OPTIMAL OSCILLATION CONTROL OF AN OVERHEAD CRANE SYSTEM USING INPUT SHAPING CONTROLLER UNDER FIXED AND PAYLOAD HOISTING

RAMONA SHAKIRAH BINTI ABD. MUTALIB

BACHELOR OF ELECTRICAL ENGINEERING WITH HONOURS
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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in partial fulfilment of the requirements for the degree of
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DECLARATION

I declare that this thesis entitled "OPTIMAL OSCILLATION CONTROL OF AN OVERHEAD CRANE SYSTEM USING INPUT SHAPING CONTROLLER UNDER FIXED AND PAYLOAD HOISTING" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature :

Name : RAMONA SHAKIRAH BINTI ABD. MUTALIB

Date : 17/6/2024

APPROVAL

I hereby declare that I have checked this report entitled "OPTIMAL OSCILLATION CONTROL OF AN OVERHEAD CRANE SYSTEM USING INPUT SHAPING CONTROLLER UNDER FIXED AND PAYLOAD HOISTING", and in my opinion, this thesis fulfils the partial requirement to be awarded the degree of Bachelor of Electrical Engineering with Honours.

Signature :

Supervisor Name : TS. DR. HAZRIQ IZZUAN BIN JAAFAR

Date : 17.06.2024

DEDICATIONS

To my beloved lecturers

To my beloved mother and father

To all my family members

To all my friends and classmates

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I would like to take this opportunity to sincerely thank the following people and organisations for their contributions to the accomplishment of my final year project, "**Optimal Oscillation Control of an Overhead Crane System Using Input Shaping Controller Under Fixed and Payload Hoisting**". A special appreciation and thank you I bid to my supervisor, Ts. Dr. Hazriq Izzuan Bin Jaafar for the invaluable guidance, support and mentorship throughout the project. He really contributed a lot to my project and without him, this project would be impossible for me.

The road of finishing this project has been amazing because it has allowed me to learn and experience a lot of new things during the development phase. I also expressed my gratitude to all the researchers worldwide who assisted me in coming up with fresh concepts based on their earlier studies and endeavours.

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ABSTRACT

The implementation of input shaping controllers for optimal oscillation control in an overhead crane system operating under the impact of fixed and payload hoisting are investigated in this project. Overhead crane systems are widely utilised for material handling in industrial settings, but it prones to oscillate and sway during transportation operations, which can compromise both efficiency and safety. To solve this issue, input shaping controller such as Zero Vibration (ZV), Zero Vibration Derivative (ZVD) and Zero Vibration Derivative-Derivative (ZVDD) are proposed as a method of reducing oscillations caused by the dynamic properties of the payload. The controller is also designed to minimize oscillation while maintaning a rapid and accurate responses in the hoisting operation. Therefore, the mathematical models are used to simulate the crane system's behaviour and evaluates the performance of the input shaping controller under fixed and payload hoisting conditions. The simulation results using MATLAB Simulink show that the ZVDD controller is effective and greatly reducing the oscillations during hoisting maneuvers, improving system stability and operational efficiency. The results demonstrate that input shaping approaches are able to reduce the payload oscillations for overhead crane systems, under fixed and payload hoisting executions.

ABSTRAK

Pelaksanaan pengawal pembentuk masukan untuk kawalan ayunan optimum dalam sistem kren atas yang beroperasi di bawah kesan pengangkatan tetap dan muatan disiasat dalam projek ini. Sistem kren atas digunakan secara meluas untuk pengendalian bahan dalam tetapan industri, tetapi ia cenderung untuk berayun dan bergoyang semasa operasi pengangkutan, yang boleh menjejaskan kecekapan dan keselamatan. Untuk menyelesaikan isu ini, pengawal pembentuk masukan seperti Getaran Sifar (ZV), Terbitan Getaran Sifar (ZVD) dan Terbitan-Terbitan Getaran Sifar (ZVDD) dicadangkan sebagai kaedah mengurangkan ayunan yang disebabkan oleh sifat dinamik muatan. Pengawal juga direka bentuk untuk meminimumkan ayunan sambil mengekalkan tindak balas yang pantas dan tepat dalam operasi angkat. Oleh itu, model matematik digunakan untuk mensimulasikan tingkah laku sistem kren dan menilai prestasi pengawal pembentuk input di bawah keadaan angkat tetap dan muatan. Keputusan simulasi menggunakan MATLAB Simulink menunjukkan bahawa pengawal ZVDD berkesan dalam mengurangkan ayunan semasa gerakan angkat, meningkatkan kestabilan sistem dan kecekapan operasi. Keputusan menunjukkan bahawa pendekatan pembentukan input mampu mengurangkan ayunan muatan untuk sistem kren atas, di bawah pelaksanaan angkat tetap dan muatan.

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LIST OF SYMBOLS AND ABBREVIATIONS

DOF	Degree of Freedom
ZV	Zero Vibration
ZVD	Zero Vibration Derivative
ZVDD	Zero Vibration Derivative-Derivative
SMC	Sliding Mode Control
FLC	Fuzzy Logic Control
NN	Neutral Network
PD	Proportional Derivative
MATLAB	Matrix-Laboratory
PID	Proportional Integral Derivative
LQR	Linear Quadratic Regulator

CHAPTER 1

INTRODUCTION

1.1 Background

The crane consists of mechanism that raises, lowers, and moves objects horizontally using a number of basic machines. It works in many different industrial sectors, such as manufacturing, material loading, ship building, and construction. Cranes are capable of moving weight both vertically (raising or lowering) and horizontally (in a straight or curved path). There are many distinct kinds of cranes with varying sizes and configuration based on the intended use or associated industry. Cranes can raise loads of up to 1,000 tons or more. Since every crane is unique, its load capacity will vary depending on a number of parameters, such as its lifting capability and its maximum height that it can reach. Figure 1-1 shows a tower crane equipped with a retractable hoist rope.

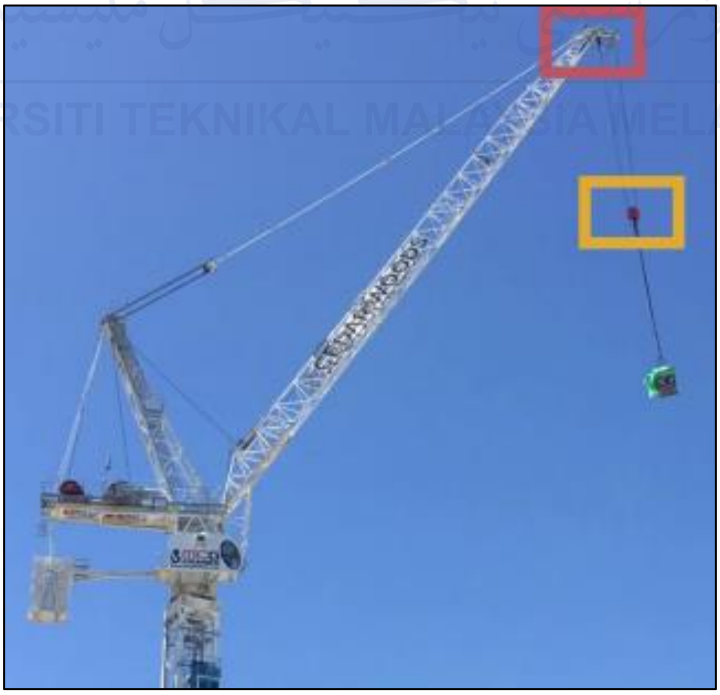


Figure 1-1: A tower crane equipped with a retractable hoist rope [1]

Overhead cranes are essential in industries that require the precise and safe movement of heavy materials. Their capability to transport loads over obstacles and within tight spaces makes them more effective than other material handling equipment. The flexibility of overhead cranes allows for customization to meet specific operational requirements, including load capacity, span and lifting height [2]. Additionally, the crane system is nonlinear and under-actuated. It also presents a multivariable problem with interdependent parameters [3], making control a callenging task. Uncontrolled oscillations can lead to inefficiency, instability and safety hazards, especially during dynamic operations like payload hoisting.

To tackle these challenges, vibration control techniques are necessary to improve the stability and efficiency of crane operations. Input shaping controllers like Zero Vibration (ZV), Zero Vibration Derivative (ZVD) and Zero Vibration Derivative-Derivative (ZVDD) have emerged as effective solutions. The input shaping is formed based on the natural frequency and damping ratio of the respective system. These controllers are able to minimize the oscillations by shaping the input commands, which in turn mitigates the resonance effects that cause vibrations and easy to implement because it does not require any modifications or the installation of additional mechanical hardware on the existing crane structure [4].

Figure 1-2: An overhead crane [5]

1.2 Motivation

On construction sites, accidents are frequent occurrence that can have a variety of causes. Accidents can result in harm, equipment damage or in worst cases, death. Primary causes of crane accidents include overturns, contact with power lines, mechanical malfunctions and falls. These accidents often occur due to factors such as instability, unsecured load or exceeding the crane’s load capacity, uneven or soft ground.

Figure 1-3: Incident at SUKE construction site [6]

One of the crane accidents that happened in Malaysia is on 22 March 2021, as shown in Figure 1-3. A crane component fell and collided resulting in three fatalities and one injured person. Investigation ouput tells that SUKE contractors were fined RM300,000 for neglecting the safety purposes. This is a serious issue and a crane that is overloaded may experience load oscillation, which makes unbalanced load placing. This may be the reason of the frequent occurence of crane collapse incidents. Based on this cases, the project is attempting to reduce the risks and hazard by proposing a control strategy that will effectively reduce payload oscillation angle and ensuring worker safety at all times.

1.3 Problem Statement

Overhead crane systems are essential in industrial situations, allowing for precise and efficient handling of heavy materials. However, these systems face numerous difficult challenges that affect the optimal performance. The changing of the crane parameters also affect to the behavior of crane's accuracy and stability. In addition, parameter variations such as hoist cable length and payload mass affect the crane's accuracy and stability, causing higher oscillations and instability [7].

The speed of the trolley in an overhead crane system significantly influences the oscillation angle of the payload. A rapidly moving troller can induce substantial oscillations, leading to higher angular displacements of the payload [8]. This not only impairs the load's accurate location, but also poses serious dangers to the surrounding environment and humans. By minimizing oscillations, these controllers enhance the stability and accuracy of crane operations, even under varying parameters and rapid trolley movements. Furthermore, the unpredictable movement of the load raises the chance of an accident, necessitating the development of control mechanisms that reduce these oscillations even at high trolley speeds.

Besides, designing an effective open-loop controller for overhead crane systems involves determining optimal parameters that minimize payload oscillation. However, this process is fundamentally difficult due to the system's complexity and the large number of interacting variables. Traditional open-loop control systems frequently fail to establish this balance, especially in the face of changing operational conditions. For instance, numerous researchers have used open-loop time optimum techniques with the crane [9]. Notable outcomes were obtained in these investigations due to the fact that the open-loop technique is dependant on the system parameters such as cable length and is unable to account for the impact of wind disturbance.

1.4 Objectives

i) To study the behavior of an overhead crane system under fixed cable length and payload hoisting in the absence of any controller.

ii) To design Zero Vibration (ZV), Zero Vibration Derivative (ZVD) and Zero Vibration Derivative-Derivative (ZVDD) as established input shaping controllers for payload oscillation control for the overhead crane system.

iii) To verify the payload oscillation performance using ZV, ZVD and ZVDD controllers under fixed cable length and payload hoisting conditions as a real engineering application.

1.5 Scope of the Project

The outline below explains the scope of this final year project:

- Study and analyze the behaviour of single-pendulum overhead crane system.
- Constructing a mathematical model of the overhead crane system using the Langrage equation.
- Real implementation of overhead crane system for fixed cable length and payload hoisting.
- Simulate and investigate the behaviour of the overhead crane system using Simulink/ MATLAB environment.
- The behavior of the overhead crane system is observed in terms of payload oscillation, cable length, trolley displacement and payload mass.
- Open-loop controllers such as Zero Vibration (ZV), Zero Vibration Derivative (ZVD) and Zero Vibration Derivative-Derivative (ZVDD) are designed to minimize the payload oscillation for both fixed cable length and payload hositing conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides examples of previous research from a variety of sources, including reports, theses, journals, and internet pieces. The evaluations were written in relation to the research for the project and covered several subthemes, such as the history of the crane system model, control techniques, and in-depth understanding of the crane controller system.

2.2 Modelling of the crane system

Cranes that are used in industrial production must not only fulfil the task of transportation but also withstand a complex and challenging manufacturing environment. Obstacles may sometimes arise along the trajectory of the payload's journey. Accident will inevitably happen if they cannot be prevented promptly [10]. As a result, both the payload swing and the payload obstacle need to be controlled to avoid the problems. Hence, the categorization of control crane systems can be divided into two distinct groups: a single-pendulum and a double pendulum system [1]. Figure 2-1 and Figure 2-2 depict an overhead crane system illustration where x and θ represent the trolley postion and the payload swing angle, respectively. In addition, L and l are stand for cable lengths.

2.2.1 Single-Pendulum Crane System

Single-pendulum crane systems are frequently used at construction sites, shipping yards and industrial facilities to perform activities such as cargo handling, material transportation and structure assembly. Typically, it appropriates for lifting operations that include moderate to significant loads. However, the crane's design and specifications can influence its range and lifting capability, which may vary. A sinlge-pendulum crane system is a simpler overhead crane concept in which the cable that suspends the payload behaves as a pendulum. It is a key system used to comprehens and analyse crane dynamics, particularly the swinging motion of the load.

