{K_i}$	$T_d = \frac{K_d}{K_p}$
P	595.681	∞	0
PI	536.113	$T_i = \frac{K_p}{K_i} = 0.1042$	0
PID	714.818	$T_i = \frac{K_p}{K_i} = 0.06252$	$T_d = \frac{K_d}{K_p} = 0.01563$

Subsequently, the PID controller parameter values as shown in Table 4.5 were applied in the PID controller. Figure 4.5 shows the transient response performance of pneumatic positioning system using PID controller based on the Ziegler-Nichols method. The transient response performance analyzed were rise time, settling time, overshoot percentage, steady state error, integral square error and integral absolute error.

Table 4.6 Transient response performance of pneumatic positioning system using PID controller based on Ziegler-Nichols tuning method

	Transient Response Performance	ARX212	AMX2111	BJ22222	OE220
PID Controller	t_r (s)	Nan	0.0040	0.1202	0.0054
	t_s (s)	Nan	0.0444	0.9488	0.0523
	OS (%)	Nan	0.1407	0	0.1412
	SSE	Nan	0	0	0.008792
	ISE	Nan	0.00106	0	0.002066
	IAE	Nan	0.2829	0	0.8854

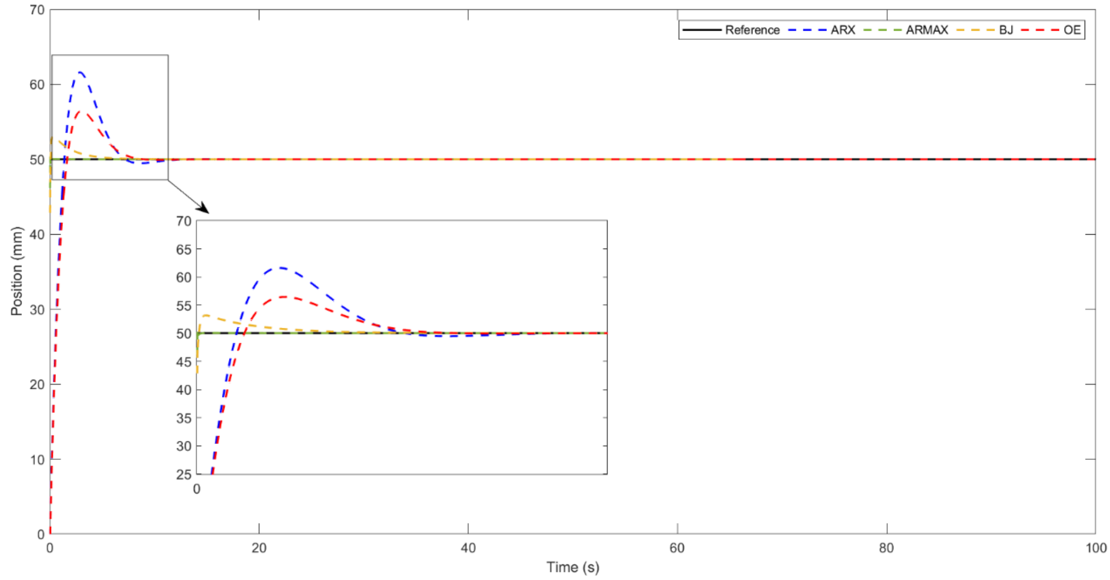
Table 4.6 shows the performance of transient response for each model. The performance of transient response consists of rise time (t_r), settling time (t_s), overshoot percentage (OS), steady state error (SSE), integral square error (ISE) and integral absolute error (IAE). The result shows the value of transient response were not a number (nan). This is because the operation has undefined numeric value. From that, the performance of transient response of ARX model cannot be analyzed to make analysis and comparison in terms of performance with other models. Therefore, Ziegler-Nichols method cannot be applied to analyzed the performance of the models since the value obtained from the simulation test is not a number (nan).

