DESIGN AND ANALYSIS OF CONTROLLER FOR MOTION CONTROL SYSTEM

By

NOR AZREEN BINTI MOHD NOR

A Final Report Submitted to the
Electrical & Electronic Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

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MAY 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NOR AZREEN BINTI MOHD NOR

ABSTRACT

In motor drive applications, the mechanical properties of electrical motor under various load and operating conditions are different. These changes highly influence the performance of motor drive systems as the system's dynamic response under these variations is affected. This project presents the design and development of a system controller for motion control system. The basic approach used in this project is by using the modern control engineering theory through the state space approach. The state space design approach was used instead of the conventional control because state space design is most suitable for nonlinear system and multi-input multi-output (MIMO) system set-up. In the initial stage, the controller system for motion control system was designed using the linearized equation of motion. For this motion control system, the load torque was selected as the input with mechanical angular position as the output. This project consists of modelling and simulation using Simulink, and performance evaluation is done through the system analysis. A satisfactory performance is achieved from the designed controller system which is better than the conventional control in terms of controllability, observability and stability to be used in motion control system.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

CNC	Computer numerically controlled
EOM	Equation of motion
LTI	Linear time invariant
MIMO	Multiple input multiple output
SISO	Single input single output

CHAPTER 1
INTRODUCTION

This chapter is to introduce and elaborate the project entitled "Design and Analysis of Controller for Motion Control System". A background of study on this project is given, followed by the problem statements to be addressed and also the objectives and the scope of study.

1.1 Background of Study

A robust motor drive system is important in industry. Stability and adaptability are the key elements to produce a robust control system. This project is to design and analyze a controller for motion control system in order to produce a robust control system as well as improve motor performance [1]. State-space is used as the main approach of this project as it provides a convenient and compact way to model and analyze a system with multiple inputs and multiple outputs. Apart from that, the operation of the motor is accomplished via computational modeling whereby a controller is being used to guide the control system accordingly.

1.2 Problem Statement

The mechanical properties of an electrical motor under various load and operating conditions are different. These changes highly influence the performance of motor drive systems as the system's dynamic response under these variations is affected [2, 3]. In order to improve the motor performance, some modifications and improvements should be performed. Various motion control systems have been proposed previously where researchers have utilized different approaches in the control system design. Among them are the classical control techniques such as the root locus technique or modern control techniques like the state space approach. However, classical controls posses several drawbacks, for which some are not adaptive and not robust. Besides, industries nowadays only focus on stability in control system. Robustness, optimality and adaptivity are often ignored.

To address this problem, the state space approach can be used in the motion controller system design. This approach was used due to its suitability to a nonlinear system and multi-input multi-output (MIMO) systems. State space methods allow greatly simplified mathematical representation of the systems. A developed controller which is expected to be better than the conventional controller in terms of the system's controllability and stability is the main outcome of this project.

1.3 Objectives

The main objective of this project is to design and analyze the modeling of a controller for motion control system using the state-space representation. Another objective is to apply the knowledge and concepts of modern control engineering in motion control system. Besides, the purpose of this project is also to do the modeling and simulation of the designed controller using MATLAB/Simulink and onward, the evaluation of the simulation performance will be performed to see the outcomes of this project.

1.4 Scope of Study

This project can be divided into a number of phases which would lead to a number of publishable works:

1. Literature review on motion control system, modern control theory and state-space representation. This will include relevant research studies in order to facilitate relative comparisons and understand the basic design of the controller.

2. Development and the modeling of controller for the motion control system using state-space representation in terms of the system's controllability and stability.
3. Simulation of the controller modeling and the analysis of the simulation results to observe the findings of this project.

1.5 Organization of Report

The whole report is divided into five chapters. First, the introductory chapter gives an overview of the project and explains the importance of the project. It also highlights the problem being investigated and justifies the need for the problem to be solved. The objectives of this project is explained so that this project will meet the purpose of doing this project and yet, solving the highlighted problem mentioned earlier.

Chapter 2 reviews and clearly explains some of the related research. The purpose of this chapter is to introduce the fundamental and key concepts of the issues involved such as modern control theory and state-space representation. Moreover, basic understanding of the motion control system is covered and presented in detail.

Chapter 3 delivers the basic method and identifies the procedure to be used for this project. This chapter also explains the project activities to be undertaken throughout this research. The process Gantt chart is presented to show the timeline of this project. Besides, the tools and materials to be used in this project are also presented.

In chapter 4, the results of the simulation studies are presented. This chapter reviews on how the results are obtained by using the Matlab and Simulink. The findings are then explained and analyzed in the analysis part of this project.

Lastly, the final chapter summarizes the overall method used and discusses results for this project. This chapter also gives concluding remarks on the overall project ingredients to show that this project actually meets its required goals.

CHAPTER 2
LITERATURE REVIEW

This chapter presents the literature reviews related to this project. This chapter explains about control system, control techniques available and the comparisons of both techniques have been summarized. Besides, this section also covers the motion control system that is being applied in this project, and the need of a controller design is briefly explained. Lastly, the state space representation which is the primary element in this project is discussed which covers some theories and sub elements that are very important to be recognized in order to improve the understanding of this project much better.

2.1 Control System

A control system consists of subsystems and processes (or plants) assembled for the purpose of obtaining a desired output with desired performance, given a specified input [4]. Control theory consists of many branches of engineering and mathematics that deals with dynamical system behavior [5]. When one or more output variables is needed to reach the desired output with respect to time, a controller is needed to manipulate the inputs of a system so that the system will be able to obtain the desired response of the system. Control system is needed because of the following reasons:

- To improve the system performance and accuracy.
- To gain beneficial economy – to maximize economic returns.
- To provide safety to the system.
- To offer reliability of the system and minimize failures.

Figure 1 shows the basic physical components of a control system.

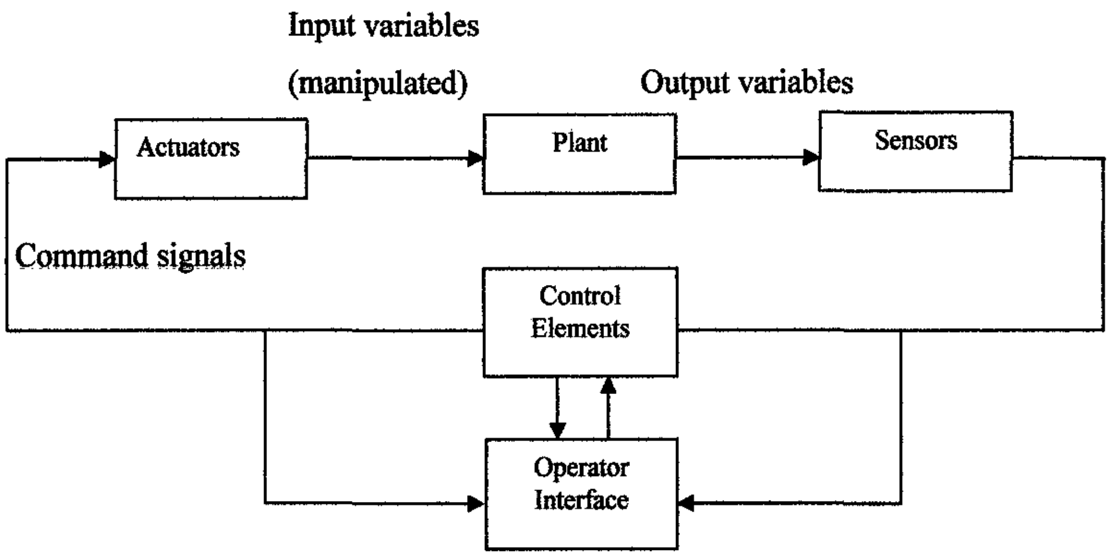

Figure 1: Physical components of a control system

There are two approaches available for design and analysis of control system which are classical (conventional) control and modern control technique.

2.1.1 Classical control technique

Classical control is developed in terms of an input-output transfer function description of a system where the output is a single-valued variable [6]. This technique is based on converting a system's differential equation to a transfer function. The advantage of this approach is it rapidly provides stability and transient response information of the system. However, this approach has some drawbacks where this method can only be applied to LTI systems and only restricted to SISO system [7]. Besides, the use of a single output variable sometimes provides inadequate information.

2.1.2 Modern control technique

Modern control technique or the time-domain state-space approach is a unified method for modeling, analyzing, and designing a wide range of systems. The system related to this technique is described by differential equations or by difference equations. This approach can be used in non-linear and time varying systems. It is also applicable to MIMO systems [7] and can be easily solved with the availability of advanced digital computer or software such as MATLAB. This approach will be explained briefly under state-space representation in the section below.

2.1.3 Classical control versus modern control.

The comparison between classical control and modern control will be discussed in more simple way as shown in Table 1 below.

Table 1: Classical control versus modern control

Classical (Conventional) Control	**Modern Control (State-Space)**
• A frequency domain approach	• A time domain approach
• Based on the steady state behavior	• Allows initial conditions to be included
• Limited to analysis of SISO-LTI systems	• Unify the analysis of SISO and MIMO linear, nonlinear, and time-invariant and time varying systems
• Based on the description of the systems in terms of input-output relationship	• Introduces states and the system is described by n-first order differential/difference equations
• Design is based on trial and errors procedures which is guided by criteria such as settling time, phase margin, etc.	• In state-space design, performance indices are defined and hence optimal systems can be designed

2.2 Motion Control System

Motion control is a sub-field of automation, in which the position and/or velocity of machines are controlled using some type of device such as a hydraulic pump, linear actuator, or an electric motor. Motion control is an important part of robotics and CNC (computer numerically controlled) machine tools, however it is more complex than in the use of specialized machines, where the kinematics are usually simpler [8].

Motion control is implemented with three major prime movers (actuators) which are hydraulic, pneumatic, and electric motors [9] and actuators is important to control the motion of motor system. Hydraulic and pneumatic are less widely used compare to electrical actuator. Motor control requires three basic elements that are a motor, a drive and one or more feedback devices. The drive controls current in order to produce torque, the drives also commonly control velocity and sometimes control position.

2.2.1 Equation of motion

The equation of motion used in this project is based on the rotational mechanical system [10]. Equation of motion (EOM) of a simple inertia-damper system is:

$$J\frac{d\omega}{dt} + B \cdot \omega + T_d = T_L \tag{2.1}$$

J is the moment of inertia element, B is damper, or also called as friction element, T_d refers to disturbance torque into the motor system and T_L is the torque generated by the motor. Mechanical systems have three passive, linear components. Two of them are spring and the mass which are referred as energy storage element, and another is viscous damper that refers to dissipated energy [4, 11]. These two energy-storage elements are analogous to inductor and capacitor in electrical system; they act as the storage elements while electrical resistance behaves as energy dissipator. The elements used in this mechanical system are moment of inertia and damper. Damper is the damping elements and damping is the friction existing in physical systems whenever mechanical system moves on sliding surface. The friction encountered for this element is viscous friction force. Instead of mass, moment of inertia is used as energy storage element of the system. Figure 2 shows the model of motor system with inertia-damper element.