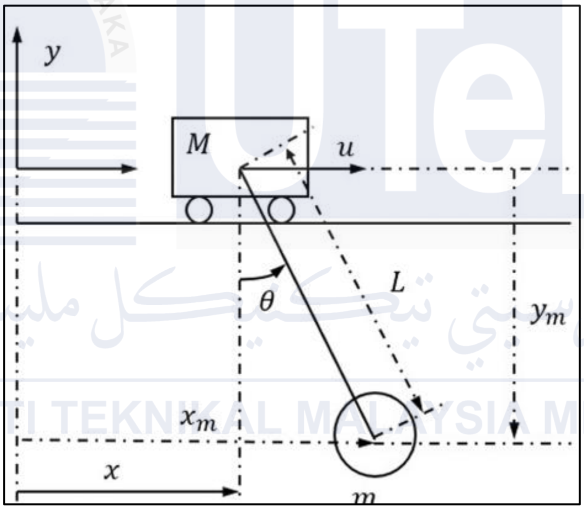


Figure 2-1: Structure of the single-pendulum [11]

During the transportation operation, the cable length is changing slowly either fixed or payload hoisting. Consequently, several studies [12] assume a fixed cable length, which simplifies the system to two states. Furthermore, if the swing angle is considered small, a linearized model can describe the system dynamics [12]. On the other hand, the model's accuracy and complexity can be enhanced by accounting for friction between moving parts [13], incorporating system uncertainties [14], or considering external disturbances.

2.2.2 Double-Pendulum Crane System

Because of one extra unactuated state variable appears for the double-pendulum, the control problem is significantly more complex than the single-pendulum crane. When dealing with a crane system, if the payload is not sufficiently small to be viewed as a single point, or if the weight of the hook cannot be ignored, the system exhibits characteristics more like to a double-pendulum crane system rather than a single-pendulum crane system [10].

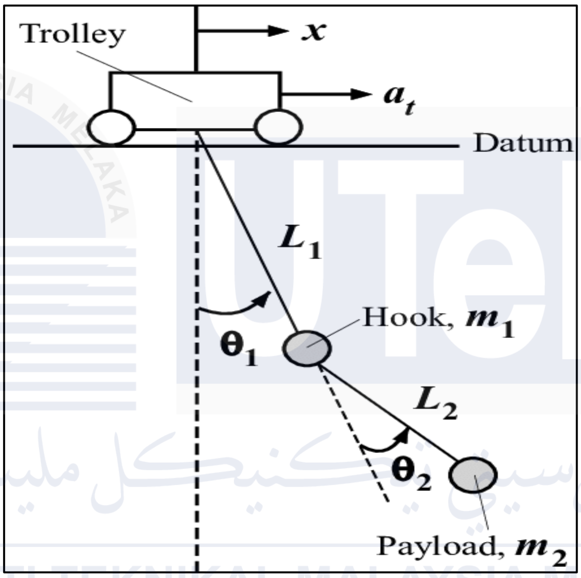


Figure 2-2: Structure of the double-pendulum [15]

The model is nonlinear and encompasses with five states: bridge position, trolley position, cable length and two swing angles. Similar to 2D overhead cranes, assuming a fixed cable length can simplify the model and reduce its states to four only [16]. In other studies [17], the linearized model is derived by assuming a constant cable length and small oscillation angles to facilitate simplification. On the other hand, for greater accuracy, certain studies [18] have explored incorporating damping coefficients, while others have considered including external disturbances such as wind forces in the model [19].

2.3 Control Strategies

The researcher’s attention has been drawn to various control approaches for crane systems. Several monitoring strategies have been suggested for crane systems. Open-loop and closed-loop control techniques are typically possible for crane systems. The act of combining these two strategies is commonly known as hybrid control. Figure 2-3 shows the control strategies for a crane system.

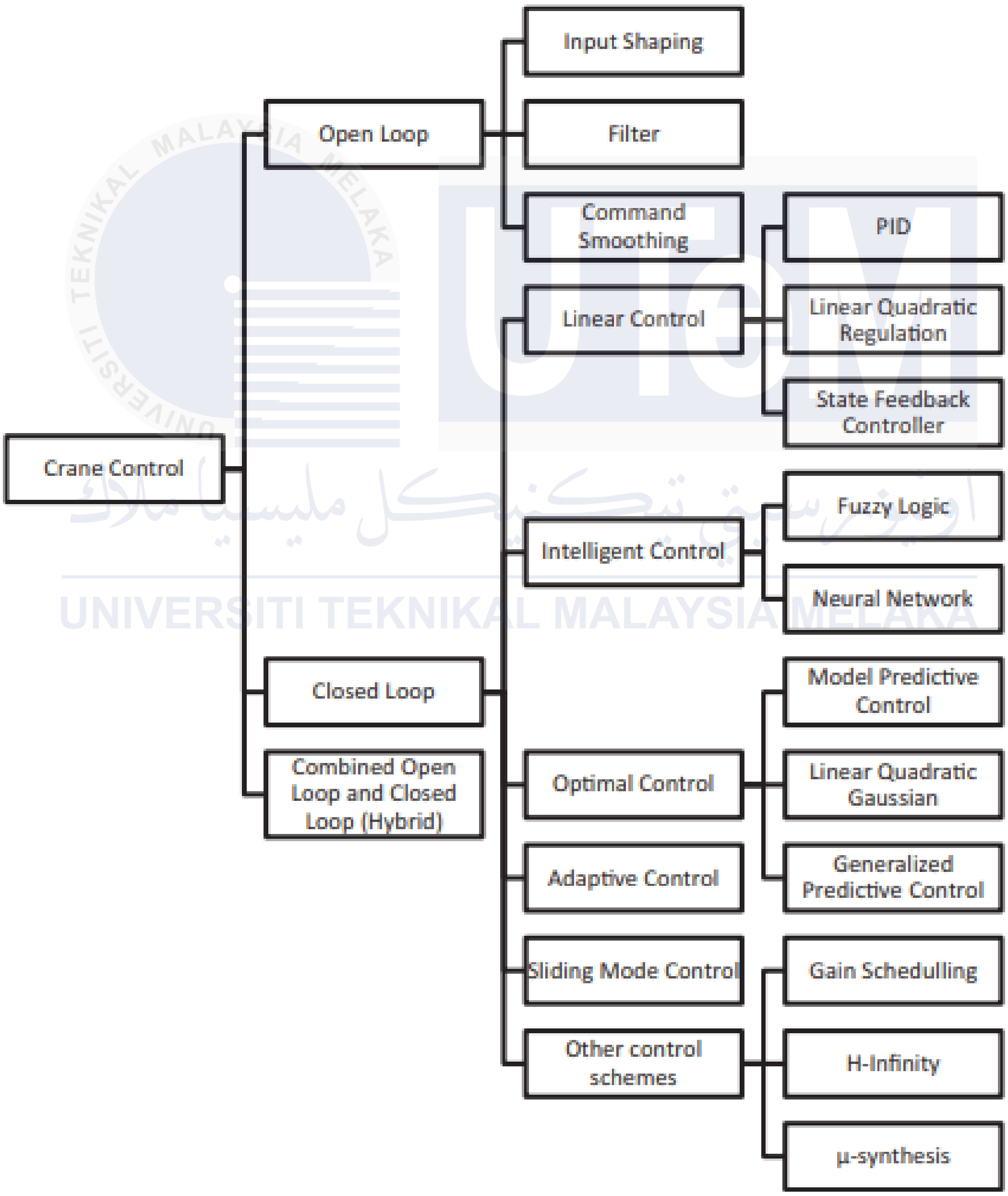


Figure 2-3: Control strategies for a crane system [20]

2.3.1 Open-loop Control

Open-loop control is a type of control system where the control action or output is not dependent on the real-time performance or feedback of the system. Furthermore, an open-loop control system is characterized by its simplicity and lower cost compared to a closed-loop control system. An inherent drawback of this form of management is its susceptibility to external disturbances. External disturbances such as wind or ocean waves consistently hinder the efficiency of cranes when used on ships. The control input for the open-loop control technique frequently fails to consider system modifications. Figure 2-4 contains a block diagram illustrating open-loop control strategies for crane systems.

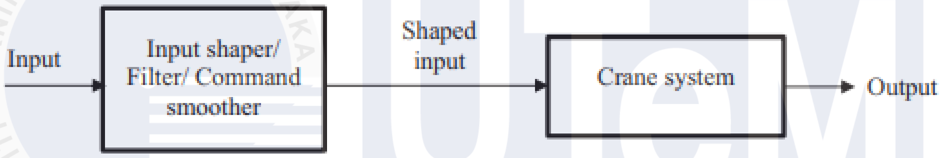


Figure 2-4: Block diagram of open-loop control strategies for a crane system [20]

2.3.1.1 Input Shaping

Input Shaping is a method used to minimise the oscillation of a crane. Input shaping is a more straightforward and efficient approach compared to time-optimal control approaches. Next, input shaping is a feedforward control method that enhances the speed at which a system stabilises and the precision of its location, while simultaneously reducing any remaining vibrations. It does not necessitate the use of closed-loop or adaptive controller feedback systems. Input shaping is achieved by merging the command signal with an impulse sequence, also known as an input shaper, in real-time [21]. The outcome of the convolution is subsequently employed to the crane motors. At each time step, real time convolution takes only a few multiplication an addition operations. As a result, it can be implemented on even the most basic digital processor. Figure 2-5 shows a simple algorithm can be represented symbolically.

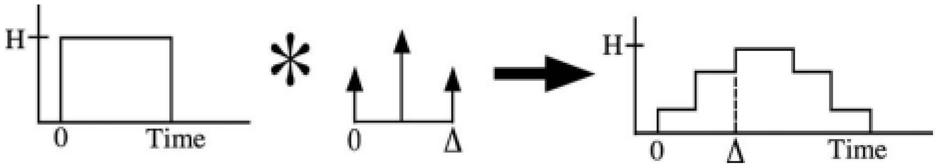


Figure 2-5: Input shaping process [22]

To examine how well input shaping methods perform and their stability, several approaches were introduced: Zero Vibration (ZV), Zero Vibration Derivative (ZVD) and Zero Vibration Derivative-Derivative (ZVDD) [23]. These methods were developed under the condition of a consistant cable length. The evaluation of these shaper's control performance is based on the degree to which they minimize the sway of the payload. The ZV shaper is the simplest shaper that consists only two impulses of fixed magnitudes. ZV shaper solved parameter euation is shown below:

$$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} A_0 & A_1 \\ t_0 & t_1 \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & 0.5\tau_d \end{bmatrix} \tag{2-1}$$

Where,

$$K = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \tag{2-2}$$

$$\tau_d = \frac{2\pi}{\omega_d} \tag{2-3}$$

$$\omega_d = \omega_n\sqrt{(1 - \zeta^2)} \tag{2-4}$$

However, frequency error robustness is not considered by the ZV shaper. The derivative order can be added to the shaper to obtain the ZVD shaper's parameter as follows, which will eliminate any remaining vibration.

$$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} A_0 & A_1 & A_2 \\ t_0 & t_1 & t_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{(1+K)^2} & \frac{2K}{(1+K)^2} & \frac{K^2}{(1+K)^2} \\ 0 & 0.5\tau_d & \tau_d \end{bmatrix} \qquad (2\text{-}5)$$

and the ZVDD shaper as:

$$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} A_0 & A_1 & A_2 & A_3 \\ t_0 & t_1 & t_2 & t_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{(1+K)^3} & \frac{3K}{(1+K)^3} & \frac{3K^2}{(1+K)^3} & \frac{K^3}{(1+K)^3} \\ 0 & 0.5\tau_d & \tau_d & 1.5\tau_d \end{bmatrix} \qquad (2\text{-}6)$$

2.3.1.2 Filter

To manage the swinging motion of a crane's load, various filters such as the Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filter have been examined [20]. Empirical evidence has shown that IIR filters lack precise phase characteristics and pose challenges in terms of control, whereas FIR filters consistently exhibit linear phase behaviour and are comparatively easier to manipulate. An IIR filtering technique has been devised for the purpose of regulating suspended payloads, specifically in relation to input shaping [24].

2.3.1.3 Command Smoothing

Command smoothing is a technique used to effectively reduce motion-induced vibration by intelligently refining the original command [25]. The construction of the smoother involves utilising estimates of the system's intrinsic frequency and damping ratio. The smoother command is integrated with the original command to generate a refined command that operates the system without any vibration [26].

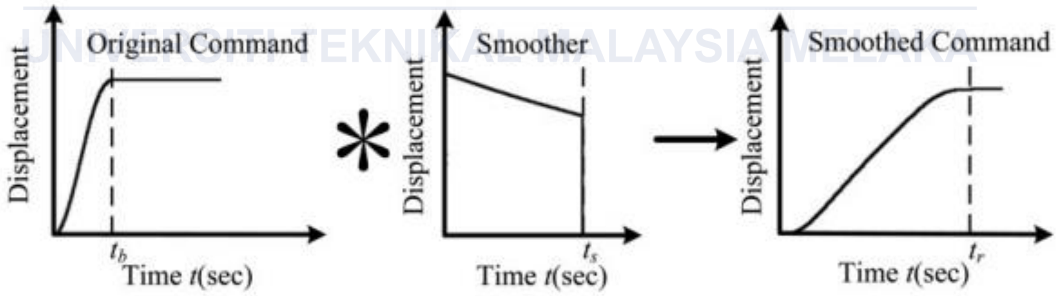


Figure 2-6: The command smoothing process [26]

2.3.2 Closed-loop Control

Closed-loop control, sometimes referred as a feedback control, that continuously monitors and adjust the output or behaviour of the system depending on feedback signals. This control system implements real-time adjustments to the input or control action using feedback from sensors or measurements of the system's output. The advantage of closed-loop is work accurately in the presence of disturbance. The closed-loop control systems exhibit greater adaptability and responsiveness than open-loop systems as they have the capacity to modify their action according to the real-time performance of the systems.

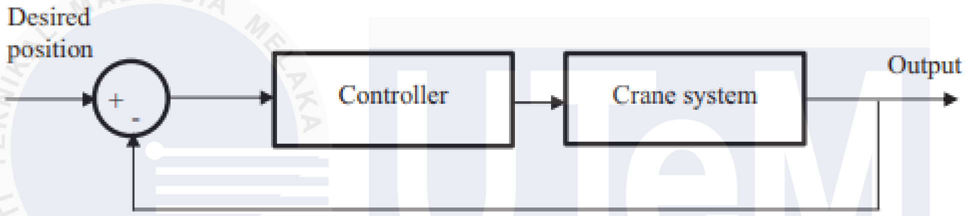


Figure 2-7: Block diagram of a closed-loop control strategies for crane system [20]

2.3.2.1 Linear Control

A control system is a collection of physical components that are used to regulate, direct or command itself or other system. Control systems can be classified into two categories: linear control systems and nonlinear control systems. For instance, the Proportional Integral Derivative (PID) controller, the Linear Quadratic Regulator (LQR) , and other methods.