4.2.2 Simulation Test Performance of Pneumatic Positioning System using PID Controller based on Heuristic Tuning Method

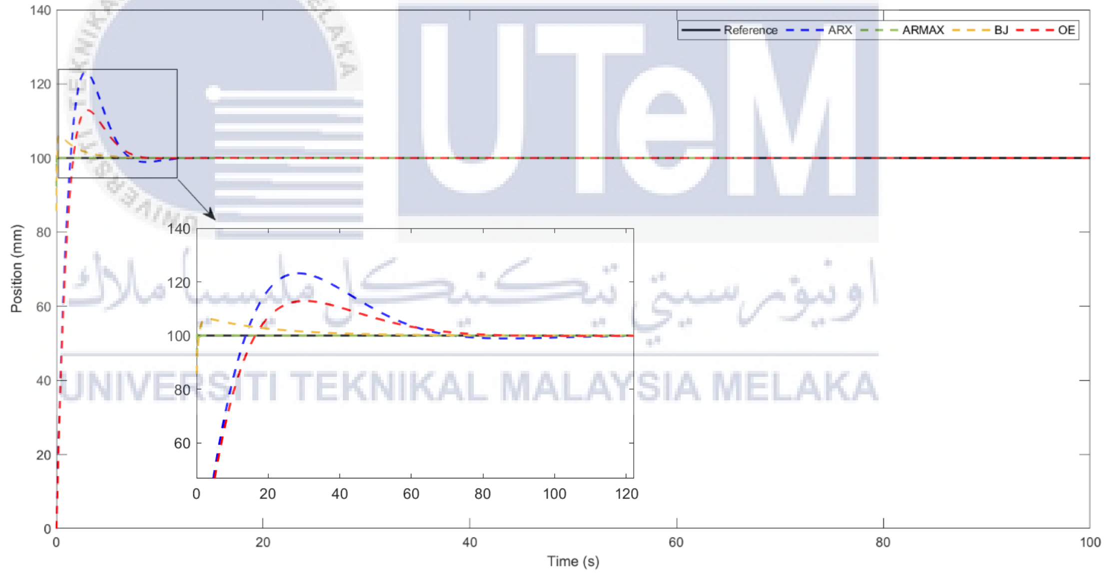
The heuristic tuning method was applied to optimize the PID controller parameters. Heuristic tuning method started by adjusting the P, I and D parameters incrementally until the controller oscillation were achieved. After that, the P, I and D parameter were reduced until stable and fast response oscillation was achieved.

4.2.2.1 Pneumatic Positioning System using PID Controller based on Heuristic Tuning Method: PID [2 1 0.1]

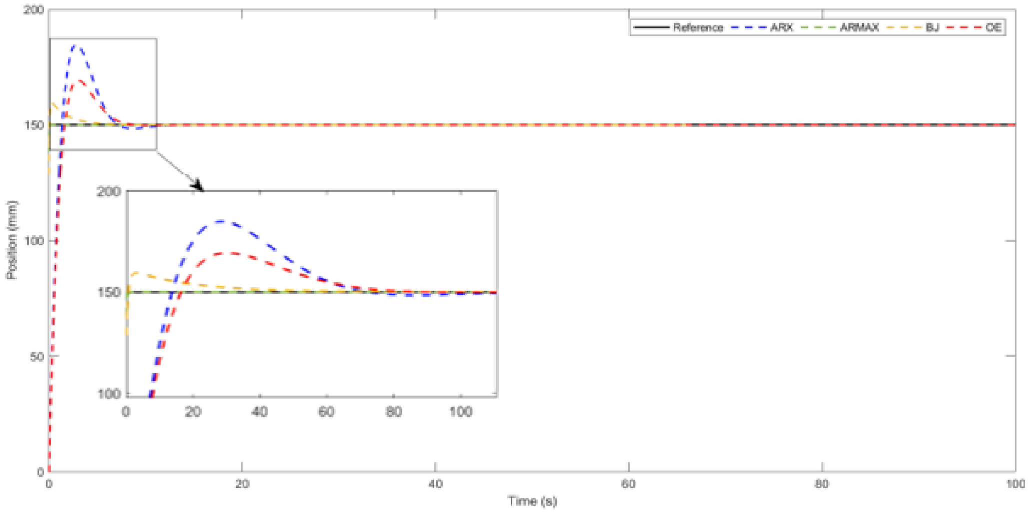
The heuristic method started with adjusting the proportional gain, K_p. K_p value was applied to improve the performance of rise time and settling time. For K_i, it was used to improve the steady-state response and K_d was used to improve the error prediction in the system.