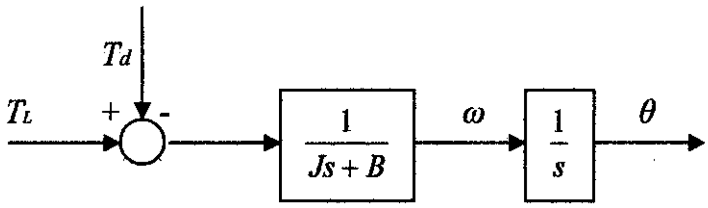

Figure 2: Modeling of the mechanical system

2.2.2 Controller design of linear system

The controller is combined with the observer (estimator) which defines the overall control system, equivalent to compensators [12]. A compensator is a sub-system inserted into the forward or feedback path for the purpose of improving the transient response or steady-state error. A controller can be designed to specifications only if the system is controllable. Observability of the system ensures that the states can be reconstructed, so observer is constructed to estimate states.

The reference input is introduced in such a way that the system output track external commands with acceptable transient characteristics and also help robust observer operation. There are two approaches in designing controller which are state space design and root locus design. In state-space design, any arbitrary desired pole location can be selected by proper design while in root-locus design, only one parameter can be designed which restricts the poles to lie only on the locus.

2.3 State Space Controller

2.3.1 Theory

In control engineering, a state space representation is a mathematical modeling of a physical system. Physical system which is referred to as the dynamics behavior of the system is characterized by a set of inputs and outputs, and state variables related by first order differential equations [6, 13]. Inputs, outputs and states variables are expressed as vectors and the differential equations are written in matrix form. The state space methods allow greatly simplified mathematical representation of the systems and this method is particularly suited for digital computer use because of their time-domain approach and vector-matrix description.

2.3.2 State space representation

The general vector-matrix form of the state space model [14] is:

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx + Du \end{aligned} \tag{2.2}$$

Where x is the state vector equation and y is the output equation. Figure 3 shows the block diagram representation of the state space equations.

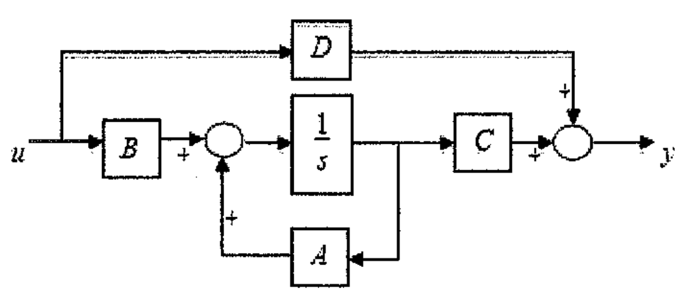

Figure 3: Block diagram of state space equation

x = state vector = derivative of the state vector with respect to time

y = output vector

u = input or control vector

A = system matrix

B = input matrix

C =output matrix

D = feed forward matrix

- **System variables:** Any variable that responds to an input or initial conditions in a system.
- **State variables:** The state of the system is a set of variables such that the knowledge of these variables and the input functions will, with the equations describing the dynamics, provide the future state and the output of the system [15].
- **State vector:** A vector whose elements are the state variables.
- **State equations:** A set of n simultaneous, first order differential equations with n variables, where the n variables to be solved are the state variables.
- **Output equations:** The algebraic equation that expresses the output variables of a system as linear combinations of the state variables and inputs.

The choice of state variables for a given system is not unique. The requirement in choosing the state variables is that they be linearly independent and that a minimum member of them be chosen. A state variable model explains clearly some complex general concepts about control systems, such as controllability and observability.

2.3.3 Controllability

Controllability is a property of the coupling between input and state. Controllability refers to the ability of a controller to arbitrarily alter the functionality of the system control [16]. Controllability plays an important role in the design of control systems using state space. The conditions of controllability may govern the existence of complete solution to the control system design problems. The solution of this problem may not exist if the system considered is not controllable. Thus, before proceeding with the modeling and simulation, controllability of the system needs to be determined.

A linear system is said to be controllable if it is possible to find some input signal $u(t)$ for all $t = [t_0, t]$, which will transfer the initial state $x(t_0)$ to any finite state $x(t)$ or $x(k)$ in finite time from $t - t_0$(or k)).

- If the system is controllable for all initial times t_0 and all initial states $x(t_0)$, the system is completely controllable.
- If a controllable canonical form exists for a given SISO system, then it is controllable.

2.3.4 Observability

Observability is a measure for how well internal states of a system can be inferred by knowledge of its external outputs. The observability and controllability of a system are mathematical duals as controllability describes that an input is available and brings any initial state to any desired final state, while observability states that knowing an output trajectory gives enough information to predict the initial state of the system [17].

A linear system is said to be observable at t_0 if $x(t_0)$ can be exactly determined from system output $y(t)$ over a time interval $t_0<t<t_f$. If the system is observable for all initial times t_0 and all initial states $x(t_0)$, the system is completely observable. If the initial state cannot so be determined, the system is unobservable [18].

2.3.5 *Feedback controller*

A controller can be designed to specifications only if the system is controllable. The reason of adding feedback is to improve the system characteristics or transient response such as settling time, overshoot and rise time. Eigenvalues determine the decay/growth of the response while eigenvectors determine the shape of the response. Figure 4 shows the block diagram of a feedback controller.

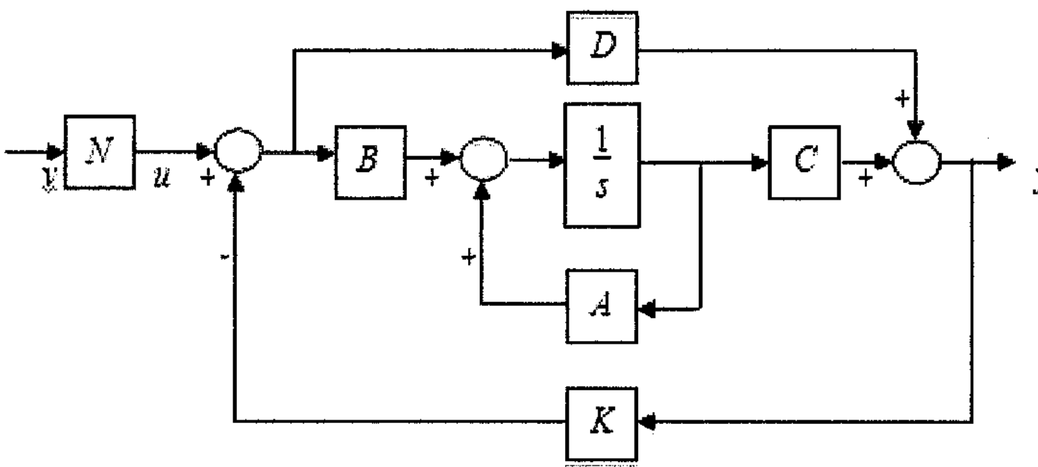

Figure 4: Block diagram of a feedback controller system

For the linear system with the state-space representation, the state feedback controller is of the form, $u = -Kx + Nv$ where u is the state feedback controller, K is the state feedback gain, N is the state feed forward gain and v is the reference input. The purpose of adding feedback is to improve the system characteristics or transient response and the reason of adding the feed forward is to eliminate the steady state error [19]. K can be calculated using the Aukerman's formula for Pole Placement technique. Such feedback control is carried out by deviating output of the system in order to influence an input (correction) back into the system [20].

2.3.6 Full state observer

Observer design is a system that models a real system in order to provide an estimate of its internal state; given measurements of the input and the output of the real system. Controller design relies upon access to the state variables for feedback through adjustable gains. This access can be provided by hardware for reasons of cost, accuracy or availability. In other applications, some of the state variables may not be available at all [21], or it is too costly to measure them or send them to the controller. If the state variables are not available because of system configuration or cost, it is possible to estimate the states. An observer is used to estimate the states. Estimated states, rather than actual states, are then fed to the controller. Before creating the estimated states, the original system is needed to be assumed as observable. Figure 5 shows block diagram of full state observer design for linear systems.

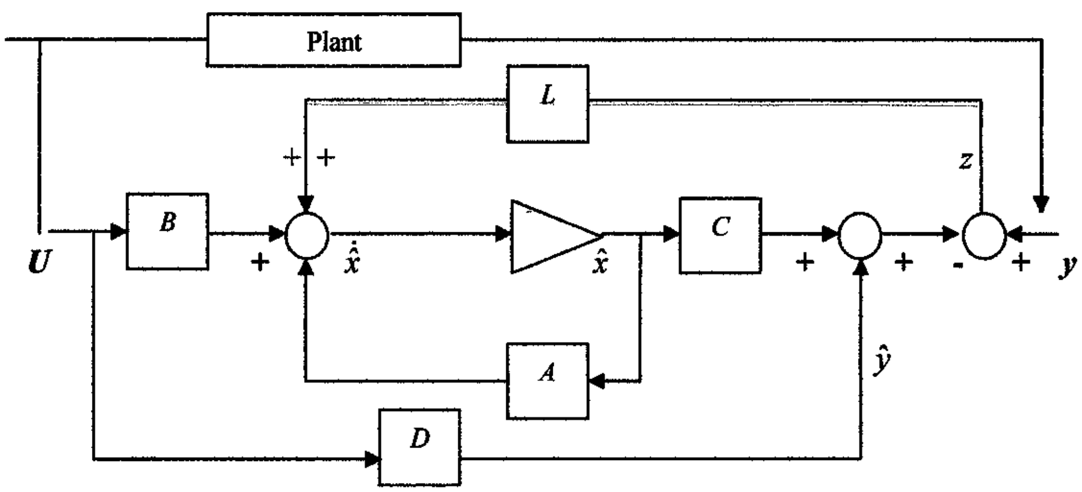

Figure 5: Block diagram of full state observer system

2.4 MATLAB

MATLAB is a numerical computing environment and fourth-generation programming language. Developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, and Fortran.

MATLAB, the application, is built around the MATLAB language. The simplest way to execute MATLAB code is to type it in at the prompt, >>, in the Command Window, one of the elements of the MATLAB Desktop. In this way, MATLAB can be used as an interactive mathematical shell. Sequences of commands can be saved in a text file, typically using the MATLAB Editor, as a script or encapsulated into a function, extending the commands available.

