ACTIVE SWAY CONTROL OF A GANTRY CRANE SYSTEM USING DELAYED FEEDBACK SIGNAL CONTROLLER

WAN MOHD SAIFUDDIN BIN W ZAMANI

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

BORANG PENGESAHAN STATUS TESIS♦

JUDUL: **ACTIVE SWAY CONTROLOF A GANTRY CRANE (SIMULATION USING DFS CONTROLLER)**

SESI PENGAJIAN: 2007/2011

Saya **WAN MOHD SAIFUDDIN BIN W ZAMANI (881111-03-5613)**
(HURUF BESAR)

mengaku membenarkan tesis (Sarjana Muda/~~Sarjana~~ /~~Doktor Falsafah~~)* ini disimpan di Perpustakaan dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hakmilik Universiti Malaysia Pahang (UMP).
2. Perpustakaan dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (√)

[ ]	**SULIT**	(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)
[ ]	**TERHAD**	(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)
[√]	**TIDAK TERHAD**	

Disahkan oleh:

______________________	______________________
(TANDATANGAN PENULIS)	(TANDATANGAN PENYELIA)

Alamat Tetap:

17 R LORONG HAJI NIK MAT,
JALAN KOTA BHARU,
16800 PASIR PUTEH,
KELANTAN.

MOHD ANWAR BIN ZAWAWI
(Nama Penyelia)

Tarikh: **21 OKTOBER 2010**

Tarikh: : **21 OKTOBER 2010**

CATATAN:
* Potong yang tidak berkenaan.
** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali tempoh tesis ini perlu dikelaskan sebagai atau TERHAD.
♦ Tesis dimaksudkan sebagai tesis bagi Ijazah doktor Falsafah dan Sarjana secara Penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM).

ACTIVE SWAY CONTROL OF A GANTRY CRANE SYSTEM USING DELAYED FEEDBACK SIGNAL CONTROLLER

WAN MOHD SAIFUDDIN BIN W ZAMANI

This thesis is submitted as partial fulfillment of the requirements for the award of the Bachelor of Electrical Engineering (Electronics)

Faculty of Electrical & Electronics Engineering
Universiti Malaysia Pahang

NOVEMBER, 2010

“All the trademark and copyrights use herein are property of their respective owner. References of information from other sources are quoted accordingly; otherwise the information presented in this report is solely work of the author.”

Signature : ______________________________

Author : WAN MOHD SAIFUDDIN BIN W ZAMANI

Date : 21 OKTOBER 2010

"I hereby acknowledge that the scope and quality of this thesis is qualified for the award of the Bachelor Degree of Electrical Engineering (Electronics)"

Signature : ____________________________

Name : EN MOHD ANWAR BIN ZAWAWI

Date : 21 OKTOBER 2010

Specially dedicated to
My Beloved Dad and Mum, My Family and My Beloved friends.
And those people who have guided and inspired me throughout my journey of education

Thank's For Everything…

ACKNOWLEDGEMENT

First and foremost, Alhamdulillah, thanks to ALLAH S.W.T for his bless and guidance, I finally finished my final year project and thesis. In preparing this thesis, I was in contact with many people, researchers, academicians and practitioners. They have contributed towards my understanding and thoughts. In this short column, I would like to express my sincere gratitude and fully appreciation to my dedicate supervisor, En Anwar Bin Zawawi for his encouragement, guidance, critics, friendship, advice, information and motivation. It would be difficult to complete this project without his direction and support from the beginning until I have done this project.

I also want to express gratitude to my family especially for my parent for their love, morale support and prayer along my study. Their fully support has given me enough strength and inspiration in pursuing my ambition in my life as well as to complete this project.

I am also indebted to Universiti Malaysia Pahang (UMP) for funding my degree study. Librarians at UMP also deserve special thanks for their assistance in supplying the relevant literatures and guiding me in using e-journal.

Last but definitely not the least, I also would like to say thanks to all my lecturers and also my coursemates especially Ariff and Khairul Azmi which always given me help technically and mentally during the journey to accomplish this project.

Thank you

Wan Mohd Saifuddin Bin W Zamani

ABSTRACT

Gantry Cranes are common industrial structures that are used in building construction, factories, and harbors. These cranes are usually operated manually. With the size of these cranes becoming larger and the motion expected to be faster, the process of controlling them became difficult without using automatic control methods. In general, the movement of cranes has no prescribed path. Cranes have to be run under different operating conditions, which makes closed-loop control preferable. The aim of this project is to develop a controller to reduce the sway angle of the rope for a two-dimensional gantry crane system. The 2D-gantry crane system consists of a cart, rope, payload, actuator as well as controller. In this project, the control technique to be implemented to control the sway angle of the rope is Delayed Feedback Signal (DFS). In DFS, the control signal is calculated based on delayed position feedback. The performance on system in 2D-gantry crane focused on the sway angle of the hoisting rope and its corresponding Power Spectral Density (PSD) on the sway angle response. Finally, the comparative assessment of the effects of the system using DFS controller is tested by using different values of the parameters such as mass of the load, length of the rode and the initial point of release load.