2.3.2.2 Optimal Control

In order to attain optimal management of a crane system, it is crucial to increase the velocity of the cart while reducing the oscillation of the hung payload [27]. Linear Quadratic Gaussian (LQG) control and Model Predictive Control (MPC) are widely employed control techniques in indutries [20].

2.3.2.3 Adaptive Control

In [28], a new adaptive nonlinear control technique was introduced for underactuated cranes that are affected by both bridge range limits and parametric uncertainty. The suggested controller guarantees that the trolley remains within the allowed range while simultaneously meeting the goals of precise positioning and eliminating swinging. These objectives are backed by Lyapunov-based stability analysis and validated through numerical simulation results.

2.3.2.4 Intelligent Control

Crane systems have made use of a number of intelligent controllers. These controllers have mostly been built on Fuzzy Logic Controllers (FLC) and Neural Network (NN) [20].

a) Fuzzy Logic Controller (FLC)

The susceptibility of open-loop systems to parameter changes and disruptions is widely acknowledged. In this paper [29] employs feedback control is used to address these issues. The study introduces fuzzy logic controllers specifically tailored for gantry crane system, leveraging insights from experienced operators. These controllers are designed based on their expertise. The research assesses the performance of the proposed controller through experimental testing on a laboratory-scale gantry crane. The experimental outcomes demostrate the effectiveness of fuzzy logic controllers, particularly in achieving favorable results for th anti-swing control of the crane.

b) Neural Network (NN)

Lately, advancements in neural networks have resulted in notable progress within control systems across a spectrum of industrial application [30]. The Neural Network (NN) is one of the intelligent controllers used in crane control systems. The application of neural networks in crane systems aims to improve several aspects of crane operations, including performance, efficiency, safety, and upgrading safety protocols. Furthermore, the use of neural networkd in crane control extends to a variety of crane systems, including overhead cranes and gantry cranes [31]. The researcher demonstrated the application of neural networks in controlling a lab-scale gantry crane, highlighting the ractical potential of neural networkbased control in crane operations. Similarly with [32] illustrated the use of a straightforward proportional-derivative (PD) controller to manage an overhead crane system, showcasing how neural network controllers can adapt accross various crane configuration.

2.3.2.5 Sliding Mode Control

Sliding mode control is commonly employed in overhead cranes, which are normally underactuated systems, in order to introduce a level of control flexibility by including sliding surfaces into the system [33]. Sliding mode control (SMC) is a robust and nonlinear control approach. Due to its numerous benefits, the SMC approach has been extensively utilized for controlling real-world systems. The system baing regulated exhibits the characteristics of order reduction, disturbance rejection, and robutsness, even in the presence of uncertainty in its parameters [34].

2.4 Summary

In summary, this chapter explores the basics of crane control systems and examines previously suggested control schemes. Finally, various researchers have looked into the optimum controller for improving the performance of overhead crane systems in reducing the payload sway. For this study, the input shaping controller are chosen to be used as a compensator to effectiely eliminate the oscillation of the payload.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The framework of this chapter encompasses a comprehensive examination of the project’s methods and progression. MATLAB Simulink software is utilized to completely model the project and describe the dynamics of the crane control system. For the early results, the dynamics and behavior of the crane system are modelled and simulated in the absence of a compensator and controller. The system is then be updated to include input shaping, which helps to improve the performance of the crane system. The research findings are showcased through a simulation environment. This approach is segmented into three distinct phases:

i) Create a mathematical model of an overhead crane system for both fixed cable length and payload hoisting using Lagrangian equations.

ii) Apply three types of input shaping technique controls (ZV, ZVD and ZVDD) to minimize the payload oscillation angle of the overhead crane system during transportation.

iii) Observe and analyse the result of the effectiveness of input shaping techniques in the overhead crane system for both conditions, fixed cable length and payload hoisting.

3.2 Project Flowchart

Figure 3-1 shows the process of the entire study for this project. The flowchart displays two stages: stage 1 is for Final Year Project 1 and stage 2 for Final Year Project 2. Stage 1 covers Objective 1 that analyse the two dimensional dynamic model of a nonlinear overhead crane system in order to create a mathematical model for the system. This model consider both the crane system without and with payload hoisting, respectively. Next, the project will continue in Final Year Project 2 that meets Objectives 2 and 3 that implement input shaping technique to reduce payload oscillation angle of the overhead crane system during transportation. Before designing the controllers, it is essential to understand the principles of input shaping and how it can be applied to the overhead crane system. The focus is on three specific types of input shapers: Zero Vibration (ZV), Zero Vibration Derivative (ZVD) and Zero Vibration Derivative-Derivative (ZVDD). The designed of the ZV, ZVD and ZVDD is assessed through simulations that replicate the overhead crane system's operation with these controllers implemented. The main criterion for evaluating their performance is the reduction in the payload oscillation angle during transportation. The simulation results are analyzed to verify the controllers effectively reduce oscillations, thus improving the stability of the overhead crane system.

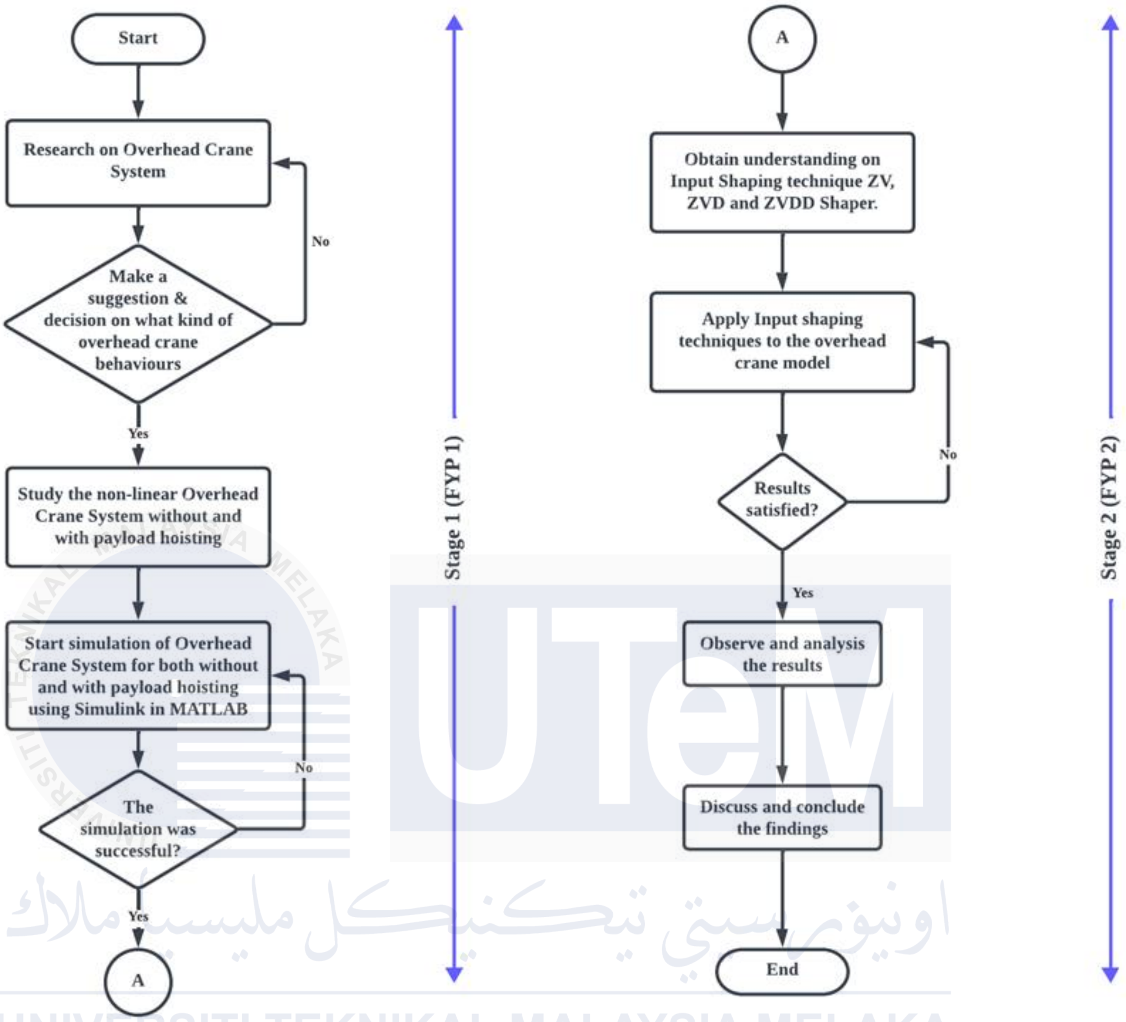


Figure 3-1: Project flowchart

3.3 Nonlinear Model of an Overhead Crane System

A crane system’s dynamic behaviour is simulated using a nonlinear crane model. Figure 3-2 is a schematic representation of a single pendulum overhead crane. Table 3-1 displays characteristics such as trolley’s mass, mass of payloads, and cable length.

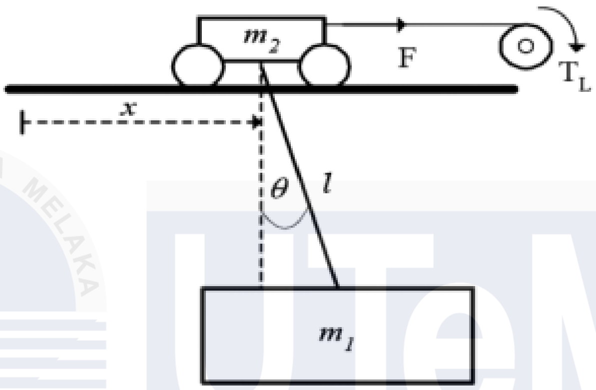


Figure 3-2: Schematic diagram of single pendulum overhead crane model [35]

Table 3-1: Parameters of the overhead crane system [36]

Parameters	**Values**
Hoisting Cable Length, $\boldsymbol{l}$	0.17 – 0.59 m
Gravitational Constant, **g**	9.8 m$\boldsymbol{s^{-2}}$
Viscous Damping Coeficient, $\boldsymbol{b_1}$,$\boldsymbol{b_2}$	82, 75 N s/m
Mass of Payloads, $\boldsymbol{m_1}$	0.74 kg, 0.24 kg
Mass of Trolley, $\boldsymbol{m_2}$	1.155 kg

The crane model is subjected to mathematical modelling using the Lagrange method that has been widely employed in the previous research studies including this paper [37]. From the modelling using suitable mathematical methodology, several nonlinear differential equations are derived as follows [37]. Equations (3-1) and (3-2) are used for an overhead crane system without payload hoisting, while Equations (3-3), (3-4) and (3-5) are used for an overhead crane system with payload hoisting, respectively.

Without payload hoisting (fixed cable length)

For trolley displacement, x :-

$$(M_1 + M_2)\ddot{x} + b_x\dot{x} + M_2 l\ddot{\theta}\cos\theta - M_2 l\dot{\theta}^2\sin\theta = F_x \tag{3-1}$$

For oscillation angle, θ :-

$$M_2 l\ddot{x}\cos\theta + M_2 l^2\ddot{\theta} + M_2 gl\sin\theta = 0 \tag{3-2}$$

With payload hoisting

For trolley displacement, x :-

$$(M_1 + M_2)\ddot{x} + b_1\dot{x} - M_2 l\dot{\theta}^2\sin\theta + M_2 l\ddot{\theta}\cos\theta + 2M_2\dot{l}\dot{\theta}\cos\theta + M_2\ddot{l}\sin\theta = Fx \tag{3-3}$$

For oscillation angle, θ :-

$$M_2 l^2\ddot{\theta} + M_2 l\ddot{x}\cos\theta + 2M_2 l\dot{l}\dot{\theta} + M_2 gl\sin\theta = 0 \tag{3-4}$$

For cable payload hoisting, l :-

$$M_2\ddot{l} + M_2\ddot{x}\sin\theta + b_x\dot{l} - M_2 l\dot{\theta}^2 - M_2 g\cos\theta = Fx \tag{3-5}$$

3.3.1 Overhead Crane System without Payload Hoisting (Fixed Cable Length)

Figure 3-3 shows an overhead crane system block without payload hoisting, while Figure 3-4 shows a subsystem block in Simulink for overhead crane system without payload hoisting.