Variables are defined with the assignment operator, =. MATLAB is a weakly dynamically typed programming language because types are implicitly converted. It is a dynamically typed language because variables can be assigned without declaring their types, except if they are to be treated as symbolic objects, and that their types can change. Values can come from constants, from computation involving values of other variables, or from the output of a function.

2.5 Simulink

Simulink is built on top of MATLAB, so a user must have MATLAB to use Simulink. It is included in the Student Edition of MATLAB, and is also available separately from the MathWorks, Inc. Simulink adds graphical multi-domain simulation and Model-Based Design for dynamic and embedded systems in MATLAB application.

Simulink provides a graphical user interface that uses various types of elements called blocks to create a simulation of a dynamic system that is a system that can be modeled with differential or difference equations whose independent variable is time [22]. The Simulink graphical interface allows the user to position the blocks, resize, label and specify block parameters, and interconnect the blocks to describe complicated systems for simulation. The applications of Simulink include communications, controls, signal processing and image processing.

CHAPTER 3
METHODOLOGY

The previous chapter gives detail on the literature review and the basic fundamental of this project. This chapter will provide the method used to complete this project. Methodology covers the procedure identification, the activities of the project based on the time line, key milestone and the Gantt chart, not to forget the tools and equipment utilized throughout the course of completing this project.

3.1 Procedure Identification

This project was started by collecting the related data for the literature review as well as getting the clear understanding on the controller used for the motion control system. Figure 6 shows the flowchart of the project.

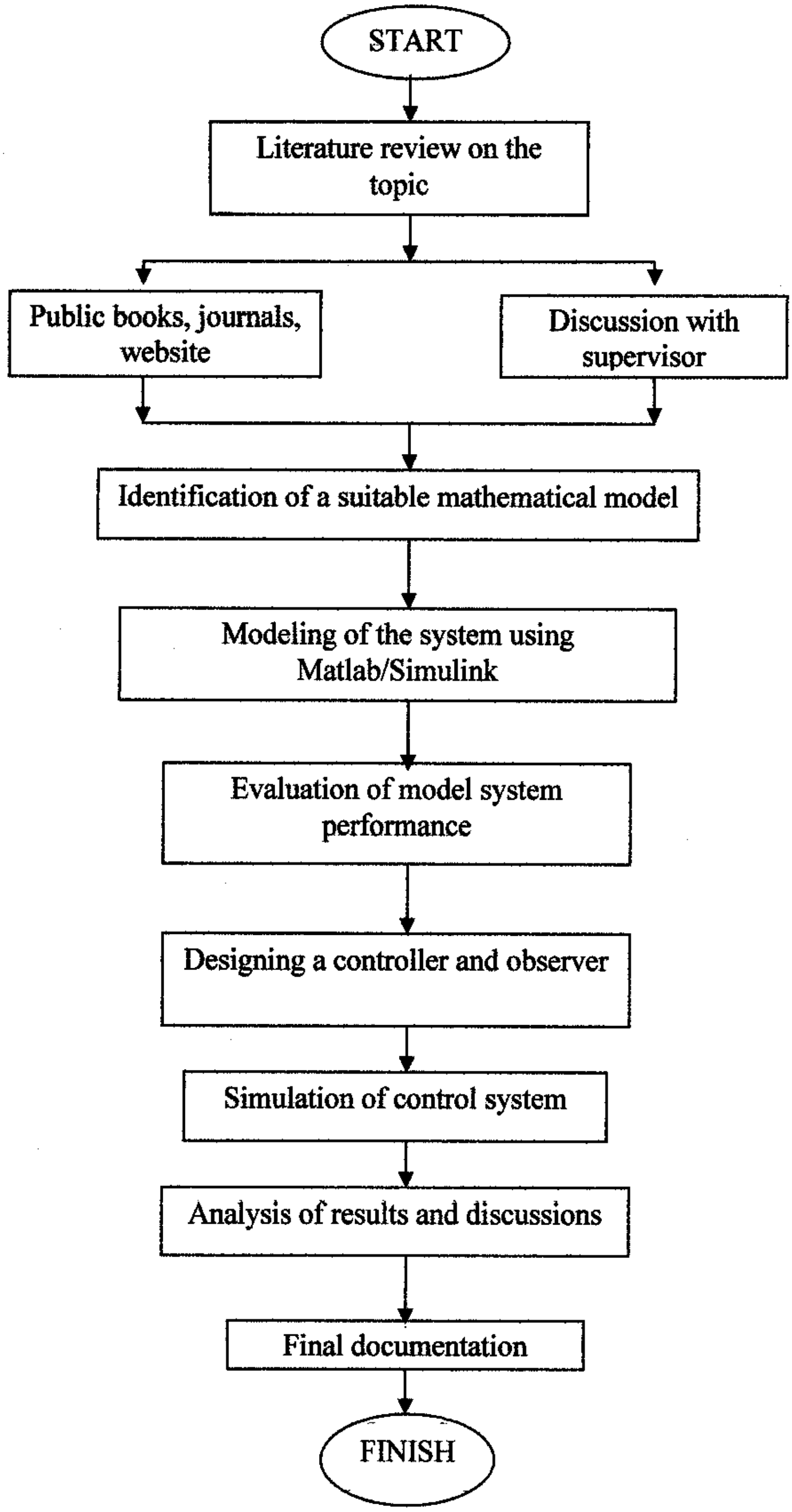

Figure 6: Project flow chart

3.2 Project Activities

Based on Figure 6, in order to achieve the objectives of this project, research and studies had been done on the motion control system, state-space representation and various controller designs which are relevant and applicable to this project. The purpose of this step is to understand the basic concepts of this topic. Thorough researches were done through internet, public books and journals to collect all available information.

All the accumulated information is analyzed to determine the most suitable approaches that can be used for analyzing controller via Matlab and Simulink. The most suitable equation using state-space approach is used in this project to make sure the best controller is to be produced.

By having the suitable equation to be implemented, the motion control system can be modeled via MATLAB/Simulink with Control System Tool Box. The modeling is then evaluated to see the motion control system performance.

Later, the controller and observer poles and gains are determined based on the model parameters, which then are used to design the controller and the observer of motion control system. The designed controller and observer are then simulated on different system types using Simulink to observe their response. Simulation is done to analyze the system performance of the motion control system.

Analysis and discussion are put into action to see how the system achieves its objectives. The end result is expected to be better than previous system performance. The conclusion and some improvement of this project will be recommended at the end of the documentation.

A Gantt chart is prepared for the completion and time management of this project based on the academic schedule and FYP guidelines (refer to APPENDIX A).

3.3 MATLAB/Simulink Simulation

This project is mainly based on the research, analysis and simulation work. The modeling and the simulation is done using MATLAB/Simulink with Control System Tools Box. Hence, all the Simulink diagram, waveforms and results from the Simulink simulation will be observed, shown and analyzed.

3.4 Analysis Performance

After all the diagram and the waveform results are implemented using Simulink, the comprehensive analysis will be done to see the outcome of this project. This is the stage to prove that the implementation of this project will meet its primary objective.

3.5 Controllability

To find controllability of the system, two methods are applicable. The controllability of the system is important as it stated that an input is available and brings any initial state to any desired final state.

Method 1

A system is found to be controllable if and only if the state representation has *n x m* matrix of $M_c = \lfloor B\, AB\, A^2B....A^{n-1}B \rfloor$ with rank *n*.

n = numbers of independent rows and columns.

Method 2

Controllable can be found by using the controllability matrix form:

$$\det|M_c| = \det[B \quad AB] \neq 0 \tag{3.1}$$

3.6 Observability

To find observability of the system, there are two methods that are applicable. The observability is crucial as knowing an output trajectory provides enough information to predict the initial state of the system.

Method 1

A system is found to be observable if and only if the state representation has *n x m* matrix of $M_o = \left[C^T \; A^T C^T \; A^{2T} C^T \ldots . A^{(n-1)T} C^T\right]$ with rank *n*.

n = numbers of independent rows and columns.

Method 2

Observability can be found by using the observability matrix form:

$$\det\left|M_o\right| = \det\left[C^T \quad A^T C^T\right] \neq 0 \tag{3.2}$$

3.7 Ackerman's Formula for Pole Placement Technique

This technique is used to find the state feedback gain, *K*, in order to develop the state feedback controller, $u = -Kx + Nv$ [23]. The procedure is as follows:

- Find the controllability matrix, M_c.
- Find the inverse of M_c, $M_c^{-1} = \dfrac{adj\, M_c}{\det M_c}$.
- Find q_i which refers to the last row of M_c inverse.
- Solve for the state feedback gain, *K*, where $K = q_i \alpha_c(A)$, and $\alpha_c(s)$ is the desired characteristic polynomial of the system.

Constant state feedback gain, K, exists only if the open-loop system is controllable. To calculate the state feed forward gain, N, following formula is used:

$$N = N_U + kN_X$$
$$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{3.3}$$

And the state feedback controller is found using:

$$u = -Kx + Nv \tag{3.4}$$

3.8 Full State Observer Design

If the original system is completely stable, then it is always possible to find the feedback gain matrix, L, which will give any set of desired eigenvalues for $(A - LC)$ in order to design the full state observer. Full state observer has the form,

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + Lz \\ \hat{y} &= C\hat{x} + Du \\ z &= y - \hat{y} = Cx - C\hat{x} \end{aligned} \tag{3.5}$$

To find L:

- First, find $A - LC$ where $L = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}$.
- Calculate $|\lambda I - (A - LC)|$.
- Calculate the actual characteristic equation using $\det|\lambda I - (A - LC)| = 0$.
- Find the desired characteristic equation using desired eigenvalues.
- Match the coefficients of the desired and actual characteristic equation to find L.

3.9 Tools and Equipment Used

We have chosen to use the following software for the purpose of this project which is MATLAB/Simulink. Simulink is built on top of the MATLAB, so MATLAB is needed to use Simulink. This software is chosen because it is a widely used tool in the engineering community. This software which includes a graphical user interface is easy to be used. It can be used for simple mathematical manipulations with matrices, for understanding and teaching basic mathematical and engineering concepts. This software greatly simplifies numerical calculations and graphs the results without complicated programming.

3.9.1 MATLAB

It is important to understand the functions and procedure on how to use MATLAB. In this project, MATLAB represents the software computation that is used to compare the calculations and results between computer calculations and manual calculations which is using the formulas. This is because, some sections in this project discussions apply two methods to calculate output results, either by using MATLAB coding or using the associated formulas. Hence, the compatibility and accuracy of the methods used can be discovered.