Reference
ARX
ARMAX
BJ
OE
Position (mm)
Time (s)

(a)


Reference
ARX
ARMAX
BJ
OE
Position (mm)
Time (s)

(b)



(c)

Figure 4.24 Simulation response when position distance at: (a) 50 mm, (b) 100 mm, and (c) 150 mm

Table 4.7 Performance of transient response for PID [5 1 0.1] for position distance 50 mm, 100 mm and 150 mm

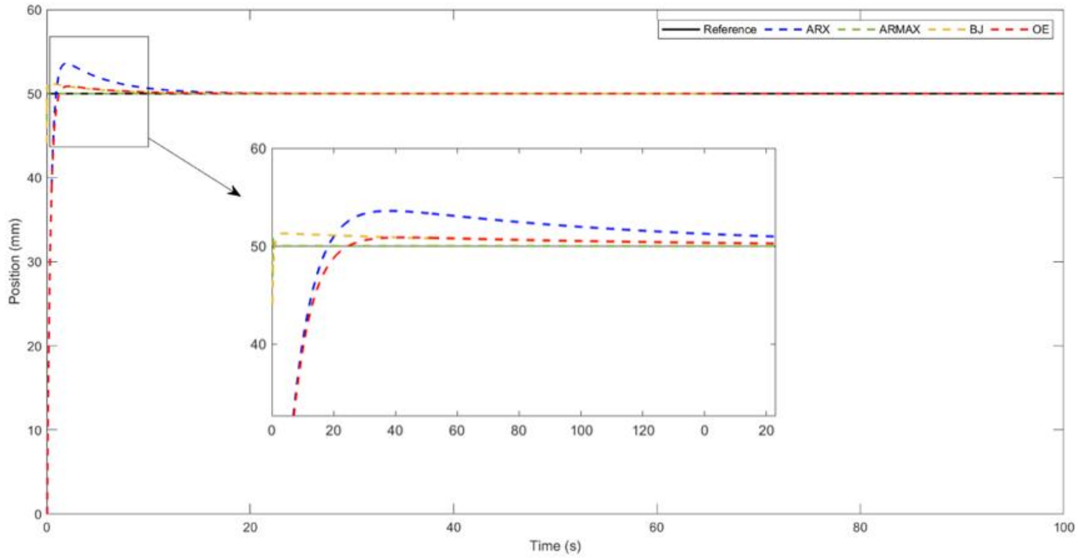
Distance (mm)	**Transient Response Performance**	**ARX212**	**AMX2111**	**BJ22222**	**OE220**
50	t_r	1.0575	0.0073	0.0441	1.2056
	t_s	6.4037	0.1055	5.9507	6.2971
	OS	23.2017	0.6950	6.3321	12.8898
	SSE	0	0	0	0
	ISE	1154	0.159	11.99	1048
	IAE	64.68	0.1353	6.658	51.94
100	t_r	1.0575	0.0073	0.0441	1.2056
	t_s	6.4037	0.1055	5.9507	6.2971
	OS	23.2017	0.6950	6.3321	12.8898
	SSE	0	0	00	0
	ISE	4616	0.6385	47.94	4194
	IAE	129.4	0.271	13.32	103.9
150	t_r	1.0575	0.0073	0.0441	1.2056
	t_s	6.4037	0.1055	5.9507	1.2056
	OS	23.2017	0.6950	6.3321	12.8898
	SSE	0	0	0	0
	ISE	0	1.437	107.9	9436
	IAE	194	0.4085	19.97	155.8