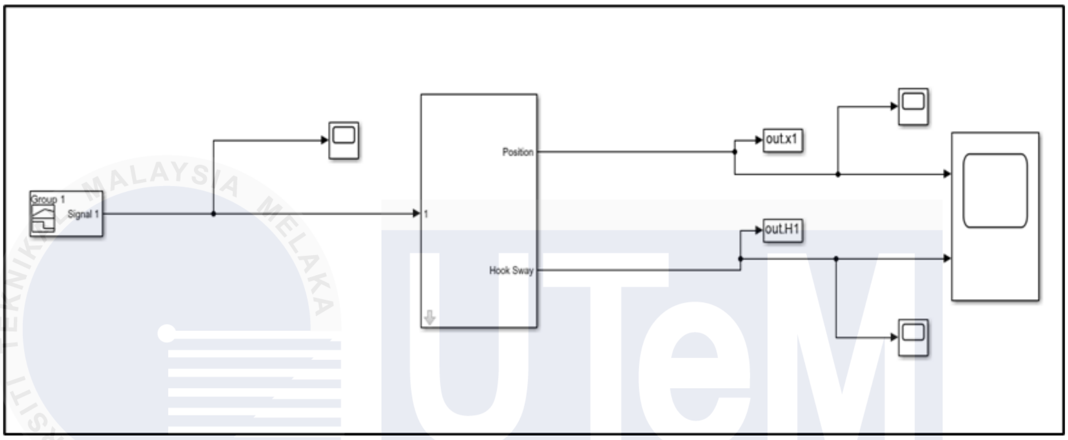


Figure 3-3: An overhead crane system block without payload hoisting

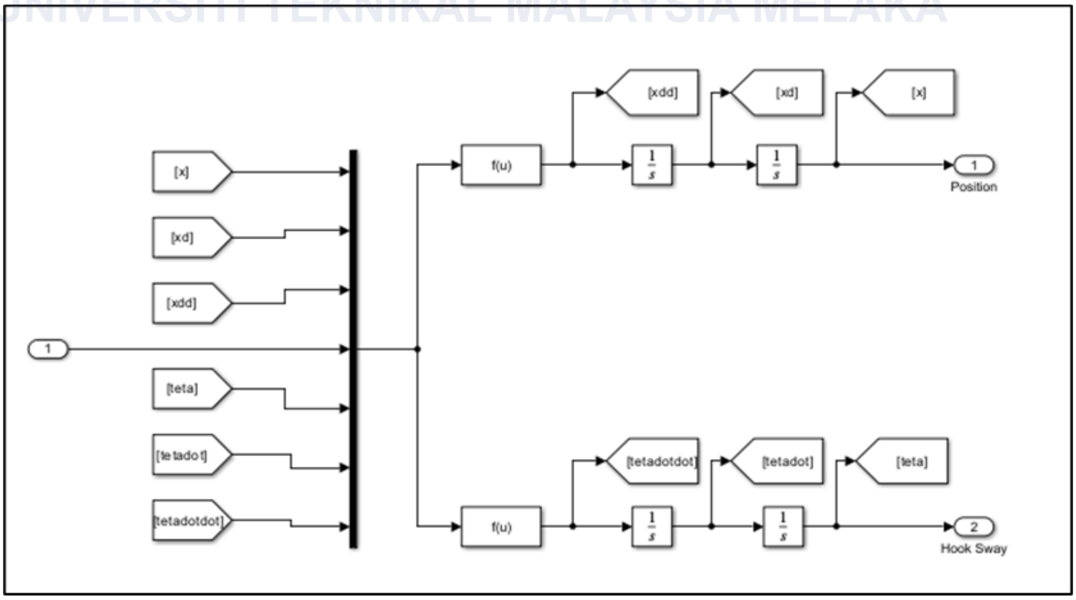


Figure 3-4: Subsystem block in Simulink for overhead crane system without payload hoisting

3.3.2 Overhead Crane System with Payload Hoisting

Figure 3-5 shows an overhead crane system block with payload hoisting while, Figure 3-6 represents a subsystem block in Simulink for overhead crane system with payload hoisting.

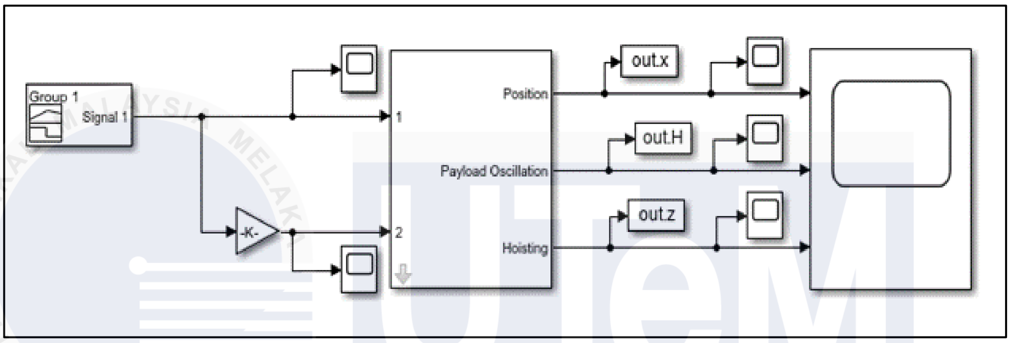


Figure 3-5: An overhead crane system block with payload hoisting

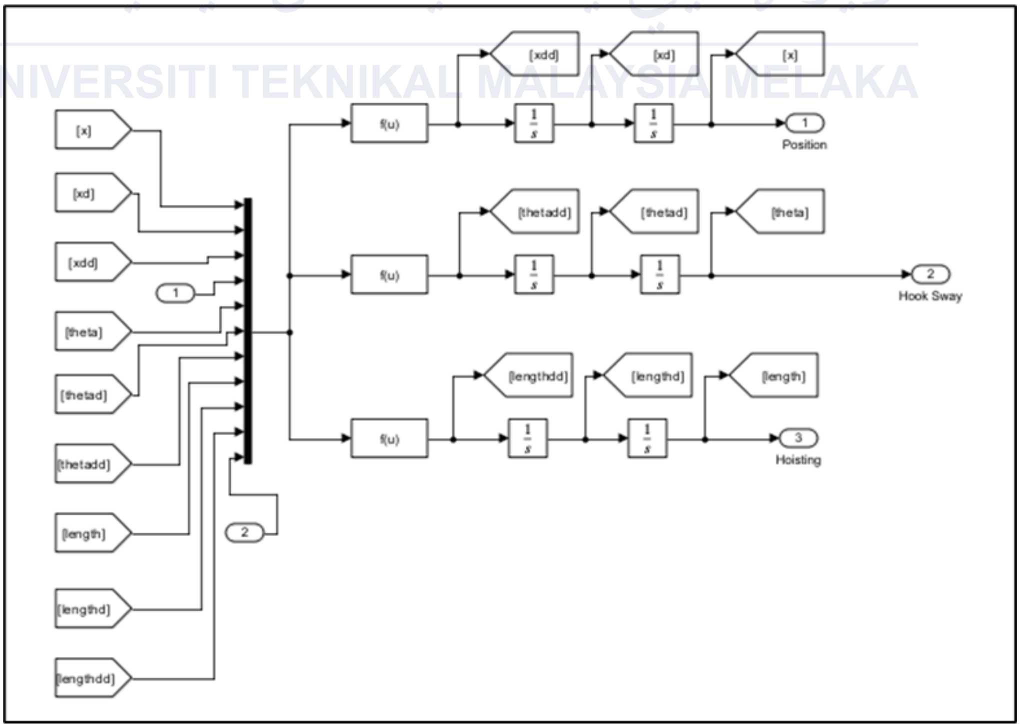


Figure 3-6: Subsystem block in Simulink for overhead crane system with payload hoisting

3.4 Nonlinear Model of an Overhead Crane System with Input Shaping Controller

One of the practical open-loop control systems for an overhead crane is input shaping. This method involves the movement of the crane over a predetermined distance along a predetermined route and relies heavily on system characteristics such as cable length and system delays. As a result, conducting an investigation into the efficacy of feedforward input shapers utilising Zero Vibration (ZV), Zero Vibration Derivative (ZVD) and Zero Vibration Derivative-Derivative (ZVDD) in reducing payload oscillation is recommendable. The designed shapers were applied to an overhead crane as a feedforwad controllers as shown in Figure 3-7.

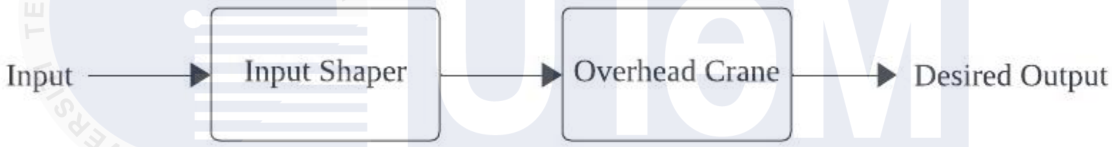


Figure 3-7: Input Shaping block diagram for an overhead crane

Equation (3-6) depicts the oscillatory behaviour of a second-order system, which forms the primary principle of input shaping. Hence, it is necessary to determine the natural frequency, ω_n and damping ratio, ζ while creating the input shaping control.

$$G(s) = \frac{{\omega_n}^2}{s^2 + 2\zeta\omega_n s + {\omega_n}^2} \tag{3-6}$$

Applying the formula in Table 3-2 will determine the magnitude and temporal position of the Zero Vibration (ZV), Zero Vibration Derivative (ZVD) and Zero Vibration Derivative-Derivative (ZVDD).

Table 3-2: Formula ZV, ZVD and ZVDD shapers [38]

Type of Shaper	**Formula**
ZV	$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} A_0 & A_1 \\ t_0 & t_1 \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & 0.5\tau_d \end{bmatrix}$
ZVD	$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} A_0 & A_1 & A_2 \\ t_0 & t_1 & t_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{(1+K)^2} & \frac{2K}{(1+K)^2} & \frac{K^2}{(1+K)^2} \\ 0 & 0.5\tau_d & \tau_d \end{bmatrix}$
ZVDD	$\begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} A_0 & A_1 & A_2 & A_3 \\ t_0 & t_1 & t_2 & t_3 \end{bmatrix}$ $= \begin{bmatrix} \frac{1}{(1+K)^3} & \frac{3K}{(1+K)^3} & \frac{3K^2}{(1+K)^3} & \frac{K^3}{(1+K)^3} \\ 0 & 0.5\tau_d & \tau_d & 1.5\tau_d \end{bmatrix}$

Where;

$$K \; = \; e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \tag{3-7}$$

$$\tau_d \; = \; \frac{2\pi}{\omega_d} \tag{3-8}$$

$$\omega_d \; = \; \omega_n\sqrt{(1 \; - \; \zeta^2)} \tag{3-9}$$

In this project, the shapers are implemented and tested within the simulation environment of an overhead crane system. Simulink is used to implement the open loop control schemes. According to reference [38], the natural frequency of the system, ω_n= 3.8080 and the damping ratio, ζ = 0.00358 were obtained. Table 3-3 shows the amplitude, A_i and time location of the signal, t_i of the ZV, ZVD and ZVDD shapers. All this shapers are simulated based on the obtained values.

Table 3-3: Input shaping control parameters [38]

Parameters	A_1	A_2	A_3	A_4	t_1	t_2	t_3	t_4
ZV	0.503	0.497	-	-	0	0.980	-	-
ZVD	0.253	0.500	0.247	-	0	0.980	1.970	-
ZVDD	0.127	0.377	0.373	0.123	0	0.980	1.970	2.950

In this approach, the ZV, ZVD and ZVDD shapers were simulated by utilizing delay units and gain units to produce shape commands as shown in Figure 3-8, Figure 3-9 and Figure 3-10 respectiely.

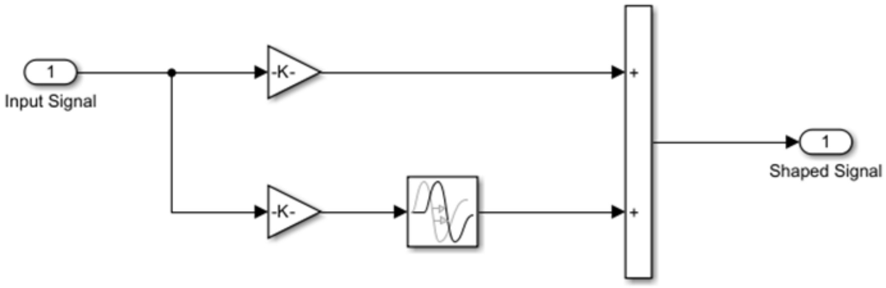


Figure 3-8: Gain delay ZV shaper

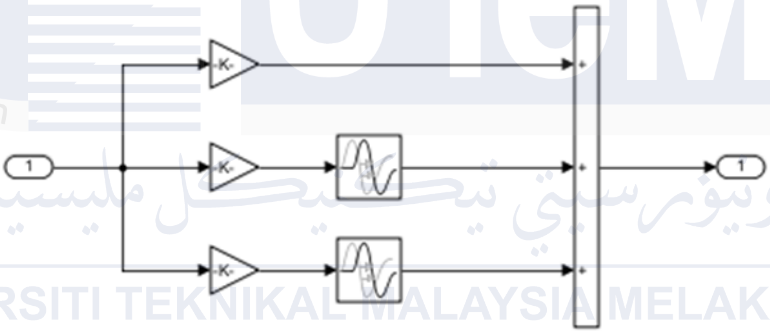


Figure 3-9: Gain delay ZVD shaper

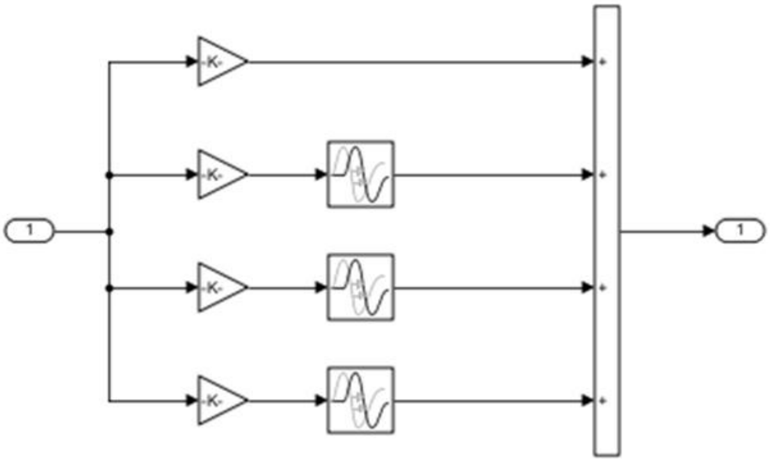


Figure 3-10: Gain delay ZVDD shaper

3.5 Mean Squared Error (MSE) and Sum Squared Error (SSE)

Equations (3-7) and (3-8) represented the formula of Mean Squared Error (MSE) and Sum Squared Error (SSE), respectively. These both formula are used to indicate the area values of the oscillation responses.

Mean Squared Error (MSE) :-

$$MSE = \left(\frac{1}{n}\right) * \sum(actual - forecast)^2 \tag{3-7}$$

Sum Squared Error (SSE) :-

$$SSE = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{3-8}$$

Where:

- n = number of samples
- $\sum$ = summation notation
- $actual$ = original or observed y-value
- $forecast$ = y-value from regression
- y_i = real/observed values
- $\hat{y}_i$ = predicted values

3.6 Summary

The dynamic model is model using Lagrange equation and evaluated the model through MATLAB Simulink software in the next Chapter 4 to describe the nonlinear overhead crane system under fixed and payload hoisting.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter simulates a dynamic model of an overhead crane system and examines the system's behavior. Two parameters, namely cable length and payload mass are compared between the overhead crane system simulation results without payload hoisting and with payload hoisting.