3.9.2 Simulink

Simulink is used to design, model and simulate the dynamic system that comes into view in this project. The Simulink diagram also called the block diagram is developed using Simulink. Simulink provides a graphical user interface that uses various types of elements called blocks to create a simulation of a dynamic system. The block diagram is built, and then simulated before the output response can be monitored using a scope. It can be seen that Simulink software application is broadly used throughout this documentation.

CHAPTER 4

RESULTS AND DISCUSSION

In the previous chapter, the methodology to deliver this project has been discussed. This chapter will discuss the outcomes of every stage and phase of the project. This chapter will cover results obtained from the simulation of the modeling of motion control system. The results of this simulation method will be displayed and the analysis of the results will be discussed throughout this chapter.

4.1 Modeling of the system

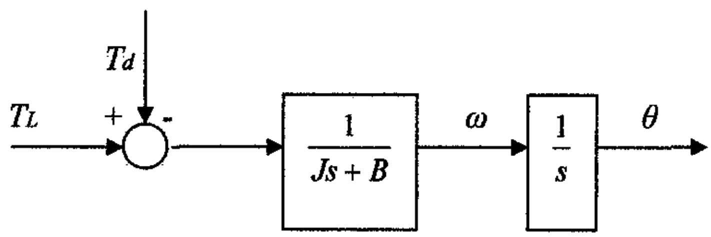

Figure 7: Model of mechanical system

The mechanical system is shown in Figure 7 and the dynamic torque equations for a motor are expressed by

$$J\frac{d\omega}{dt} + B \cdot \omega + T_d = T_L \tag{4.1}$$

$$\frac{d\theta}{dt} = \omega \tag{4.2}$$

Where;

ω = mechanical angular velocity or speed, in radians/second

θ = mechanical angular position, in radians

J = moment of inertia, in kg-m^2

B = viscous damping coefficient, in Nm/rad/s

T_L = load torque, in Nm

T_d = disturbance external torque, in Nm

In Figure 7, there are two inputs to the motor drive which are the generated torque T_L and the external disturbance torque T_d. Both of these inputs affect motor response. Motor torque can be measured via current feedback with good accuracy, but the external disturbance cannot be measured directly. T_d is introduced as an augmented state variable, and it is assumed that the load torque is a constant value and its derivative is zero.

$$T_d = 0 \tag{4.3}$$

So, rearrange equation (4.1);

$$\frac{d\omega}{dt} = -\frac{B}{J}\omega + \frac{1}{J}T_L \tag{4.4}$$

The general vector-matrix form of the state space model is:

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx + Du \end{aligned} \tag{4.5}$$

Where x is the state vector equation and y is the output equation. The state vector equation consists of two state variables which are θ and ω, and one input variable, T_L, so the vector-matrix will be in the form:

$$\begin{bmatrix} \dot{\theta} \\ - \\ \dot{\omega} \end{bmatrix} = A \begin{bmatrix} \theta \\ - \\ \omega \end{bmatrix} + B(T_L),$$
$$y = C \begin{bmatrix} \theta \\ - \\ \omega \end{bmatrix} + D(T_L) \tag{4.6}$$

The first row of A and the first row of B are the coefficients of the first state equation, $\dot{\theta}$ (equation 4.2). Likewise the second row of A and the second row of B are the coefficients of the second state equation, $\dot{\omega}$ (equation 4.4). C and D are the coefficients of the output equation, y [24]. This yield:

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{B}{J} \end{bmatrix} \begin{bmatrix} \theta \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{1}{J} \end{bmatrix} T_L$$
$$T = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ - \\ \omega \end{bmatrix} + 0(T_L) \tag{4.7}$$

Therefore

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{B}{J} \end{bmatrix}$$
$$B = \begin{bmatrix} 0 \\ \dfrac{1}{J} \end{bmatrix} \tag{4.8}$$
$$C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$
$$D = [0]$$

In order to enter a state space model into MATLAB, the variables must be given a numerical value, because MATLAB cannot manipulate symbolic variables. Thus, reasonable parameters for this equation were chosen as:

$B = 4$ Nm/rad/s; $J = 1$ kg-m^2.

Therefore, (4.7) can be rewritten as

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix} \begin{bmatrix} \theta \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} T_L$$
$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \overline{\omega} \end{bmatrix} \tag{4.9}$$

The input variable is the generated torque, the state variables are the mechanical angular position and the speed, and the output variable is the mechanical angular position.

4.2 Building Model in MATLAB

The state-space matrix (4.7) to be evaluated is:

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix} \begin{bmatrix} \theta \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} T_L$$
$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \overline{\omega} \end{bmatrix}$$

In order to get the mechanical angular position graphs with respect to time, we have to find the transfer function of the system. Based on the pre-determined equation, the state space model above is transferred to a transfer function model using two methods namely the command window in MATLAB and the transfer function matrix. To obtain the transfer function, the above equation is utilized as below:

Method 1: Using MATLAB Command Window

```
>> A=[0 1;0 -4];
>> B=[0 1]';
>> C=[1 0];
>> D=0;
>> T=ss(A,B,C,D);
>> T=tf(T)

Transfer function:
   1
----------
s^2 + 4 s
```

Method 2: Using Transfer Function Matrix Formula

Formula of transfer function matrix is;

$$G(s) = C(sI - A)^{-1}B + D \tag{4.10}$$

By putting the coefficients from equation (4.7) into (4.10), this yields:

$$\begin{aligned} A &= \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix} \quad ; \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\ C &= \begin{bmatrix} 1 & 0 \end{bmatrix} \quad ; \quad D = [0] \\ sI &= \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} \end{aligned} \tag{4.11}$$

$$\begin{aligned} G(s) &= \begin{bmatrix} 1 & 0 \end{bmatrix} \left(\begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix} \right)^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} + 0 \\ G(s) &= \begin{bmatrix} 1 & 0 \end{bmatrix} \left(\frac{\begin{bmatrix} s+4 & 1 \\ 0 & s \end{bmatrix}}{s^2 + 4s} \right) \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\ G(s) &= \frac{1}{s^2 + 4s} \end{aligned} \tag{4.12}$$

The results from methods 1 and 2 are clearly compatible to each other. Thus, the transfer function of this motion control system is:

$$G(s) = \frac{1}{s^2 + 4s} \tag{4.13}$$

Here in this project, we are considering the mechanical angular position of motion control system.

4.3 Simulation of the System

Simulink diagram is built based on the state space matrix from equation (4.7) as shown in Figure 8.

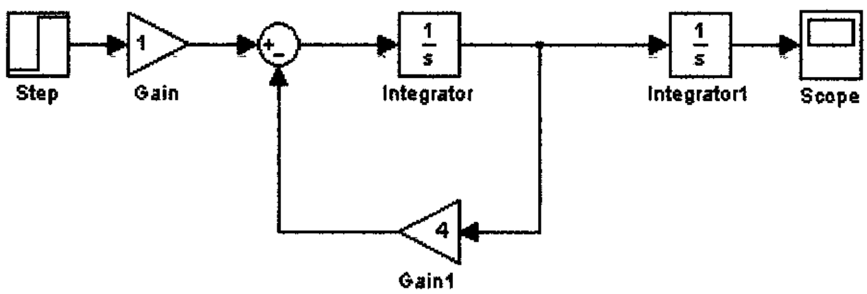

Figure 8: State space simulink diagram

Simulink diagram is also built based on the transfer function obtained from equation (4.13) as shown in Figure 9.

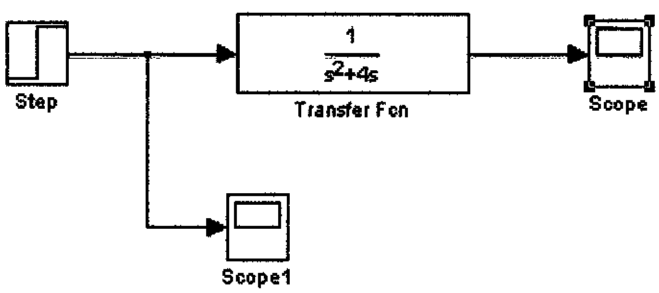

Figure 9: Transfer function simulink diagram

Both models are then simulated in the same stage at the same time to see their responses as shown in Figure 10.

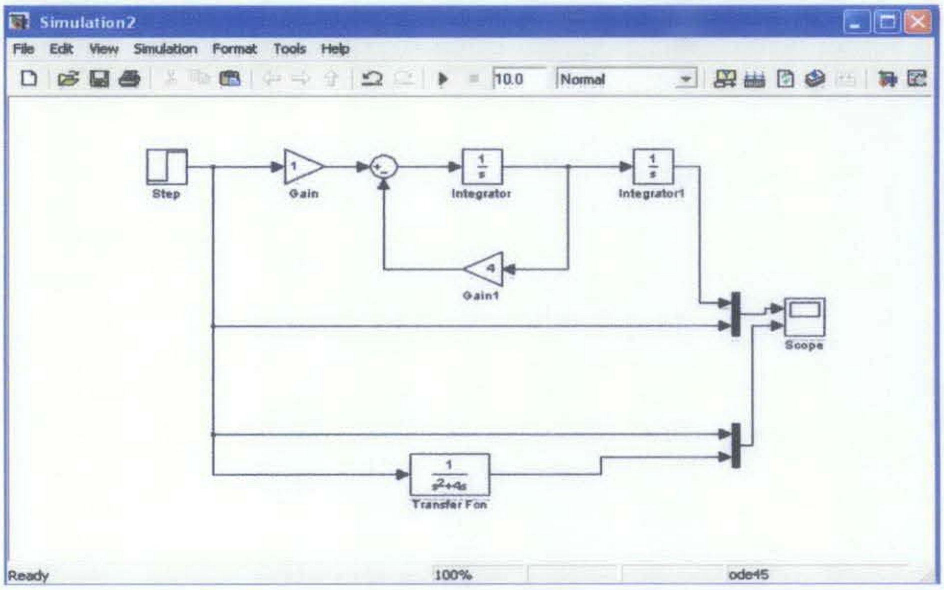

Figure 10: Simulation diagram of state space and transfer function

The output of transfer function representation is fed to a scope for monitoring purpose. A unit step input as shown in Figure 11 is applied and the monitored output is as shown in Figure 12.