The table 4.7 shows the performance of transient response of all model for PID controller with K_p value of 2, K_i value of 1 and K_d value of 0.1 in terms of rise time, settling time, overshoot percentage, steady-state error, integral square error and integral absolute error. The simulation results show BJ model has the fastest rise time (0.0441 s) compared to others. The model with the slowest rise time is OE model (1.2056 s). For the settling time, the model with the fastest settling time is ARMAX model (0.1055 s) while ARX model has the slowest settling time (6.4037 s). Next, the model with lowest overshoot percentage is ARMAX model (0.6950 s). The model with the highest overshoot percentage is ARX model (23.2017 s).

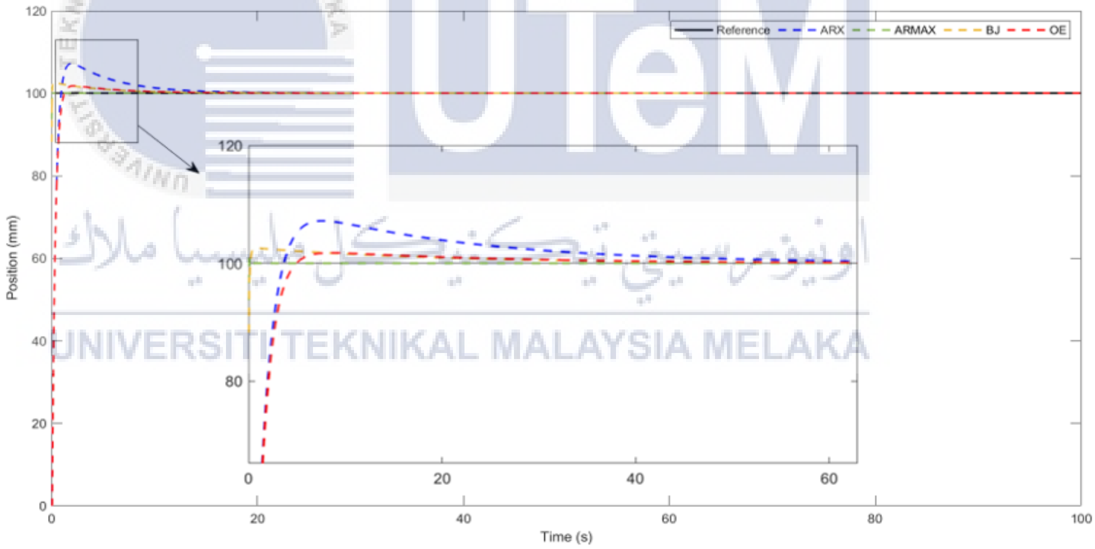
Based on the simulation result, the rise time, settling time and overshoot percentage are similar although the position distance was varied at 50 mm, 100 mm and 150 mm. The comparison between the model structures shows that ARMAX model successfully controlled the pneumatic cylinder stroke the fastest in order to achieve a positioning distance of 50 mm, 100 mm, and 150 mm. The observation through the data in Table 4.7 shows ARMAX model has the best performance of transient response for PID controller with K_p value of 2, K_i value of 1 and K_d value of 0.25.