4.2 Simulation of Nonlinear Overhead Crane System without Controller

This section presents a comprehensive examination of the outcomes acquired from the simulation. Section 4.2.1 displays the Simulink block diagram of the overhead crane without payload hoisting and Section 4.2.2 with payload hoisting, respectively. The analysis has been conducted to achieve the same target by considering different system features such as cable length and payload mass. Figure 4-1 shows the input signal using signal builder in Simulink MATLAB for both without and with payload hoisting, while Figure 4-2 shows system response for trolley position for both without and with payload hoisting.

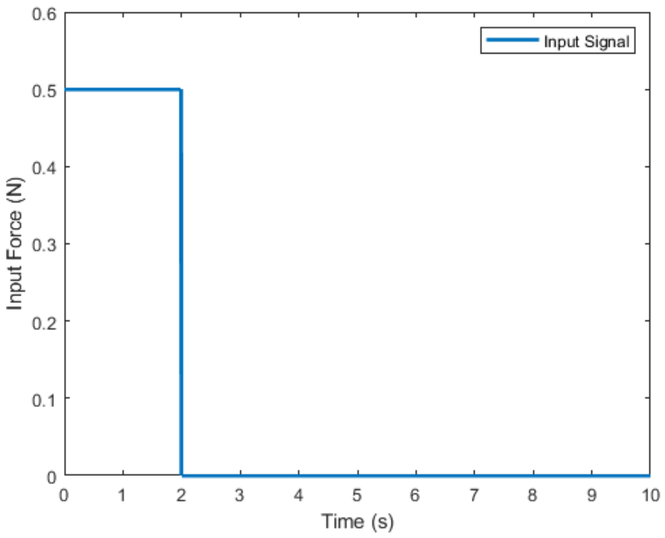


Figure 4-1: Input Signal for both without and with payload hoisting

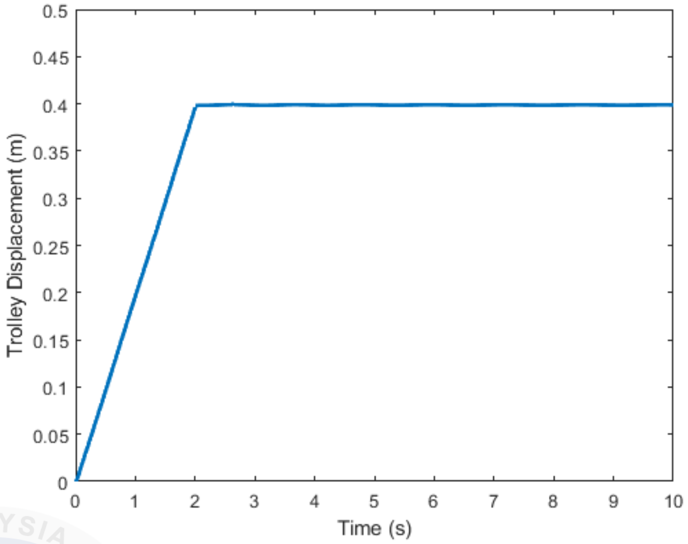


Figure 4-2: System response for trolley position for both without and with payload hoisting

4.2.1 Overhead Crane System without Payload Hoisting (Fixed Cable Length)

In this scenario, fixed cable length with various payload mass ranging from 0.14kg to 0.74kg **(**Figure 4-3) and fixed payload masses with various cable length ranging from 0.17m to 0.59m (Figure 4-4) are investigated in the absence of payload hoisting.

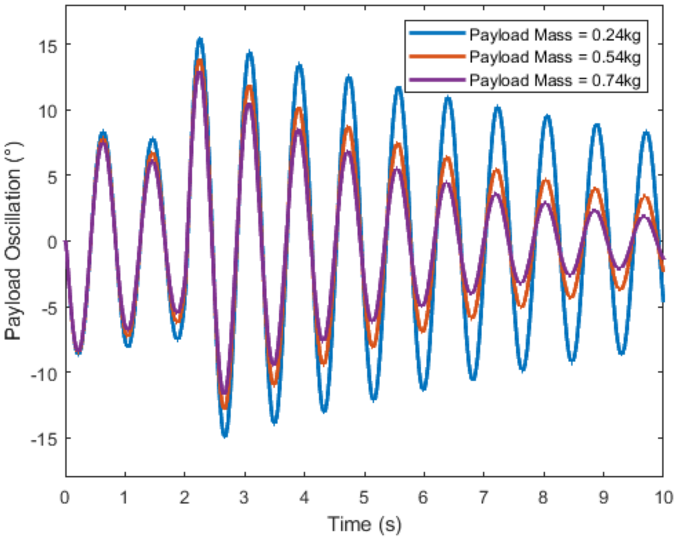


Figure 4-3: System response for sway angle without payload hoisting

(different payload masses)

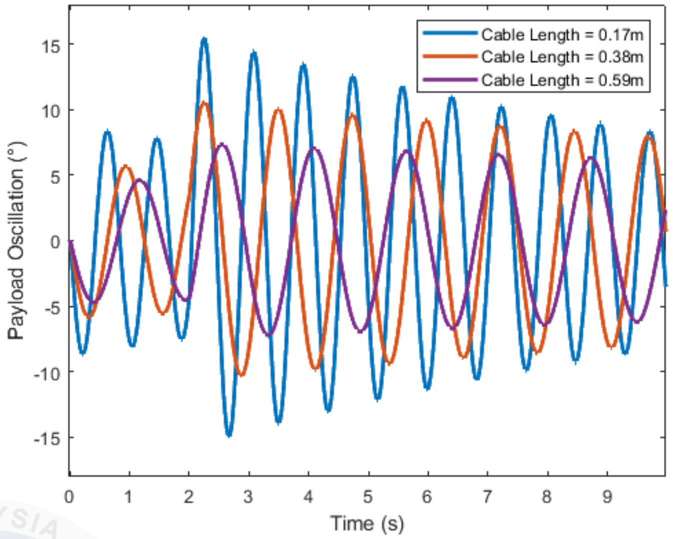
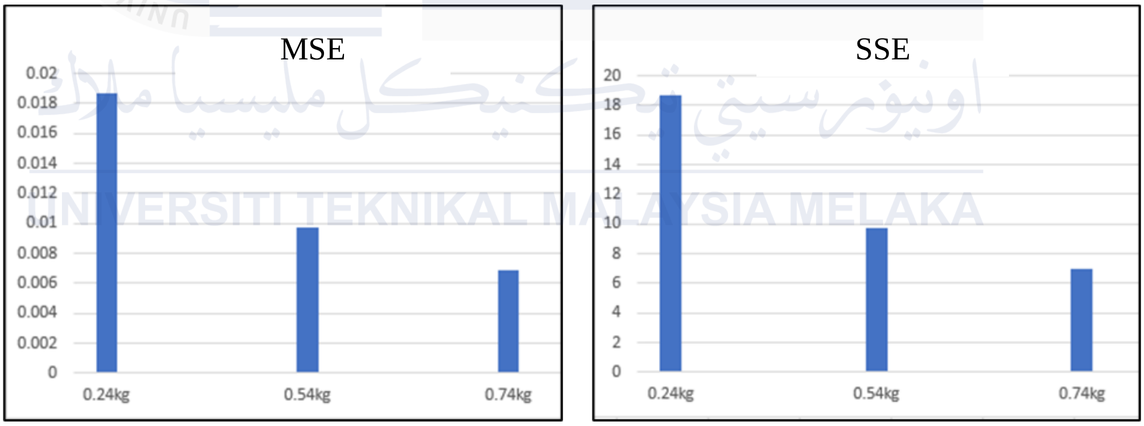


Figure 4-4: System response for sway angle without payload hoisting

(fixed payload mass, 0.24 kg with different cable length)



(a)

(b)

Figure 4-5: Performance of the overhead crane system without payload hoisting

(a) MSE (b) SSE

4.2.2 Overhead Crane System with Payload Hoisting

An instance involving the lifting of a payload was examined while the trolley was in motion. Figure 4-6 illustrates the process of raising the payload hoisting from 0.17m to 0.59m. Throughout this lifting operation, the system was investigated under conditions with a constant payload mass and varying payload masses.

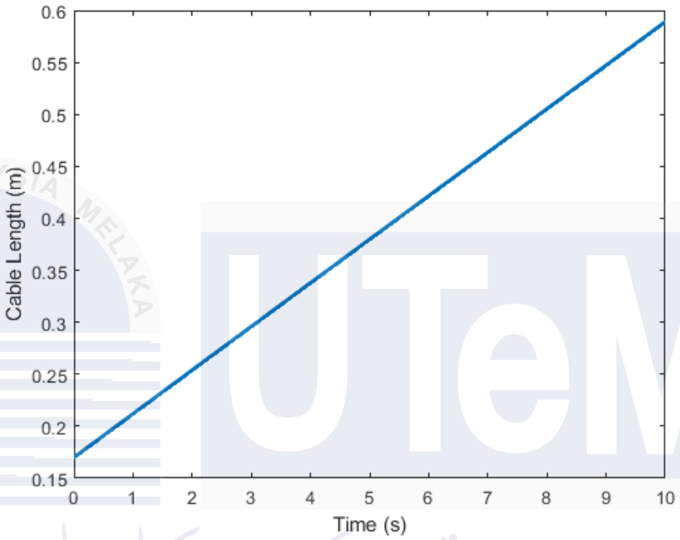


Figure 4-6: System response for payload hoisting

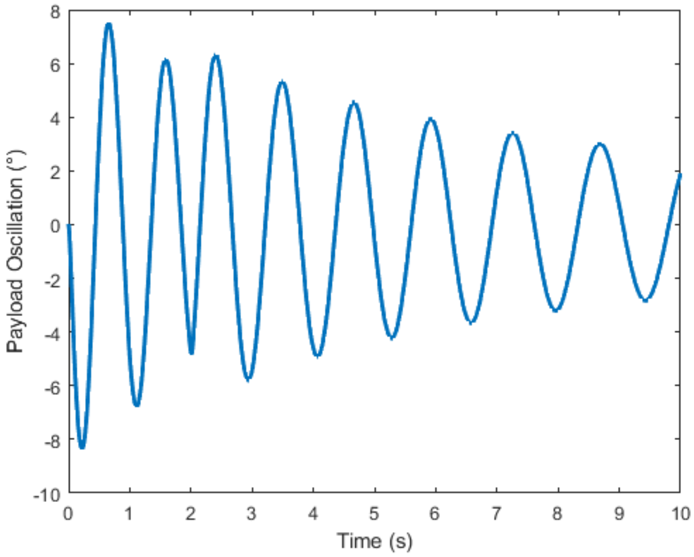


Figure 4-7: System response for payload oscillation with payload hoisting

(fixed payload mass, 0.24kg)

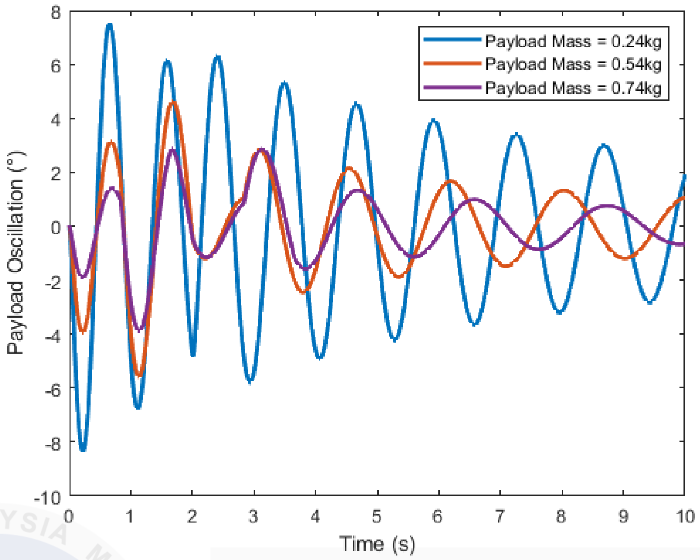
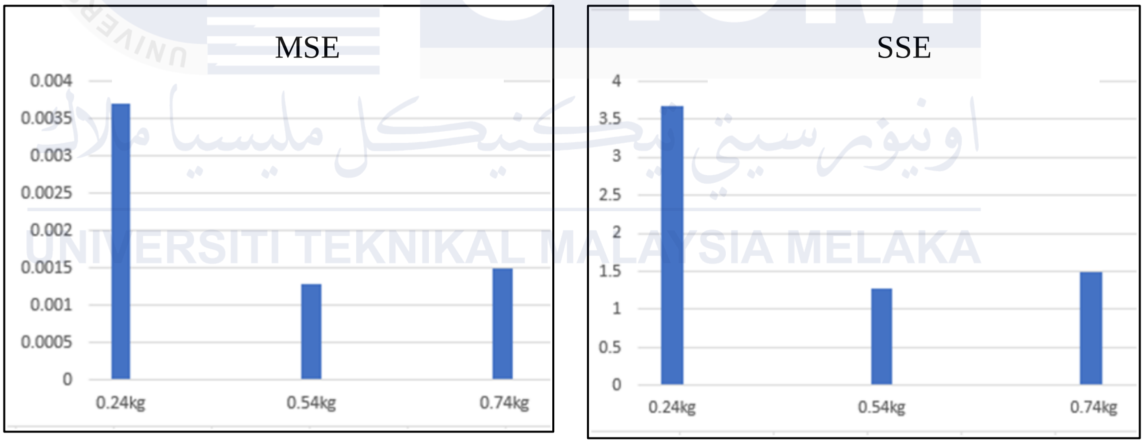


Figure 4-8: System response for sway angle with payload hoisting

(different payload masses)



(a) (b)

Figure 4-9: Performance of the overhead crane system with payload hoisting

(a) MSE (b) SSE

Based on the previous findings, it can be inferred that:

- The higher the cable length, provided low payload oscillation.
- Payload oscillation is decreased as the payload mass increased.