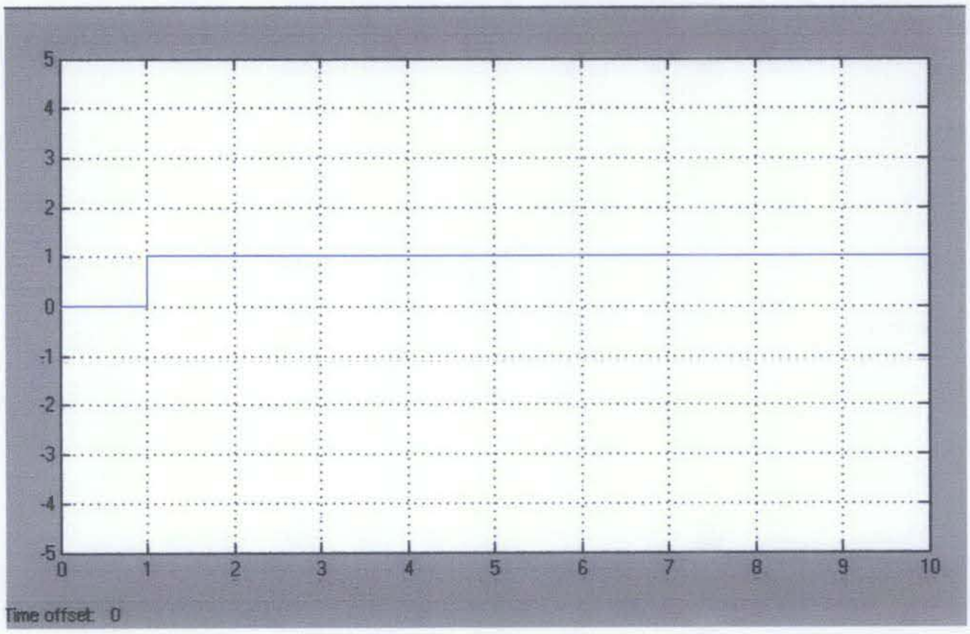

Figure 11: Step input

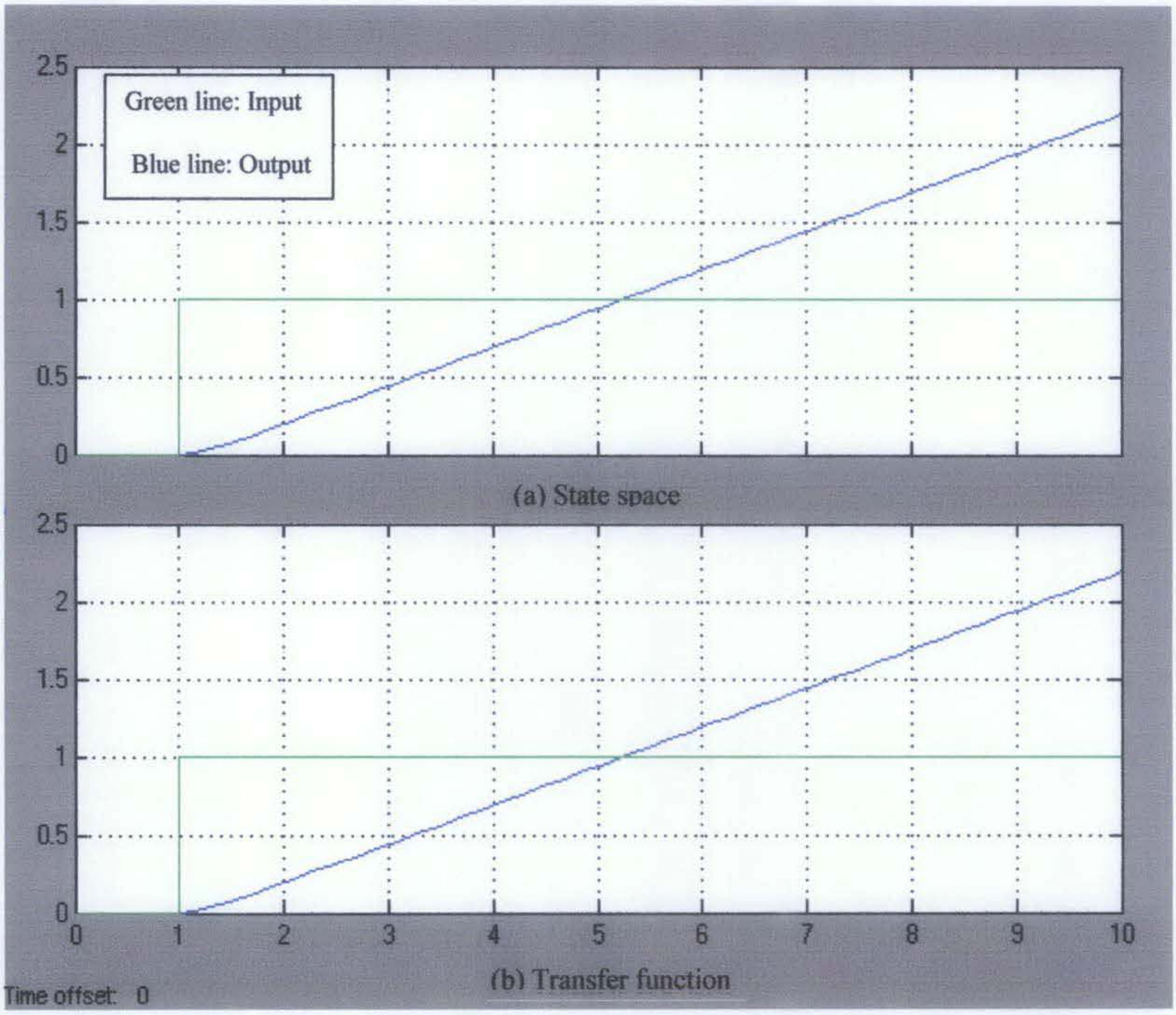

Figure 12: The output response of simulation using (a) state space; (b) transfer function

As can be seen in Figure 12, both models produce the same result. It is shown that both increasing lines indicate that the system is unstable in open loop. It is obvious from this plot that some sort of control will have to be designed to improve the dynamics of the system. When step input is applied to the system, the angular position is linearly increasing with respect to time and it has no overshoot, no settling time and the rise time of the response is 1.2 sec. However, to make sure that the state feedback can be designed, the controllability and observability of the system need to be examined using MATLAB.

4.3.1 Controllability

The controllability of the system is important as it describes that an input is available and brings any initial state to any desired final state. Check on system controllability is performed as below:

Method 1: Using MATLAB Command Window

```
>> A=[0 1;0 -4];
>> B=[0 1]';
>> C=[1 0];
>> D=0;
>> m=ctrb(A,B)

m =
    0    1
    1   -2

>> rankm=rank(m)

rankm =
    2
```

The system is of rank 2 and is found to be controllable.

Method 2: Using Controllability Matrix

$$A=\begin{bmatrix}0 & 1\\ 0 & -4\end{bmatrix}\ ;\ B=\begin{bmatrix}0\\ 1\end{bmatrix}$$

$$AB=\begin{bmatrix}1\\ -4\end{bmatrix}$$

$$M_c=[B \quad AB]=\begin{bmatrix}0 & 1\\ 1 & -4\end{bmatrix}$$

$$\det M_c=\det\begin{bmatrix}0 & 1\\ 1 & -4\end{bmatrix}=-1\neq 0$$

Thus, the system is controllable.

4.3.2 Observability

Observability is crucial as knowing an output trajectory provides enough information to predict the initial state of the system. Check on the system observability is performed as below:

Method 1: Using MATLAB Command Window

```
>> A=[0 1;0 -4];
>> B=[0 1]';
>> C=[1 0];
>> D=0;
>> n=obsv(A,C)

n =
    1    0
    0    1

>> rankn=rank(n)

rankm =
    2
```

The system is of rank 2 and is found to be observable.

Method 2: Using Observability Matrix

$$A=\begin{bmatrix}0 & 1\\ 0 & -4\end{bmatrix} \;;\; C=\begin{bmatrix}1 & 0\end{bmatrix}$$

$$A^T C^T=\begin{bmatrix}0 & 0\\ 1 & -4\end{bmatrix}\begin{bmatrix}1\\ 0\end{bmatrix}$$

$$M_O=\begin{bmatrix}C^T & A^T C^T\end{bmatrix}=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$$

$$\det M_c=\det\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}=1\neq 0$$

The system is controllable. Thus, the system is controllable and observable and state feedback loop can be designed.

4.4 Feedback Controller

To develop a controller, we need first to find the state feedback gain, K, and the state feed forward gain, N, of the system. A feedback control system is valuable because it provides the ability to adjust the transient response, reduce the sensitivity of the system and the effect of disturbances. A controller can be designed to specifications only if the system is controllable.

4.4.1 State feedback gain, K

The purpose of adding feedback is to improve the system characteristics or transient response such as settling time, overshoot and rise time. The state feedback controller of controller design for linear system is of the form:

$$u = -Kx + Nv$$

Since the system is controllable, state feedback gain, K, can be calculated using the Auckerman's formula for Pole Placement technique.
From the controllability matrix, we have

$$M_c = [B \quad AB] = \begin{bmatrix} 0 & 1 \\ 1 & -4 \end{bmatrix}$$

$$M_c^{-1} = \frac{adj\, M_c}{\det M_c} = -1\begin{bmatrix} -4 & -1 \\ -1 & 0 \end{bmatrix} = \begin{bmatrix} 4 & 1 \\ 1 & 0 \end{bmatrix}$$

$$q_i = [1 \quad 0]$$

Suppose the criteria for this controller were settling time < 2 sec and overshoot < 22%. Assuming the poles of the closed loop system are at -2.5+j5, -2.5-j5. The desired characteristic polynomial is:

$$\alpha_c(s) = (s + 2.5 + j5)(s + 2.5 - j5) = s^2 + 5s + 31.25$$

$$\alpha_c(A) = A^2 + 5A + 31.25I$$

$$K = q_l \alpha_c(A) = q_l \left\{ \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix}^2 \right\} + 5 \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix} + \begin{bmatrix} 31.25 & 0 \\ 0 & 31.25 \end{bmatrix}$$

$$= q_l \left\{ \begin{bmatrix} 31.25 & 1 \\ 0 & 27.25 \end{bmatrix} \right\}$$

$$= \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} 31.25 & 1 \\ 0 & 27.25 \end{bmatrix}$$

$$K = \begin{bmatrix} 31.25 & 1 \end{bmatrix}$$

4.4.2 State feed forward gain, N

The purpose of adding the feed forward is to eliminate the steady state error. State feed forward gain, *N*, is calculated using:

$$N = N_U + kN_X$$

$$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -4 & 1 \\ 1 & 0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} N_X \\ N_U \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 4 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$[N_X] = \begin{bmatrix} 1 \\ 0 \end{bmatrix} and [N_U] = [0]$$

$$N = N_U + kN_X = 0 + \begin{bmatrix} 31.25 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$N = 31.25$$

Thus, the state feedback controller, $u = -Kx + Nv = -\begin{bmatrix} 31.25 & 1 \end{bmatrix} x + 31.25v$

After determining the state feedback gain and feed forward gain, the feedback controller model is then created and designed using Simulink as shown in Figure 13.