4.2.2.2 Pneumatic Positioning System using PID Controller based on Heuristic Tuning Method: PID [1 1 0.1]

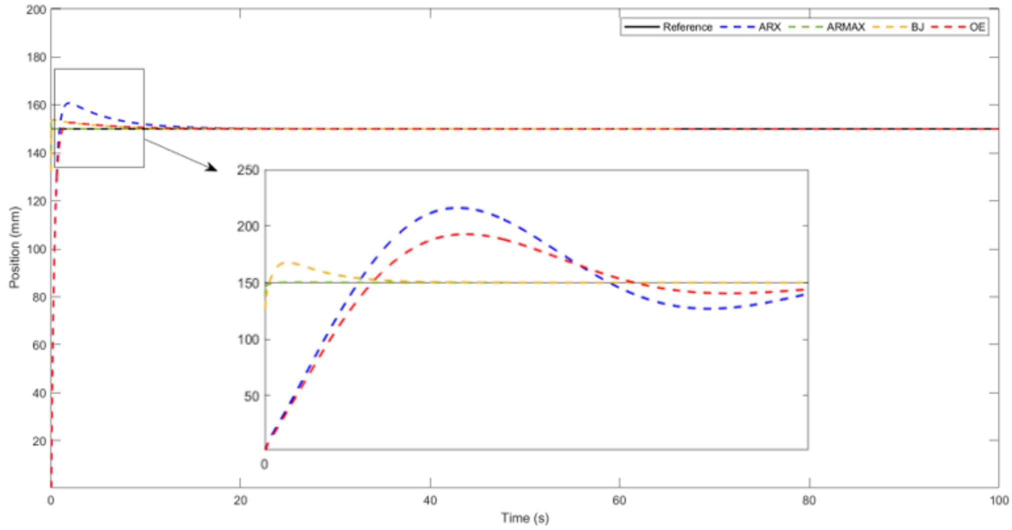
For this section, the value of proportional gain K_p was adjusted from value of 2 to value of 1. Table 4.8 shows the performance of transient response of all models after adjusting K_p value to 1 from distance of 50 mm to 150 mm.


Reference
ARX
ARMAX
BJ
OE
Position (mm)
Time (s)

(a)


Reference
ARX
ARMAX
BJ
OE
Position (mm)
Time (s)

(b)



(c)

Figure 4.25 Simulation response when position distance at (a) 50 mm, (b) 100 mm, and 150 m

Table 4.8 Performance of transient response for PID [1 1 0.1] for position distance 50 mm, 100 mm and 150 mm.

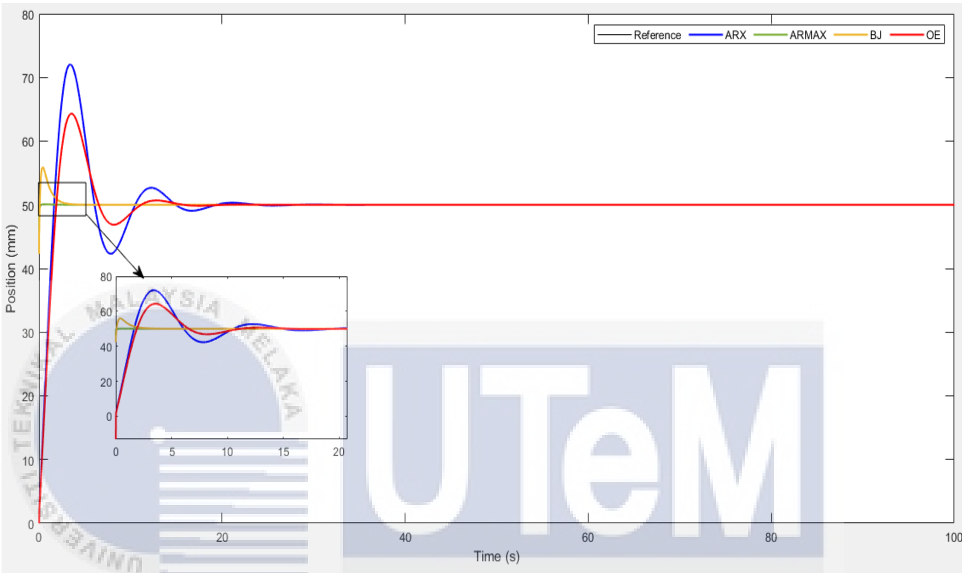
Distance (mm)	Transient Response Performance	ARX212	AMX2111	BJ22222	OE220
50	t_r (s)	0.5873	0.0063	0.0260	0.5976
	t_s (s)	8.0190	0.0267	11.8028	0.9663
	OS (%)	7.1966	1.6514	2.5746	0.7724
	SSE	488.5	0.1055	4.622	496.5
	ISE	34.83	0.07656	6.515	21.48
	IAE				
100	t_r (s)	0.5873	0.0063	0.0260	0.5976
	t_s (s)	8.0190	0.0267	11.8028	0.9663
	OS (%)	7.1966	1.6514	2.5746	0.7724
	SSE	0	0	0	0
	ISE	1874	0.4221	18.49	1986
	IAE	1874	0.1531	13.03	42.91
150	t_r (s)	0.5873	0.0063	0.0260	0.5976
	t_s (s)	8.0190	0.0267	11.8028	0.9663
	OS (%)	7.1966	1.6514	2.5746	0.7724
	SSE	0	0	0	0
	ISE	4218	0.9497	41.6	4469
	IAE	1045	0.2297	19.54	64.37