4.3 Simulation of Nonlinear Overhead Crane System with Input Shaping Controller

Since overhead crane systems frequently transport payloads of varying weights, research was done to determine how well the controller performed when the payload mass varied. In actuality, the payload mass varies during crane operations, while the trolley masses remain constant. When the payload mass of 0.24 kg, 0.54 kg and 0.74 kg was tested on the system, the payload sway output response was detected and recorded for payload oscillation. The robustness of the controller was further investigated by considering a different payload mass and trolley displacement. Figures 4-10 to 4-13 show the input signal of the overhead crane system for both without and with controller.

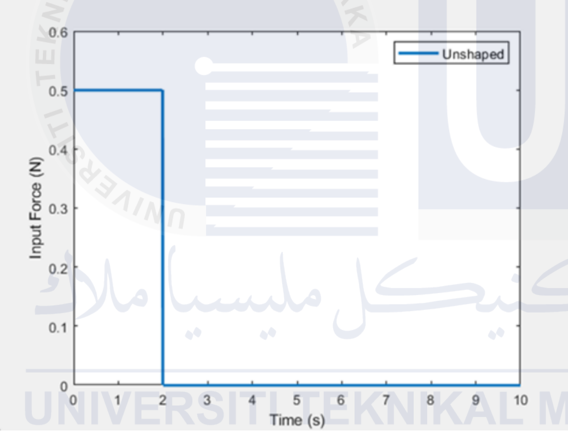


Figure 4-10: Without controller

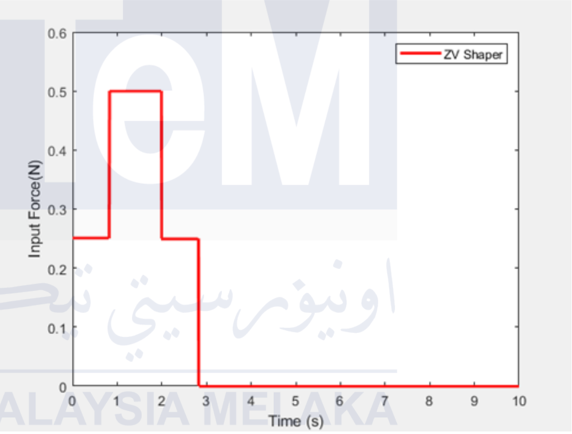


Figure 4-11: With ZV Shaper controller

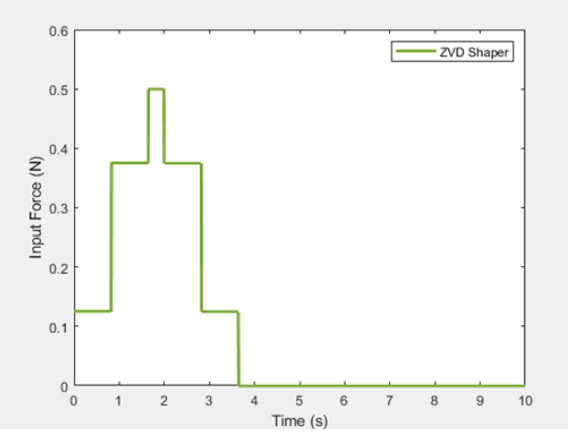


Figure 4-12: With ZVD Shaper controller

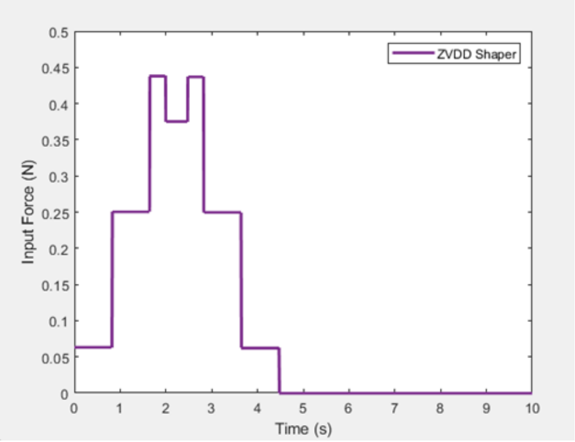


Figure 4-13: With ZVDD Shaper controller

4.3.1 Overhead Crane System without Payload Hoisting (Fixed Cable Length)

Vibration control is a critical aspect of managing overhead crane systems to maintain accurate and smooth operations. Effective methods for reducing vibrations are provided by input shaping controllers, such as the ZV, ZVD and ZVDD shapers are shown in Table 4-1 to Table 4-6. These controllers are especially useful in situations with a fixed cable length and during payload hoisting, where the system dynamics can change significantly. The performance of input shaping controlllers, can be evaluated based on their handling of payload mass, cable length and the resulting maximum oscillation. The ZV shaper effectively minimizes oscillations under stable conditions, changes in payload mass or cable length can cause higher maximum oscillations due to its limited adaptability. On the other hand, the ZVD shaper makes use of derivative action to increase its resistance to variations in cable length and payload mass. It effectively manages variations in mass and offers improved vibration suppression across a wider range of payload masses.

Table 4-1: System response for Fixed Cable Length = 0.17m

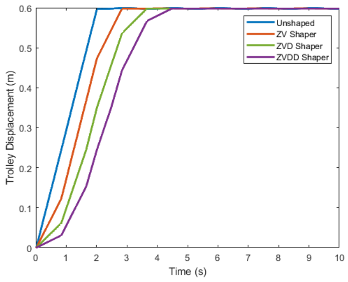
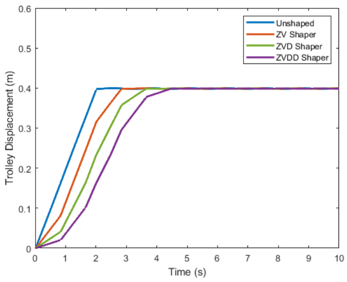
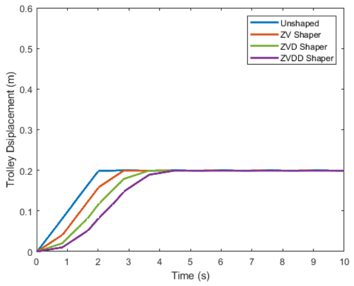
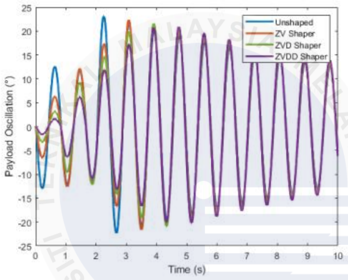
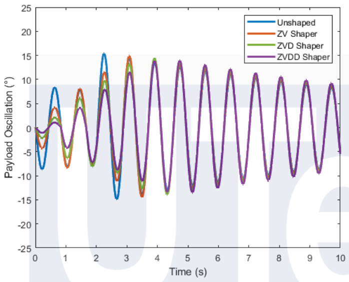
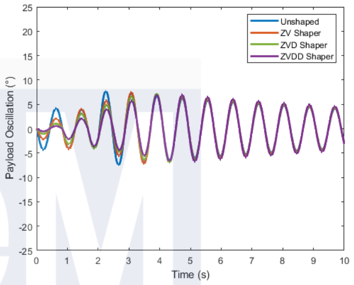
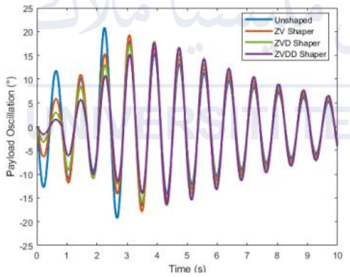
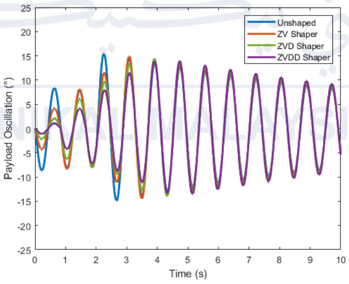
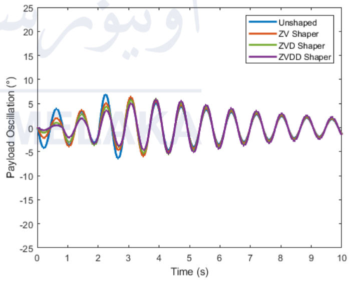
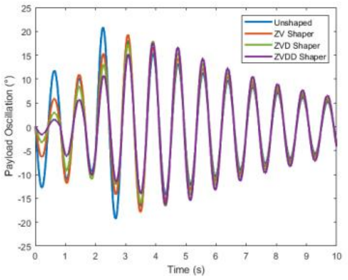
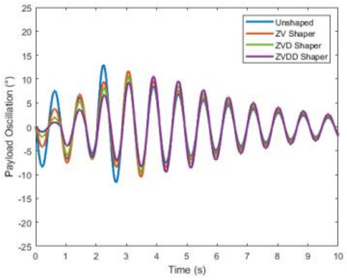
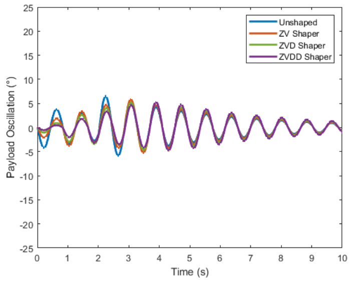
Input Force = 0.75 N	**Input Force = 0.50 N**	**Input Force = 0.25 N**
		
Payload Mass = 0.24kg 	Payload Mass = 0.24kg 	Payload Mass = 0.24kg 
Payload Mass = 0.54kg 	Payload Mass = 0.54kg 	Payload Mass = 0.54kg 
Payload Mass = 0.74kg 	Payload Mass = 0.74kg 	Payload Mass = 0.74kg 

Table 4-2: Value of SSE and maximum oscillation for Fixed Cable Length = 0.17m

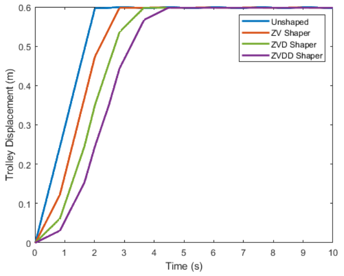
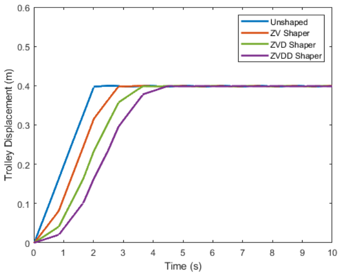
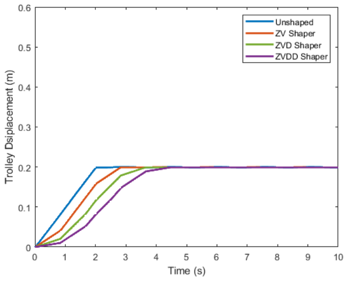
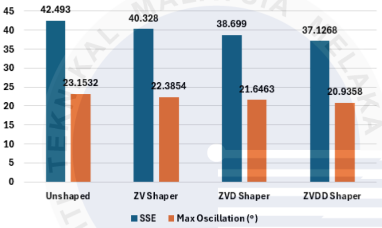
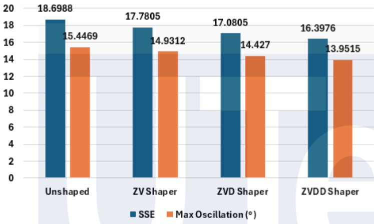
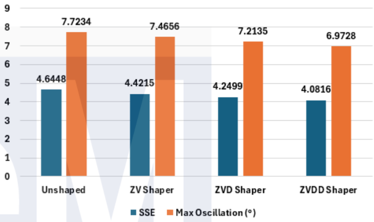
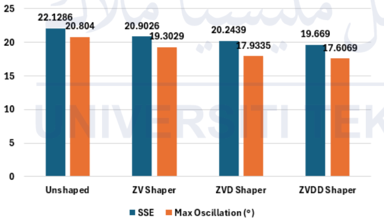
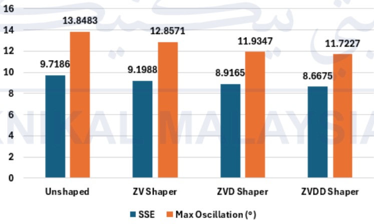
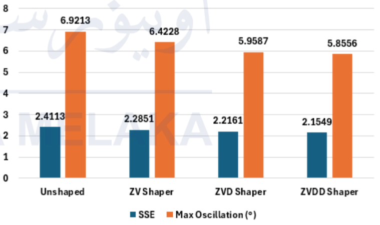
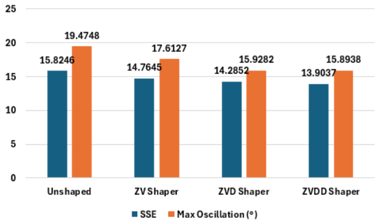
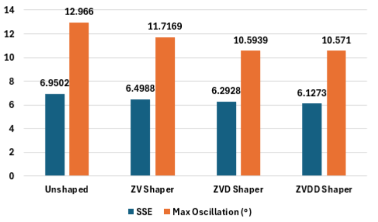
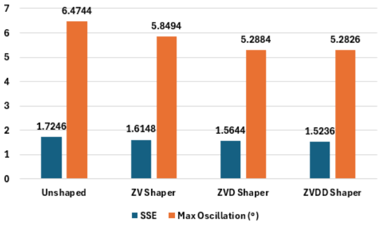
Input Force = 0.75 N	**Input Force = 0.50 N**	**Input Force = 0.25 N**
		
Payload Mass = 0.24kg 	Payload Mass = 0.24kg 	Payload Mass = 0.24kg 
Payload Mass = 0.54kg 	Payload Mass = 0.54kg 	Payload Mass = 0.54kg 
Payload Mass = 0.74kg 	Payload Mass = 0.74kg 	Payload Mass = 0.74kg 