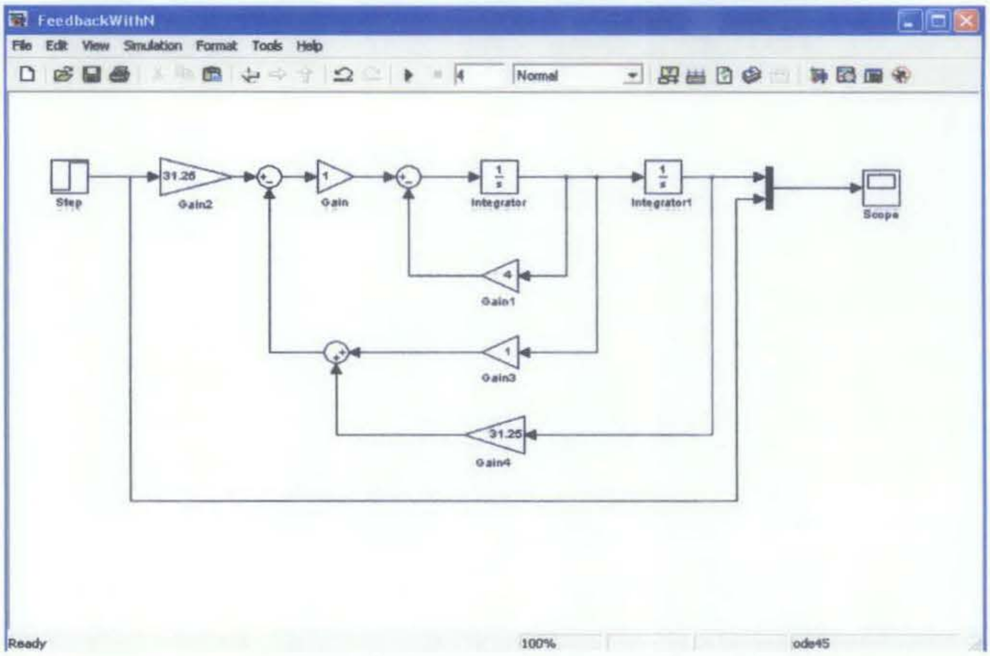

Figure 13: Simulink diagram of feedback controller

The following blue line in Figure 14 shows the response of angular position with respect to time using the feedback controller with state forward gain.

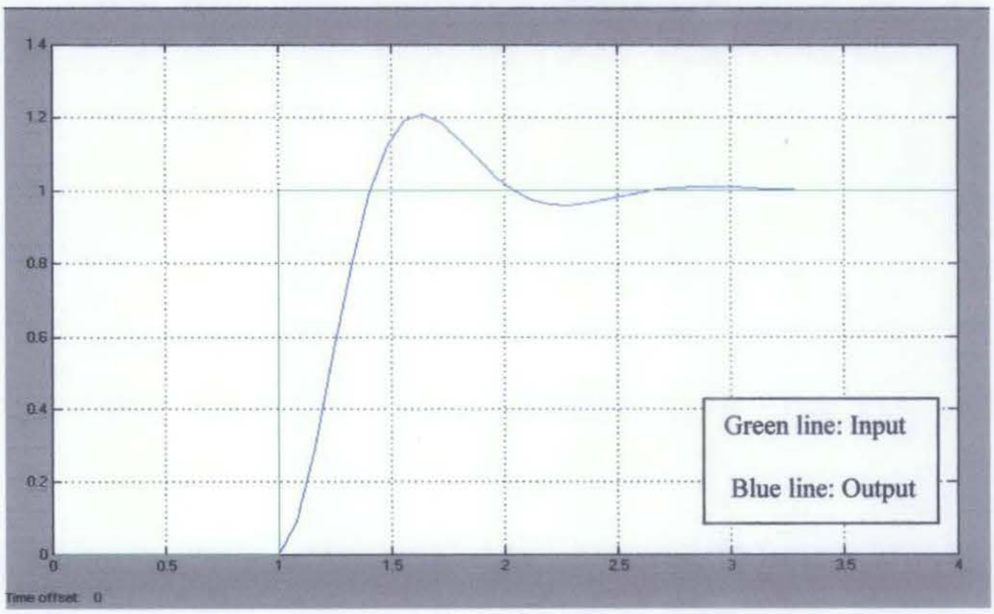

Figure 14: Output response of feedback controller

Then, the model is being simulated without the state feed forward gain as shown in Figure 15. This model is designed to see the differences and the effect of not having the state feed forward gain in the system.

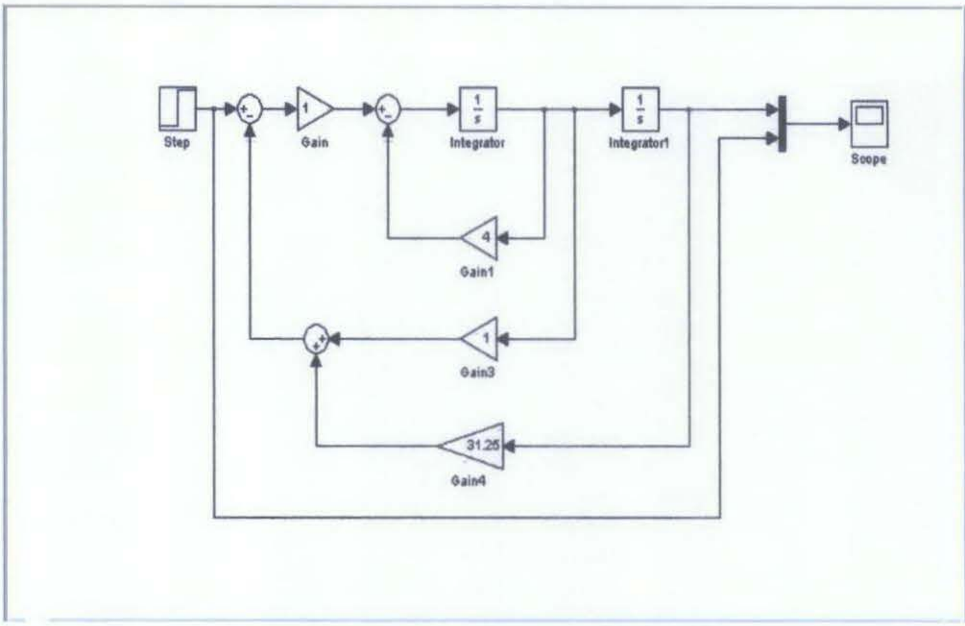

Figure 15: Feedback controller without feed forward gain

The blue line in Figure 16 shows the system response of angular position with respect to time by excluding the state feed forward gain in the system.

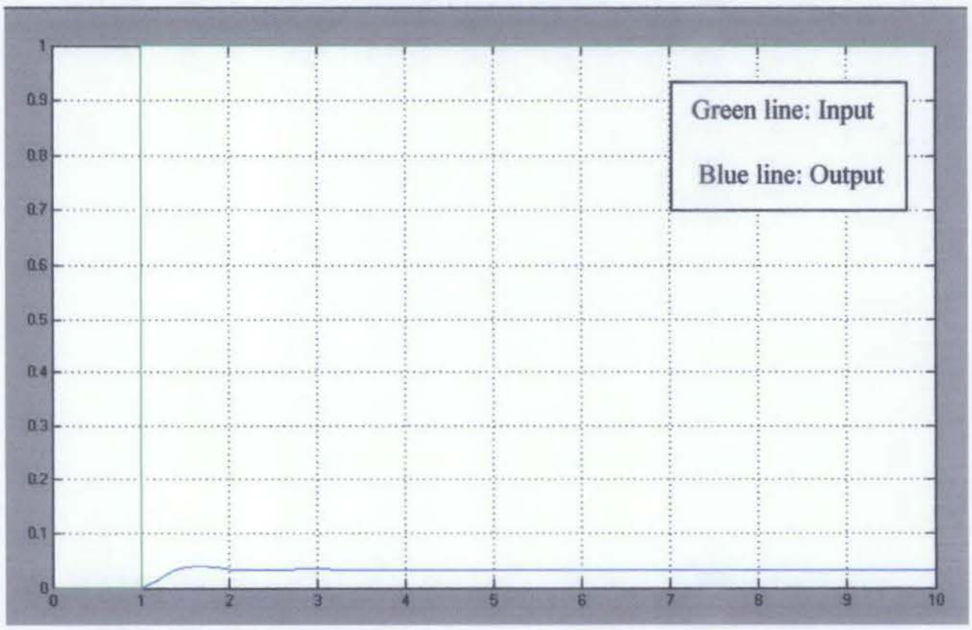

Figure 16: Output response of feedback controller without feed forward gain

4.4.3 Analysis of feedback controller simulation

From Figure 14, the mechanical angular position response with respect to time with feed forward gain is more stable compared with the system response without the feed forward gain. The behavior shown in Figure 14 is underdamped second order systems. The underdamped second order system is a common model for physical problems which displays unique behavior. Transient specifications associated with underdamped responses are percent overshoot, settling time and peak time. Underdamped is a stable response because it has lower overshoot, short settling time and little oscillation. By adding the feed forward gain, the steady state error can be reduced or eliminated where it helps to stabilize the system. Settling time is the time required for the transient's damped oscillations to reach and stay within the steady state value. Peak time is the time required to reach the first or maximum peak, and percent overshoot is the amount that the waveform overshoots the steady state, expressed as a percentage of the steady state value. The settling time, peak time and overshoot percentage can be calculated from the system response.