Table 4.8 shows the performance of transient response of all model for PID controller with K_p value of 1, K_i value of 1 and K_d value of 0.1 in terms of rise time, settling time, overshoot percentage, steady-state error, integral square error and integral absolute error. The simulation results show ARMAX model has the fastest rise time (0.0079 s) compared to others. The model with the slowest rise time is OE model (1.5707 s). For the settling time, the model with the fastest settling time is ARMAX model (0.7546 s) while ARX model has the slowest settling time (14.1082s). Next, the model with lowest overshoot percentage is ARMAX model (0.1915 s). The model with the highest overshoot percentage is ARX model (44.1027 s).

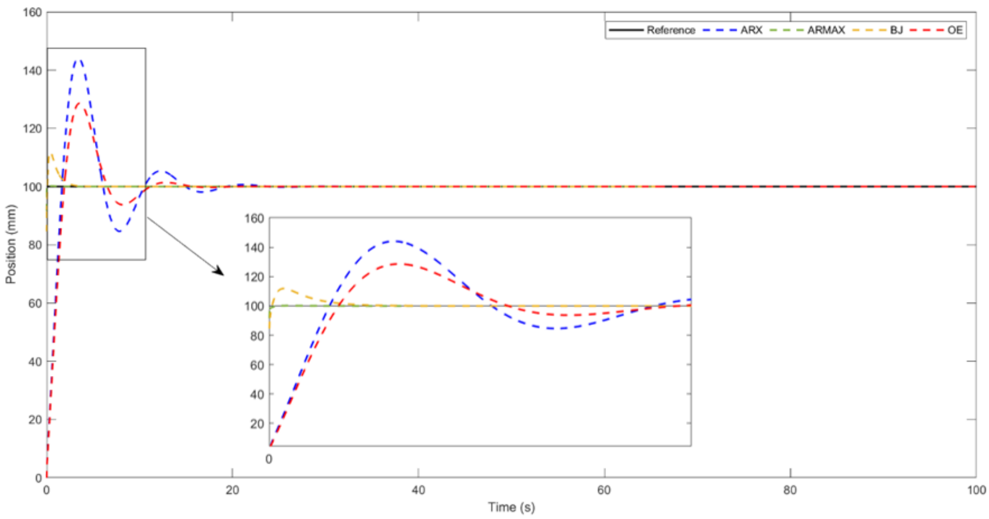
Based on the simulation result, the rise time, settling time and overshoot percentage are similar although the position distance was varied at 50 mm, 100 mm and 150 mm. The comparison between the model structures shows that ARMAX model successfully controlled the pneumatic cylinder stroke the fastest in order to achieve a positioning distance of 50 mm, 100 mm, and 150 mm. The observation through the data in Table 4.8 shows ARMAX model has the best performance of transient response for PID controller with K_p value of 1, K_i value of 1 and K_d value of 0.1.