Table 4-3: System response for Fixed Cable Length = 0.38m

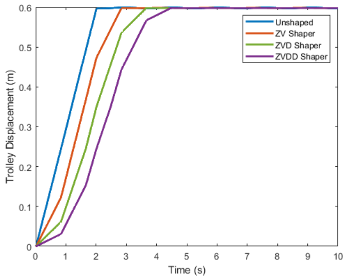
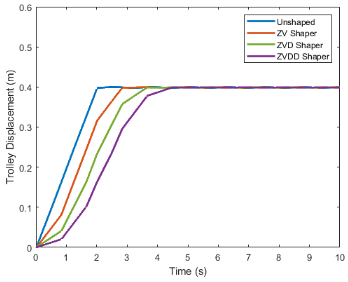
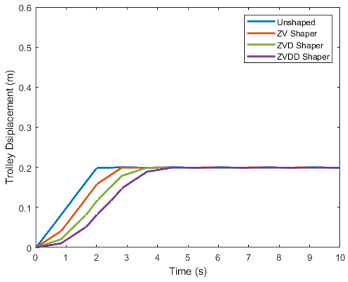
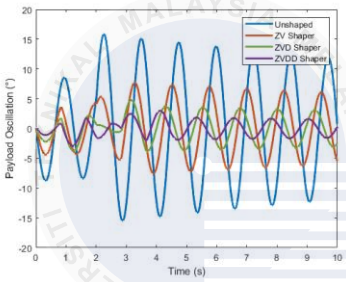
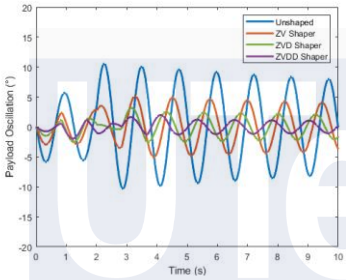
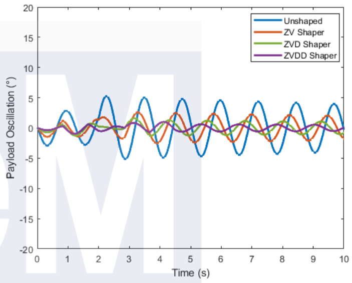
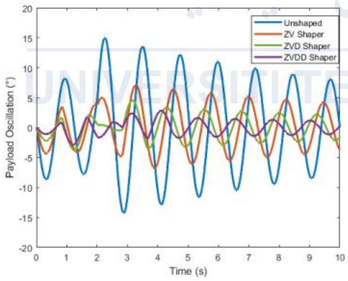
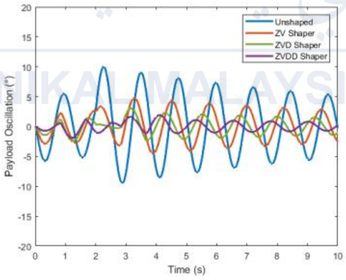
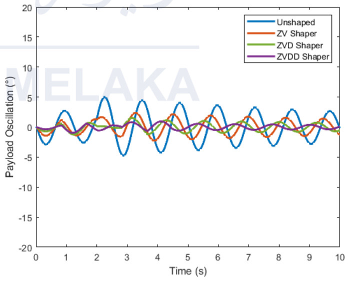
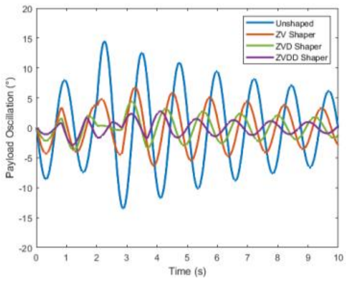
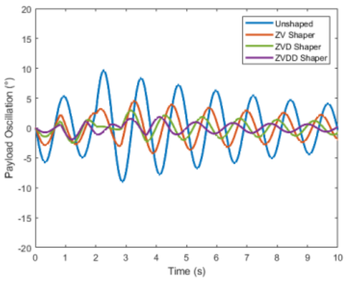
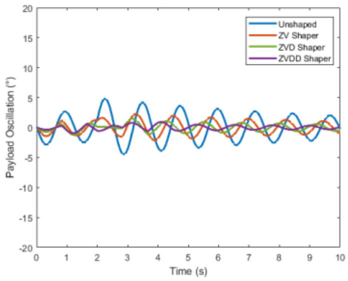
Input Force = 0.75 N	**Input Force = 0.50 N**	**Input Force = 0.25 N**
		
Payload Mass = 0.24kg 	Payload Mass = 0.24kg 	Payload Mass = 0.24kg 
Payload Mass = 0.54kg 	Payload Mass = 0.54kg 	Payload Mass = 0.54kg 
Payload Mass = 0.74kg 	Payload Mass = 0.74kg 	Payload Mass = 0.74kg 

Table 4-4: Value of SSE and maximum oscillation for Fixed Cable Length = 0.38m

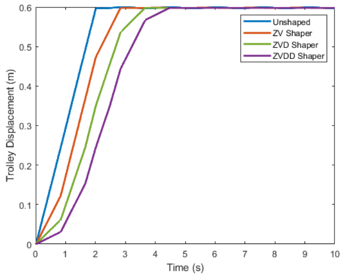
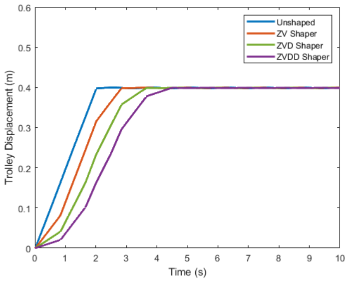
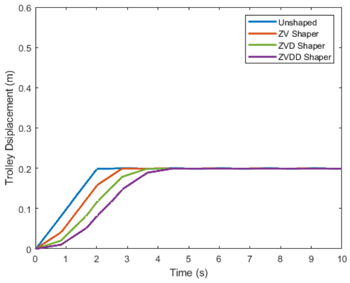
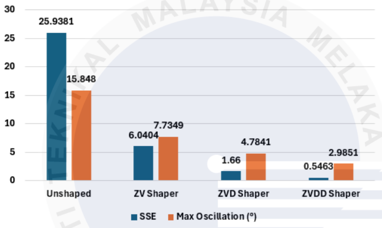
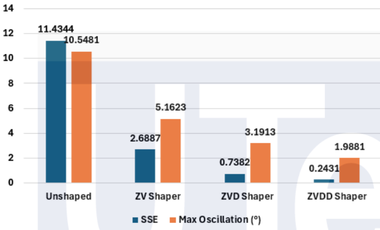
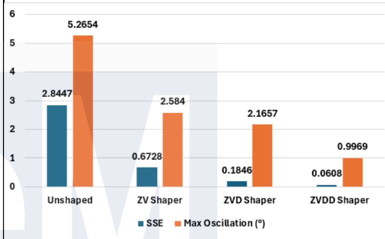
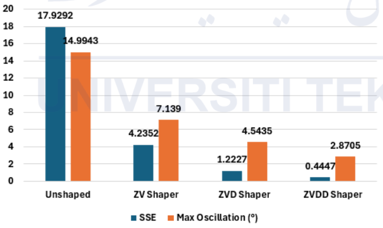
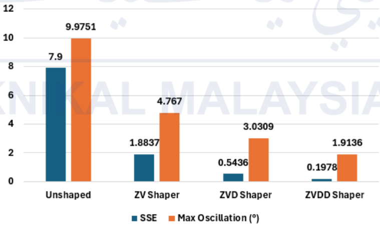
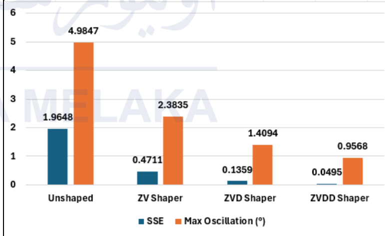
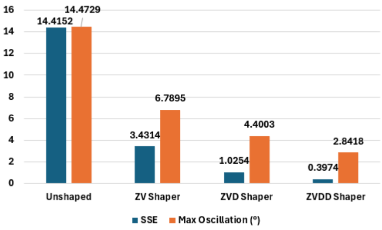
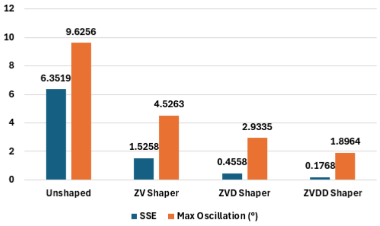
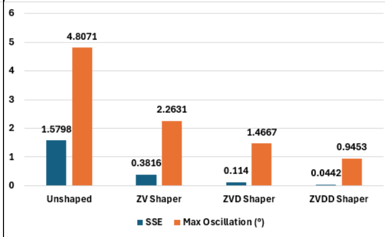
Input Force = 0.75 N	**Input Force = 0.50 N**	**Input Force = 0.25 N**
 	 	
Payload Mass = 0.24kg	Payload Mass = 0.24kg	Payload Mass = 0.24kg
 	 	
Payload Mass = 0.54kg	Payload Mass = 0.54kg	Payload Mass = 0.54kg
 	 	
Payload Mass = 0.74kg	Payload Mass = 0.74kg	Payload Mass = 0.74kg
 	 	

Table 4-5: System response for Fixed Cable Length = 0.59m

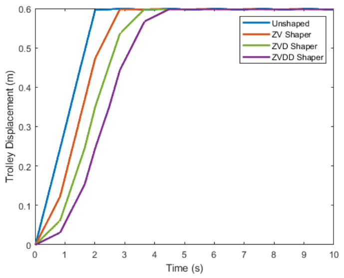
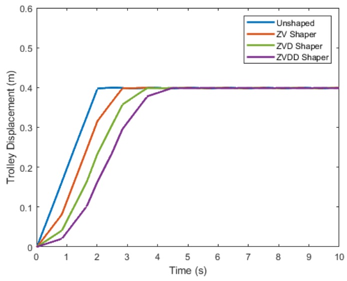
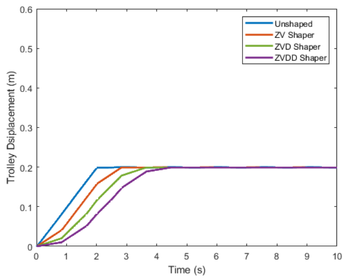
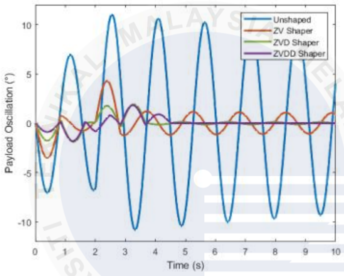
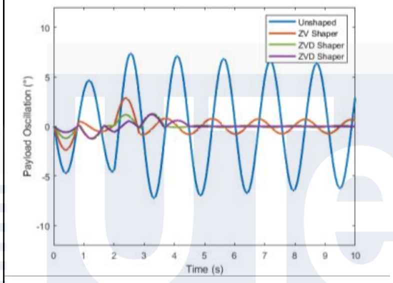
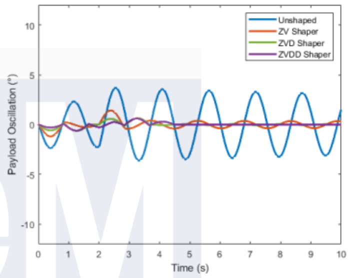
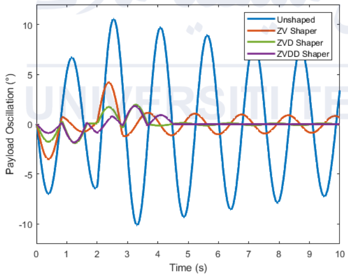
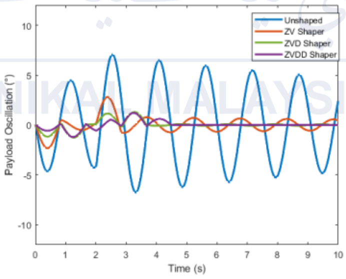
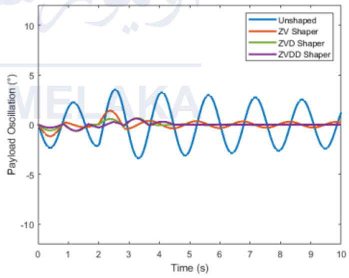
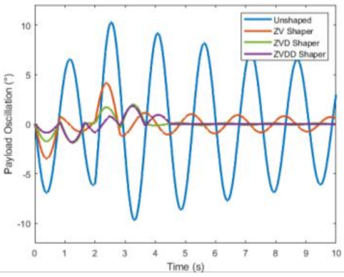
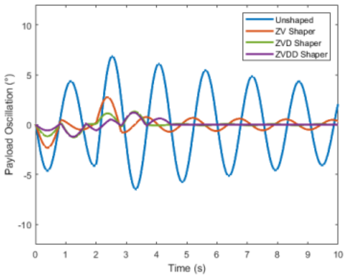
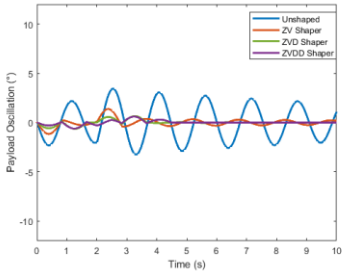
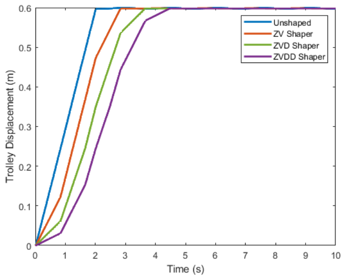
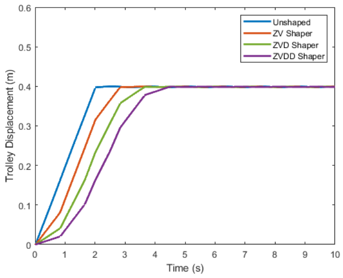
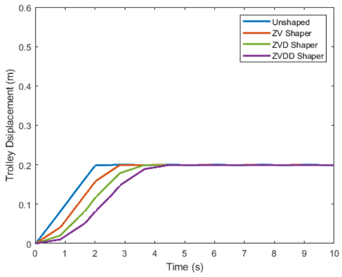
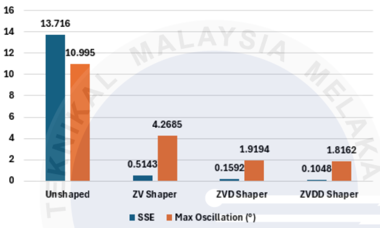
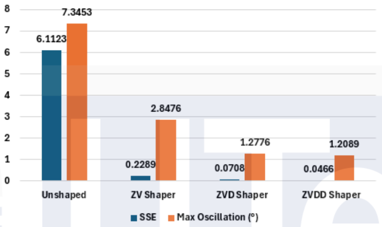
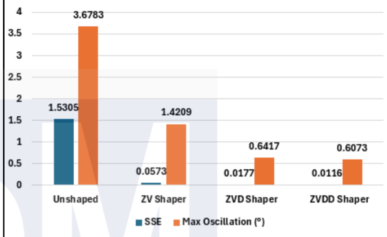
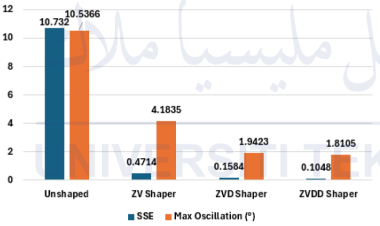
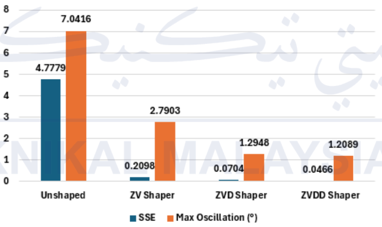
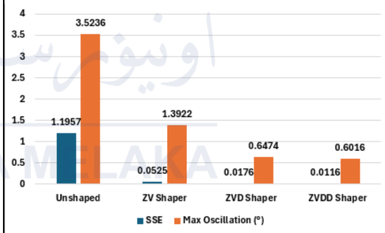
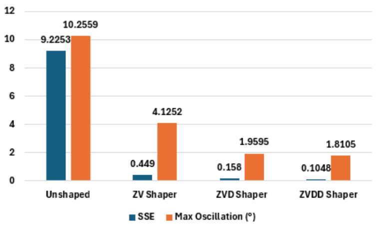
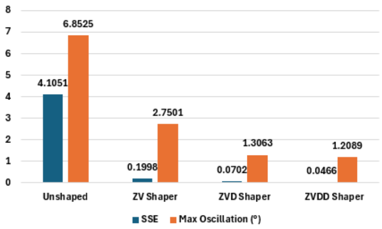
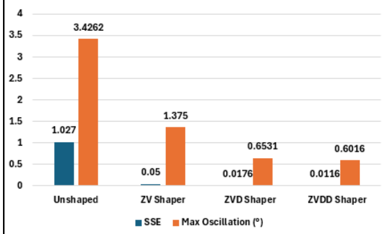
Input Force = 0.75 N	**Input Force = 0.50 N**	**Input Force = 0.25 N**
		