Method 1: Using Second-order underdamped response specifications

From the second order underdamped response specifications in Figure 17, the transient response of simulation in Figure 14 can be calculated as follows:

Settling time = $T_s = 2.63 - 1.0 = 1.63$ sec

Peak time = $T_p = 1.625 - 1.0 = 0.625$ sec

$$\%\ \text{Overshoot} = \frac{c_{\max} - c_{final}}{c_{final}} \times 100 = \frac{1.20 - 1.00}{1.00} \times 100 = 20.0\%$$

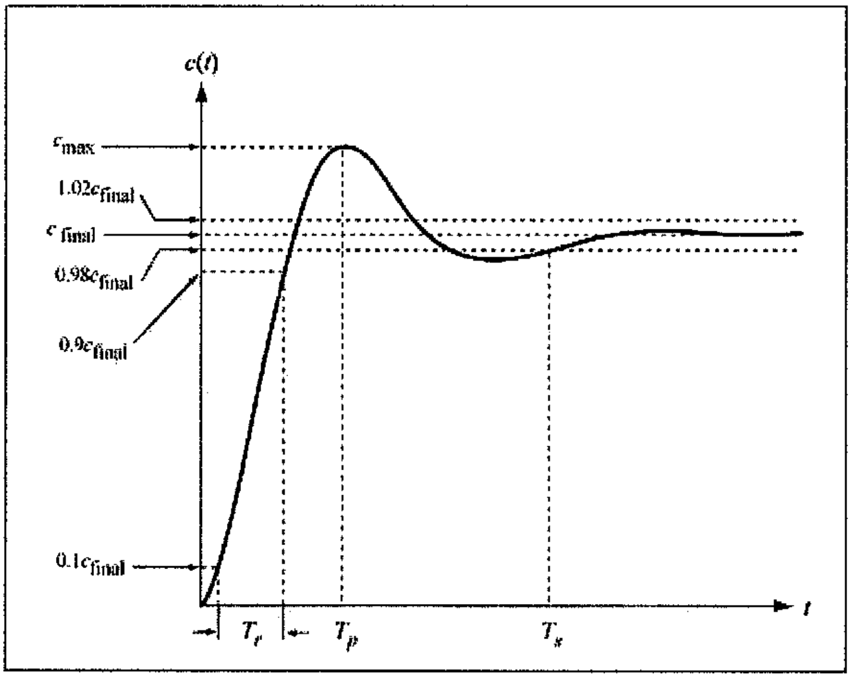

Figure 17: Second-order underdamped response specifications

Method 2: Using formula of underdamped second order system

Poles = $-\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2} = -2.5 \pm j5$

So, $\zeta\omega_n = 2.5\, and\;\; j\omega_n\sqrt{1-\zeta^2} = j5$

$$\omega_n = \frac{2.5}{\zeta} and\, \omega_n = \frac{5}{\sqrt{1-\zeta^2}};$$

So, we get $\zeta = 0.447\, and\, \omega_n = 5.593$

$$T_S = \frac{4}{\zeta\omega_n} = \frac{4}{(0.447)(5.593)} = 1.6\,\mathrm{sec}$$

$$T_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} = \frac{\pi}{5.593\sqrt{1-(0.447)^2}} = 0.63\,\mathrm{sec}$$

$$\%\,Overshoot = e^{-(\zeta\Pi/\sqrt{1-\zeta^2})} \times 100$$
$$= e^{-1.56986} \times 100$$
$$= 21\%$$

The analysis shows that the result of method 1 is compatible with the result of method 2; thus, the system is acceptable for the feedback controller design. The desired poles for feedback controller system are -2.5+j5 and -2.5-j5. Figure 14 shows that the system response is having a small percent overshoot and less oscillation before it reaches its steady state. Compared to Figure 16, the system response does not reach the steady state at all. Thus, the feed forward gain has significant impact in designing a good controller as it helps to reduce the steady state error.

4.5 Full State Observer

To develop a full state observer, we need first to find the feedback gain matrix, *L*, of the system. Observer is used to estimate the states since not all state variables are measurable. The feedback gain matrix can be found if the original system is completely observable.

To design the observer for continuous time system, the poles must be at least five times far towards the LHP side than the closed loop poles chosen previously (-2.5+j5, -2.5-j5). Now, we assume the poles are located at $-15 \pm j5$.

Using the variables below, $(A-LC)$ can be found.

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix} \; ; \; L = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}$$
$$C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

The eigenvalues of matrix $(A-LC)$;

$$A - LC = \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix} - \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \end{bmatrix}$$
$$= \begin{bmatrix} 0 & 1 \\ 0 & -4 \end{bmatrix} - \begin{bmatrix} l_1 & 0 \\ l_2 & 0 \end{bmatrix} = \begin{bmatrix} -l_1 & 1 \\ -l_2 & -4 \end{bmatrix}$$

Hence, the actual observer characteristic equation is;

$$|\lambda I - (A - LC)| = 0$$

$$|\lambda I - (A - LC)| = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} - \begin{bmatrix} -l_1 & 0 \\ -l_2 & 0 \end{bmatrix} = \begin{bmatrix} \lambda + l_1 & -1 \\ l_2 & \lambda + 4 \end{bmatrix}$$

By finding the determinant of the above equation, we get,

$$\lambda^2 + (4 + l_1)\lambda + (4l_1 + l_2) = 0$$

For the desired eigenvalues of $-15 \pm j5$, the desired characteristic equation is:

$$\lambda^2 + 30\lambda + 250 = 0$$

Matching the coefficients of the desired and actual characteristic equation gives,

$$L = \begin{bmatrix} 26 \\ 146 \end{bmatrix}$$

By having the feedback gain, *L*, the full state observer is then designed and simulated using Simulink as shown in Figure 18.

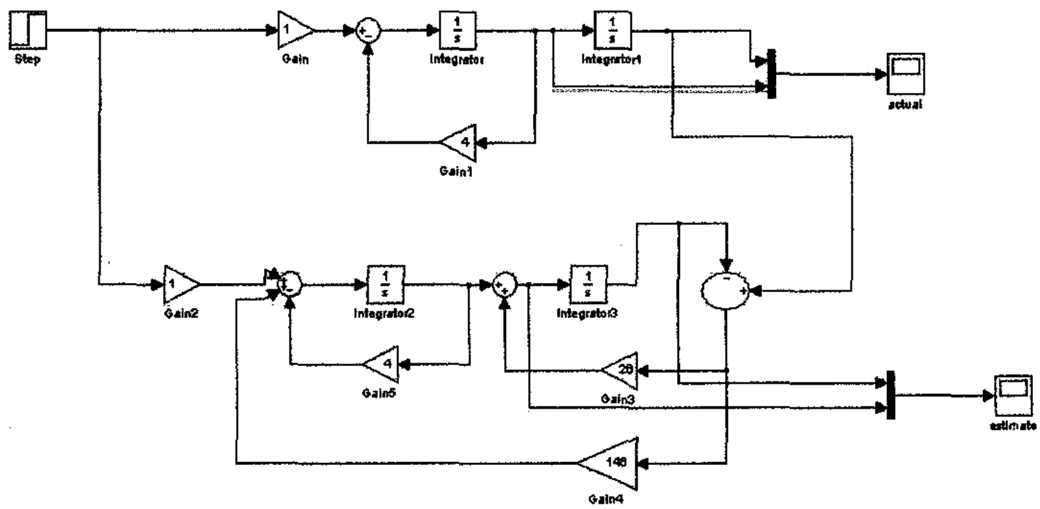

Figure 18: Full state observer in Simulink

The observer is basically a copy of the plant; it has the same input and almost the same differential equation. An extra term compares the actual measured output y to the estimated output, $\hat{y}$, this will cause the estimated states , $\hat{x}$, to approach the values of the actual states x.

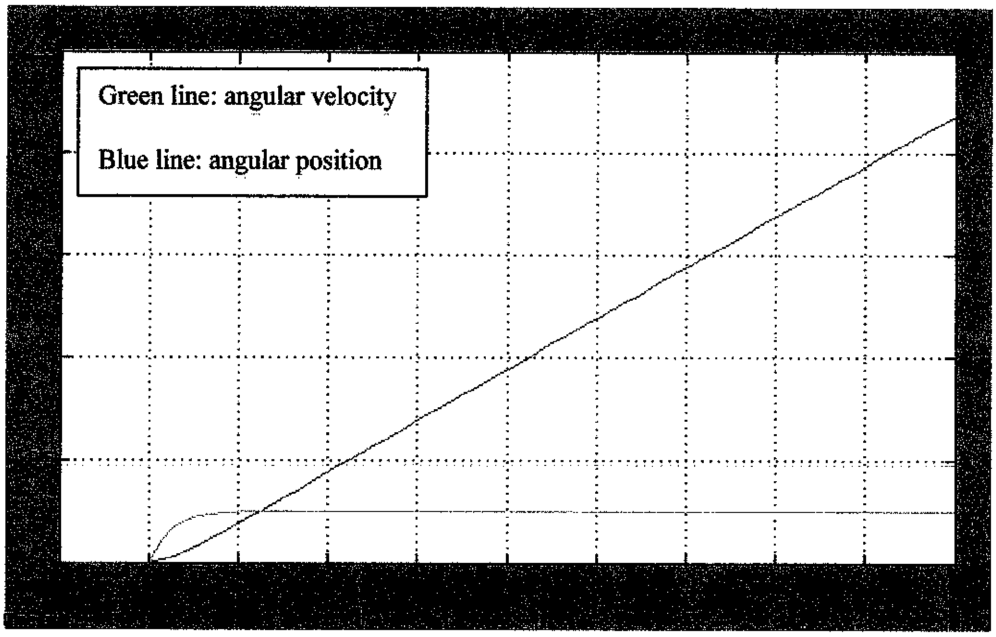

Figure 19: Output response of full state observer at actual scope (actual state)

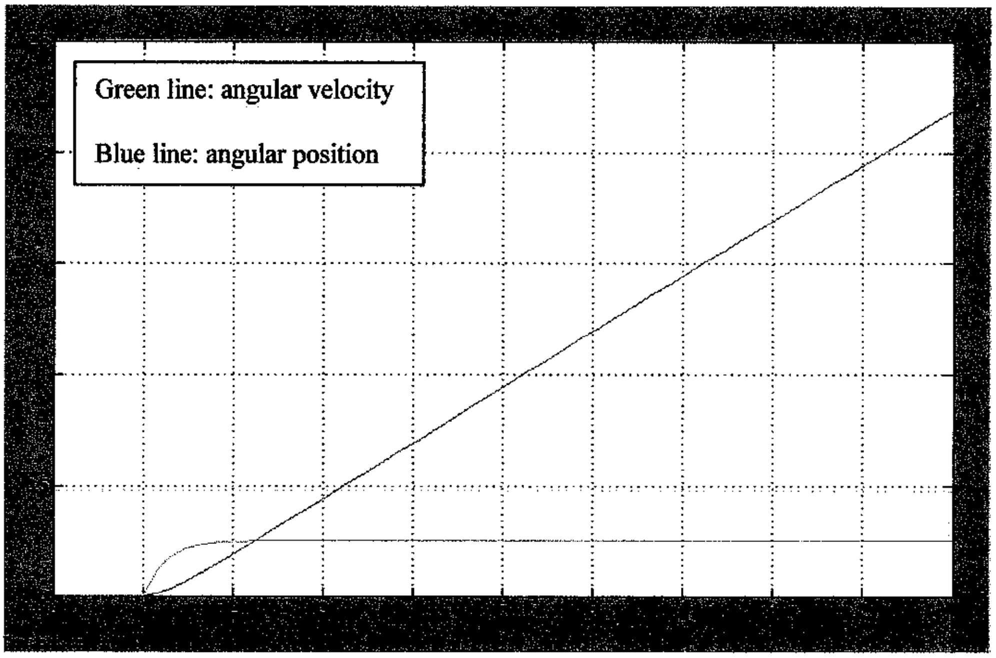

Figure 20: Output response of full state observer at estimate scope (estimated state)

Figure 19 and 20 show the simulation result for full state observer. The blue line indicates the mechanical angular position with respect to time, and the green line indicates the mechanical angular velocity with respect to time. The output response of the system for using the exact closed-loop pole positions is slow and with large overshoot. However, as the observer pole positions moves further from the origin (more negative poles) than the closed-loop poles, we notice that the performance of the observer is getting almost nearer to the real system without observer.