4.2.2.3 Pneumatic Positioning System using PID Controller based on Heuristic Tuning Method: PID [5 1 0.1]

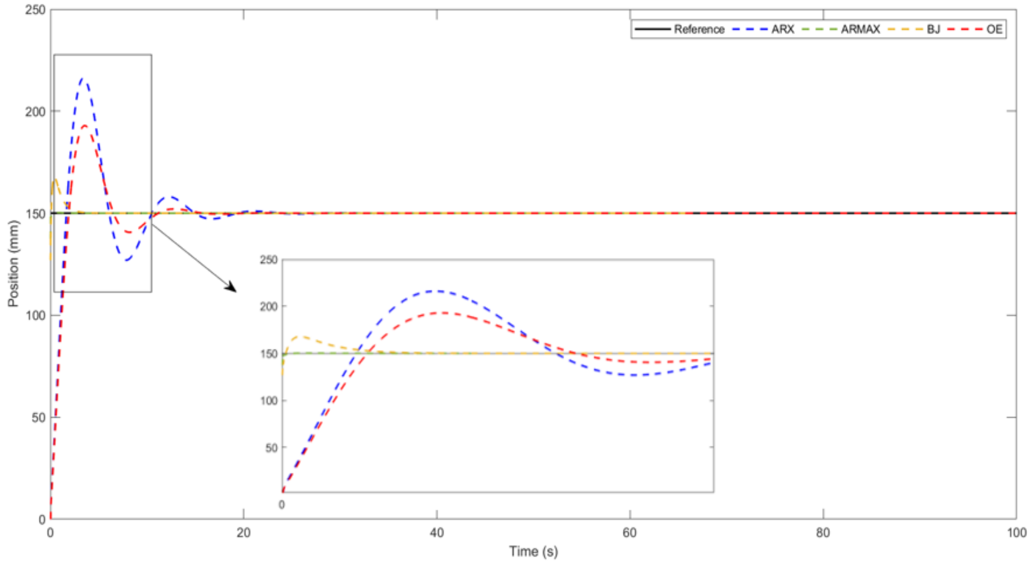
For this section, the value of proportional gain K_p was adjusted from value of 2 to value of 1. Table 4.9 shows the performance of transient response of all models after adjusting K_p value increasing from 1 to 5 from distance of 50 mm to 150 mm.



(a)



(b)



(c)

Figure 4.26 Simulation response when position distance at (a) 50 mm, (b) 100 mm, and 150 mm

Table 4.9 Performance of transient response for PID [5 1 0.1] for position distance 50 mm, 100 mm and 150 mm.

Distance (mm)	Transient Response Performance	ARX212	AMX2111	BJ22222	OE220
50	t_r (s)	1.3376	0.0079	0.0586	1.5707
	t_s (s)	14.1082	0.7546	3.1562	10.0590
	OS (%)	44.1027	0.1915	11.8810	28.6123
	SSE	0	0	0	0
	ISE	2457	0.2149	25.66	1880
	IAE	132	0.225	6.782	94.67
100	t_r (s)	1.3376	0.0079	0.0586	1.5707
	t_s (s)	14.1082	0.7546	3.1562	10.0590
	OS (%)	44.1027	0.1915	11.8810	28.6123
	SSE	0	0	0	0
	ISE	9829	0.8596	102.6	7522
	IAE	264	0.45	13.56	189.3
150	t_r (s)	1.3376	0.0079	0.0586	1.5707
	t_s (s)	14.1082	0.7546	3.1562	10.0590
	OS (%)	44.1027	0.1915	11.8810	28.6123
	SSE	0	0	0	0
	ISE	0	1.934	230.9	0
	IAE	396.1	0.675	20.39	284

Table 4.9 shows the performance of transient response of all model for PID controller with K_p value of 5, K_i value of 1 and K_d value of 0.1 in terms of rise time, settling time, overshoot percentage, steady-state error, integral square error and integral absolute error. The simulation results show ARMAX model has the fastest rise time (0.0063 s) compared to others. The model with the slowest rise time is OE model (0.9663 s). For the settling time, the model with the fastest settling time is ARMAX model (0.0267 s) while BJ model has the slowest settling time (11.8028 s). Next, the model with lowest overshoot percentage is ARMAX model (1.6514 s). The model with the highest overshoot percentage is ARX model (7.1966 s).