Payload Mass = 0.24kg 	Payload Mass = 0.24kg 	Payload Mass = 0.24kg 
Payload Mass = 0.54kg 	Payload Mass = 0.54kg 	Payload Mass = 0.54kg 
Payload Mass = 0.74kg 	Payload Mass = 0.74kg 	Payload Mass = 0.74kg 

Table 4-6: Value of SSE and maximum oscillation for Fixed Cable Length = 0.59m

Input Force = 0.75 N	**Input Force = 0.50 N**	**Input Force = 0.25 N**
		
Payload Mass = 0.24kg 	Payload Mass = 0.24kg 	Payload Mass = 0.24kg 
Payload Mass = 0.54kg 	Payload Mass = 0.54kg 	Payload Mass = 0.54kg 
Payload Mass = 0.74kg 	Payload Mass = 0.74kg 	Payload Mass = 0.74kg 

4.3.2 Overhead Crane System with Payload Hoisting

The ZVD shaper adjusts more smoothly to changes in cable length. It achieves lower maximum oscillation under varying conditions, demonstrating superior performance and adaptability compared to the ZV shaper. Next, the ZVDD shaper is appropriate for applications with great deal of variability because of its double derivative action, which efficiently handles variations in payload mass and cable length. It consistently reduces vibration accross a wide range of masses and adapt well to changes in cable length, ensuring system stability. Typically achieving the lowest maximum oscillation among the three controllers. The ZVDD shaper guarantees superior vibration control even in demanding operating conditions, while the ZV shaper is effective under stable conditions as shown in Table 4-7 and Table 4-8.

Table 4-7: System response for Payload Hoisting

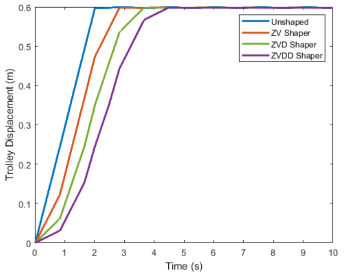
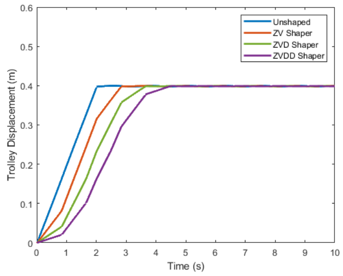
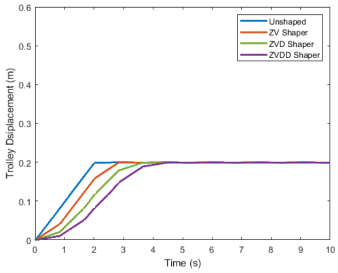
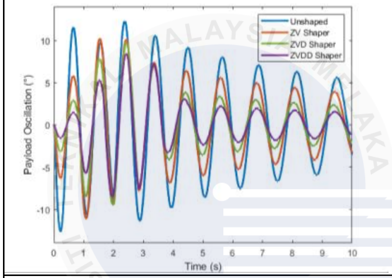
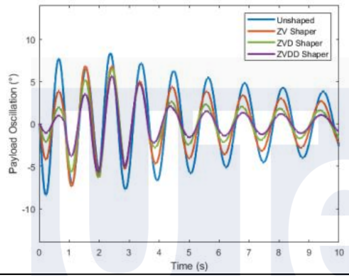
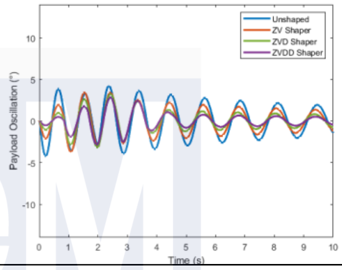
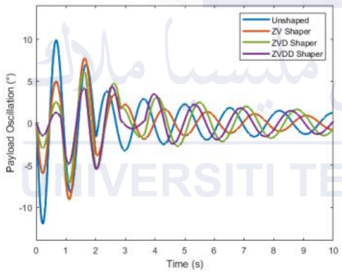
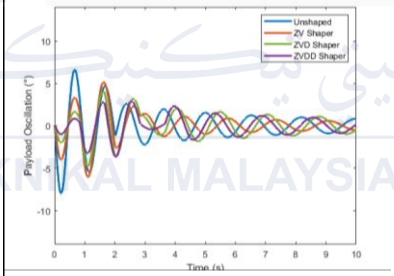
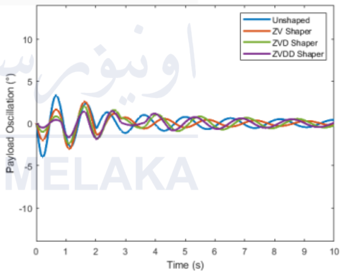
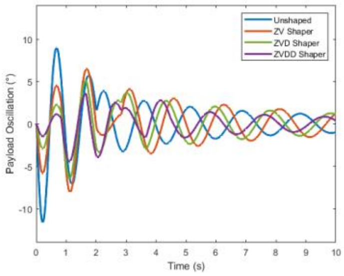
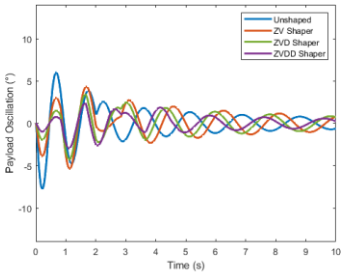
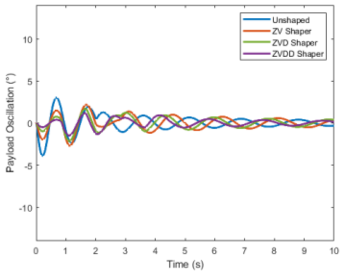
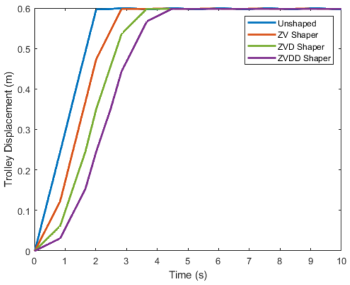
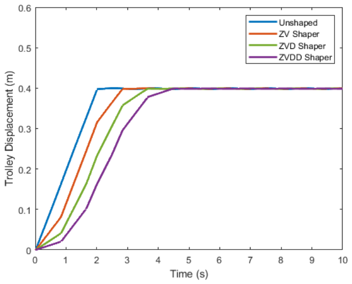
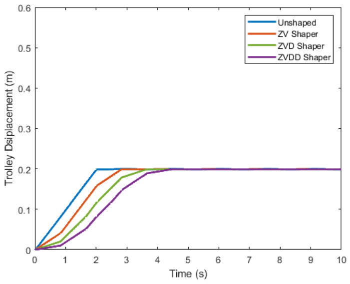
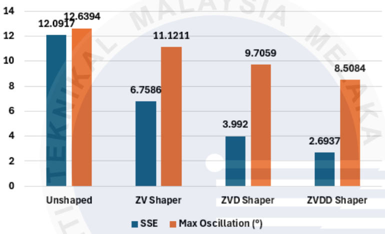
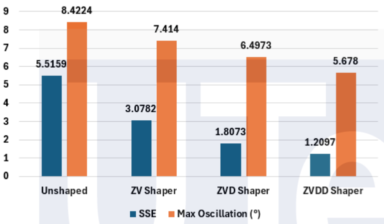
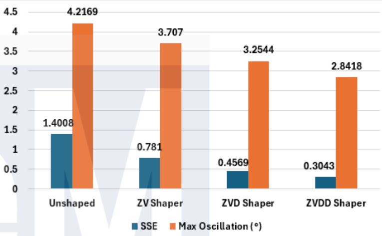
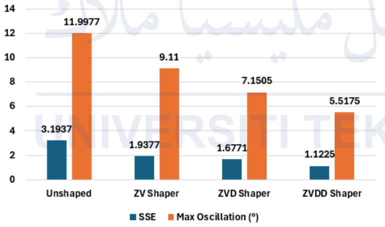
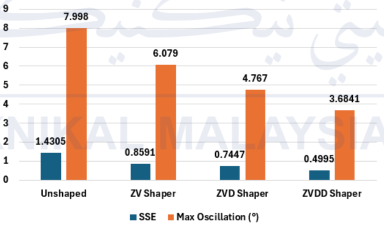
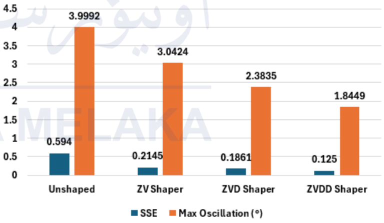
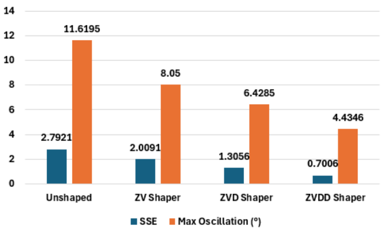
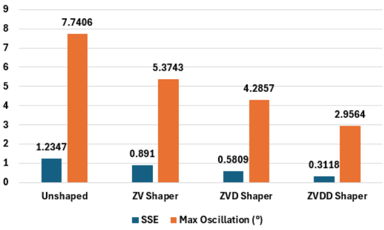
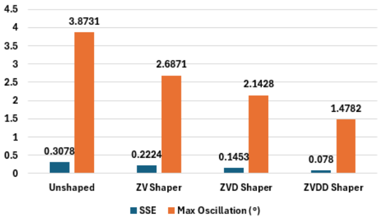
Input Force = 0.75 N  	**Input Force = 0.50 N**  	**Input Force = 0.25 N** 
Payload Mass = 0.24kg  	Payload Mass = 0.24kg  	Payload Mass = 0.24kg 
Payload Mass = 0.54kg  	Payload Mass = 0.54kg  	Payload Mass = 0.54kg 
Payload Mass = 0.74 N  	Payload Mass = 0.74kg  	Payload Mass = 0.74kg 

Table 4-8: Value of SSE and maximum oscillation for Payload Hoisting

Input Force = 0.75 N	**Input Force = 0.50 N**	**Input Force = 0.25 N**
		
Payload Mass = 0.24kg 	Payload Mass = 0.24kg 	Payload Mass = 0.24kg 
Payload Mass = 0.54kg 	Payload Mass = 0.54kg 	Payload Mass = 0.54kg 
Payload Mass = 0.74kg 	Payload Mass = 0.74kg 	Payload Mass = 0.74kg 

The ZVDD shaper guarantees superior vibration control even in demanding operating conditions. While the ZV shaper is effective under stable conditions. The ZVD and ZVDD shapers perform best in dynamic circumstances, whereas the ZVDD shaper offers the most comprehenisve oscillations control for efficient and precise operation of overhead crane systems.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

To summarize, all of the objectives for the project are succesfully achieved with the simulation movement of the trolley and payload oscillation of the crane system. Input shaping controllers, specifically ZV, ZVD and ZVDD, are highly effective for managing vibrations in overhead crane systems. Each controller has its own strengths, with the ZV controller offering reliable basic control while the ZVD and ZVDD controllers providing advanced capabilities for more complex situations. The ZVD and ZVDD controllers, enhanced with derivative components, excel in performance, especially in dynamic conditions with variable payload hoisting.

5.2 Future Works

Future research could investigate integrating these input shaping controllers with other advanced control strategies, like adaptive and predictive controls, to further improve system performance. Additionally, experimental validation of these controllers in real-world crane systems would offer valuable insights and confirm their practical effectiveness.

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