4.5.1 Full state observer with feedback controller

Next, the full order state design in the previous section will be modeled with the feedback gain, *K*. The representation of full state is built with the plant state space equation and combined with the state feedback controller equation. Figure 21 shows the full state observer with feedback gains controller.

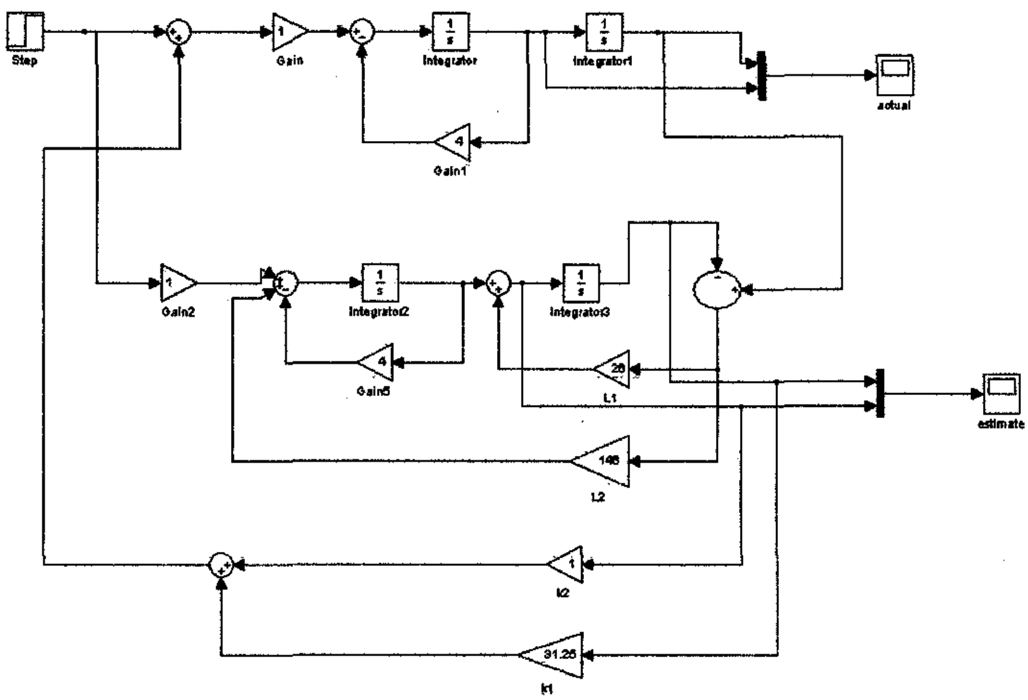

Figure 21: Full state observer with feedback gains in Simulink

Based on the simulation diagram in Figure 21, the simulation is done through both scopes which are actual scope for the actual state, and estimate scope for the estimated state.

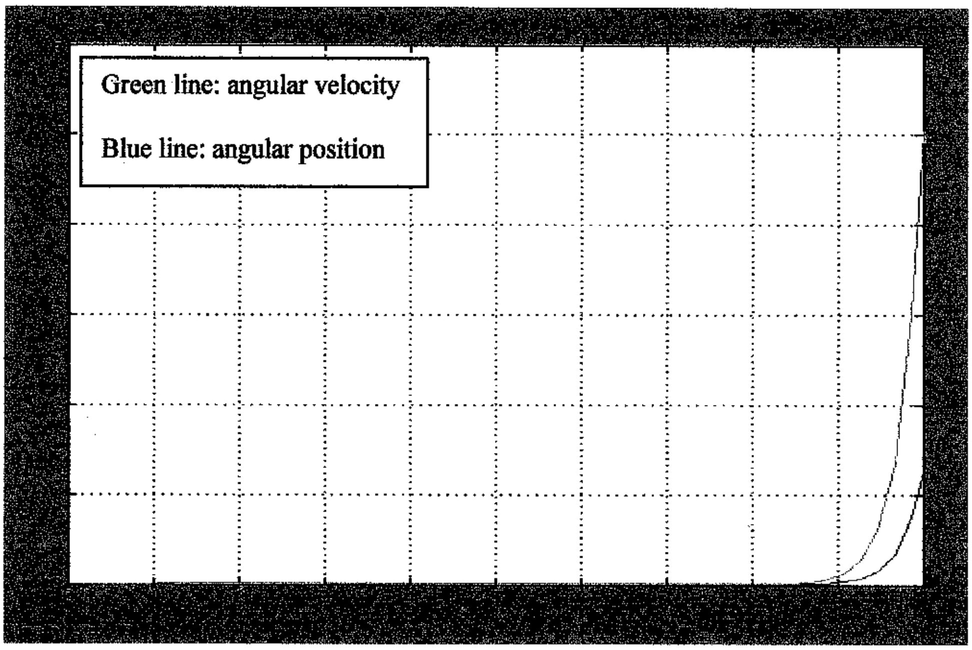

Figure 22: Output response of full state observer with feedback controller for actual state

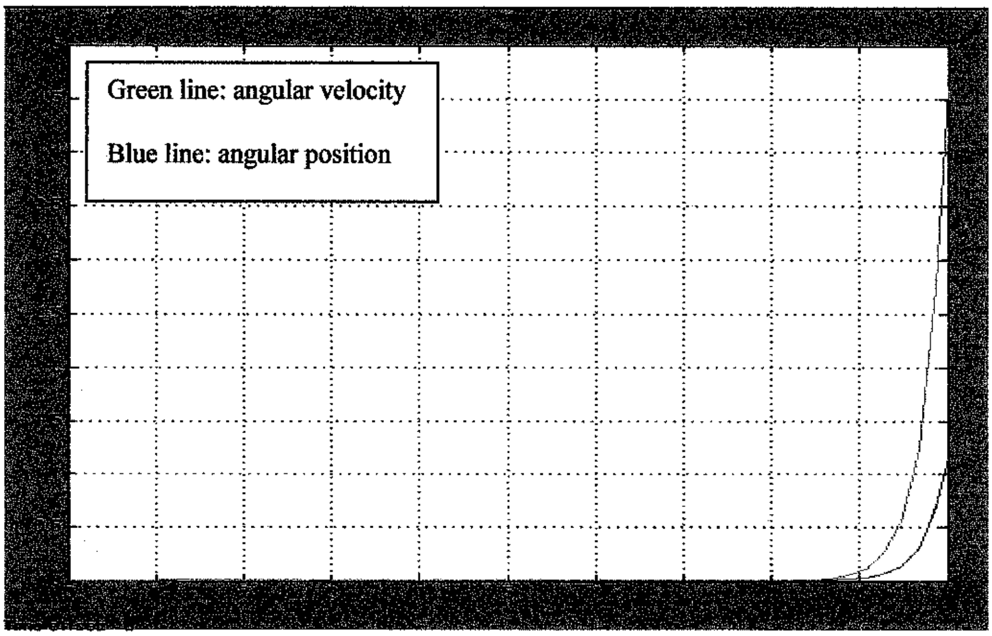

Figure 23: Output response of full state observer with feedback controller for estimated state

Figures 22 and 23 show the output responses of full state observer with feedback controller. The blue line and green line indicate the mechanical angular position and mechanical angular velocity respectively with respect to time. It can be seen that the responses of both variables for the estimated states in Figure 23 are tracking the responses of the actual states in Figure 22. So, observer design with feedback controller design is possible to be implemented in order to improve the stability, controllability and observability to be used in motion control system.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In this chapter, the overall conclusions based on the presented work are drawn. Also, possible directions of future work are outlined.

5.1 Conclusion

Motion control systems have a significant impact on the performance of motor response and any motion structures allowing them to perform tasks in motor drive applications. The purpose of this project is to design and analyze controller design that fits motion control system in terms of controllability and stability.

From the knowledge of modern control engineering course, design and analysis of a controller is performed from the mathematical modeling until the Simulink simulation . A controller for motion control system was successfully modeled using MATLAB/Simulink right from the process of choosing the reasonable data until the stage of producing the actual simulated response. The controller and observer were effectively designed using the pole placement method which produced results that indicate the modern control theory used in motion control system. Based on the results from Matlab/Simulink simulation, the details of the characteristics and stability of the system are analyzed and identified.

At the end of the studies, it is expected to produce a design of controller that is better than the previous controller in terms of controllability and stability to control the motion control system and enhance the overall motor system performance.

5.2 Recommendation

After the controller and observer are successfully modeled and simulated in order to produce the desired output, this design can be improved and validated by implementing the controller and observer on actual motion control system. This scope of work is recommended for future work so that the accuracy and the effectiveness of the designed controller and observer can be proven and functional to be as an alternative of the control strategy for motion control system.

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APPENDICES

APPENDIX A

Table A.1: Project Gantt Chart for Final Year Project Part 1

No.	Detail / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	Topic Selection														
2.	Background Study and Problem Statement														
3.	Preliminary Report Submission				X										
4.	Literature Review and Research Work														
5.	Progress Report Submission								X						
6.	Seminar									X					
7.	Methodology and Simulation Study														
8.	Results & Discussion on Project Work														
9.	Interim Report Submission													X	
10.	Oral Presentation														X

Table A.2: Project Gantt Chart for Final Year Project Part 2

No.	Detail / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1.	Study on Simulink/MATLAB Program															
2.	Studies on existing techniques															
3.	Research Work on Simulation															
4.	Work on the simulation															
5.	Progress Report Submission								X							
6.	Continue on Simulation Studies															
7.	Results & Discussions on Project Work															
8.	Concluding the Project Work															
9.	Draft Report Submission													X		
10.	Final Report and Technical Report Submission														X	
11.	Oral/ Viva Presentation															X