Based on the simulation result, the rise time, settling time and overshoot percentage are similar although the position distance was varied at 50 mm, 100 mm and 150 mm. The comparison between the model structures shows that ARMAX model successfully controlled the pneumatic cylinder stroke the fastest in order to achieve a positioning distance of 50 mm, 100 mm, and 150 mm. The observation through the data in Table 4.9 shows ARMAX model has the best performance of transient response for PID controller with K_p value of 5, K_i value of 1 and K_d value of 0.1.

4.3 Summary

This chapter analyzed the results obtained from the simulation in the MATLAB software in terms of modelling of the pneumatic system using System Identification Tool and controller design in the Simulink. The modelling of the pneumatic system shows the linear second-order for all model has the best performance in terms of system identification criteria and accepted to represent the pneumatic system that will be adopted into the PID controller. Apart from that, this chapter also discussed the performances of the identified model through simulation in terms of transient response based on different distance position. The results show ARMAX model has the best performance of transient response such as rise time, settling time, overshoot percentage and others.

4.4 Environmental and Sustainability

Nowadays, United Nation has designed 17 Sustainable Development Goal (SDG) as a framework to guide country in creating sustainable environment. In response to the 17 Sustainable Development Goal (SDG), this project has implemented one of the SDG goals which is responsible consumption and production (SDG12). This goal act as indicator to consume resources efficiently. In this project, there are no usage of chemical or any materials that can be harmful to the environment. Moreover, this project also environmental-friendly where the air compressor uses air, therefore it is proven clean and does not pollute to the environment.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

As the conclusion, the study was mainly about the modelling of pneumatic system using system identification approach. First, the experimental setup and data validation of the pneumatic system was design. The experimental setup was designed to collect data from real-time experiment of the pneumatic system.

Second, the mathematical model that represent the pneumatic system based on ARX, ARMAX, BJ and OE model structure using system identification were determined. The mathematical model of all model structures (ARX, ARMAX, BJ and OE) are from first-order until fifth-order.

Third, the validity of the identified ARX, ARMAX, BJ and OE model structures in terms of system identification criteria. The identified models were second-order for all model structures were accepted to represent the pneumatic system based on the system identification criteria.

Lastly, the performance of pneumatic positioning control using PID controller based on simulation test were evaluated. All second-order model structures were adopted into the PID controller to analyze the pneumatic positioning control based on three different position distance which are 50 mm, 100 mm and 150 mm. The PID parameters were determined through two methods which are Ziegler-Nicols tuning method and heuristic tuning method. Based on the result, ARMAX model has the best performance in rems of transient response. ARMAX model has the fastest rise time and settling time. ARMAX model also has the lowest overshoot percentage and the fastest to reach steady-state.

5.2 Future Works

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:

1) Add more controller to analyzed the performance of pneumatic system transient response. For example, Constrained Model Predictive Controller (CMPC) and Predictive Functional Controller with Observer (PFC-O) controller can be implemented to improve the performance of pneumatic positioning system.
2) Vary the tuning method for obtaining PID controller parameters. The method can be Internal Model Control (IMC), genetic algorithm (GA),

pole-placement method, artificial neural network and particle swarm optimization (PSO). Thus, the performance in terms of transient response can be compared using different tuning methods.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

1. **Laila Nadhirah Mohd Asri** and Siti Fatimah Sulaiman (2021). Modelling of Pneumatic System using System Identification Approach. In *Virtual Innovation and Technology Competition (INOTEK) 2021*.