ABSTRAK

Kren Gantri adalah struktur industri umum yang digunakan dalam pembinaan bangunan, kilang, dan pelabuhan. Kren ini biasanya dikendalikan secara manual. Dengan saiz kren yang lebih besar dan gerakan yang diharapkan akan lebih cepat, proses kawalan kren tersebut menjadi sukar tanpa menggunakan kaedah kawalan automatik.Objektif projek ini ialah untuk membina pengawal untuk mengurangkan ayunan pada kren gantri dua dimensi. Sistem kren gantri 2-D dilengkapi dengan pengangkut,tali dan beban sebagai pengawal. Dalam projek in,teknik untuk mengawal yang digunakan dalam melaksananankannya ialah Tangguhan Masa Maklumbalas. Tangguhan Masa Maklumbalas dikira berdasarkan pada tangguhan posisi maklumbalas. Pada persembahan untuk sistem kren gantri 2-D difokuskan pada ayunan pengankutan tali dan Kepadatan Kuasa Spektral. Akhirnya, penilaian perbandingan kesan penggunaan DFS controller ke atas sistem diuji dengan menggunakan nilai yang berbeza dari segi parameter jisim beban, panjang rod dan sudut awal beban dilepaskan.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

DFS	Delay Feedback Signal
PSD	Power Spectral Density

CHAPTER 1

INTRODUCTION

1.1 Crane : Overview

In our environment, it is hard to lift or transfer a heavy object from one place to another place. To solve that problem, cranes are commonly employed in industries either in domestic industries or warehouse. For example, crane is used in transport industry for the loading and unloading of equipment, in the construction industry for the movement of materials and in the manufacturing industry for the assembling of heavy material. These materials are usually heavy, large and hazardous, which cannot be handling by workers. A crane consists of a hoisting and a support mechanism. The loads suspended on cables from a hook at a point on the support mechanism. Then, the support mechanism will move the hanged load into the crane workspace. After that, the hoisting mechanism will lift the load to be placed to the desired. One of the challenging in the control of the cranes is to reduce the swaying. These sway typically caused by movement of the trolley. This swaying not only reduces the efficiency of the cranes, but also can cause safety problem in the complicated working environment.

1.1.1 Type of Crane

Crane can be dividing into two types, mobile crane and fixed crane which they have a different function.

1.1.1.1 Mobile Crane

A mobile crane is generally a crane which consist a travelling device with rubber-tired wheel that is easily moveable from one location to another. The mobile crane provides great mobility during operations in the site area. Mobile crane is responsible for the most accidents and injuries. To avoid a serious injury due to an accident, it must be operated by trained staff. Besides that, the staff also should to wear safety boot, hard hats and high visibility clothing when working around the crane. To ensure that the load is properly installed, a spotter must be required. The advantage of a mobile crane is it can be easily moved from one site to the other site. It also makes operations easy and fast by moving quickly to any point within a jobsite. Otherwise, the mobile crane does not need any special installation. It can start working as soon as it enters the site. Mobile crane is widely used today in the fields of transportation, construction, mechanical manufacturing factories etc. In transportation industry a mobile crane is commonly used on harbors and airports, to load and unload heavy objects. While in the construction industry, mobile crane plays an important role in shifting heavy construction material and blocks. In some factories, mobile crane is used to assemble heavy metal spare parts. There are several types of mobile crane commonly use like truck, side lift, aerial crane, railroad, and crawler.

Most people are familiar with the truck crane. A truck mounted crane is great for move heavy construction loads. All work truck cranes provide 360° rotation when mounting on truck bed. Hand pump actuates hydraulic cylinder to lift loads.

This crane is able to travel on main roads and highways. However, the movement or speed of a truck mounted crane is quite slow, because of its heavy load. This additional flexibility makes it possible to transport large loads and access a wide range of locations.

Figure 1.1: Truck Crane

Another type of mobile crane is side lift. This crane is able to transport materials and hoist large containers. The added benefit of this mobile crane is that it can be used to lift a container either from the ground or from a railway vehicle. To lift a very large containers are using a pair of side lift cranes. Aerial crane is another type of mobile crane which able to travel or to lift in areas that are difficult to reach by other cranes. Ariel cranes are most commonly used in construction of building or tower. They can lift anything within their lifting capacity. It is also cable to use in extinguishing the fire with carry a bucket of water and pour onto the fire.

Figure 1.2: Side Lift Crane

Figure 1.3: Aerial Crane

A railroad crane is specifically designed with flanged wheels so it can travel along railroad tracks. These units are used for maintenance work and loading freight into railway cars. On occasion, they are also involved in recovery operations when trucks tip over or spill their load. The other mobile crane is crawler crane which it able to work on soft ground. It is made more stable allows users to avoid the process to stabilize the crane. One of the features that allow a crawler crane to lift such enormous loads is a counterweight. Some of the larger crawler crane counterweight assemblies weigh as much as several hundred tons. Many crawler cranes have booms that reach several hundred feet in the air. Such reach and lift capabilities make the machines perfect for large construction projects.

Figure 1.4: Rail Road Crane

Figure 1.5: Crawler Train

1.1.1.2 Fixed Crane

Fixed crane is described as a crane of which the principal structure is mounted on permanent or semi permanent foundations. They do not move during used this crane. Usually fixed crane have the ability to lift and move the greater loads due to their increase stability. A fixed crane has a greater weight capacity and can lift loads much higher compare to mobile crane because it does not have the mobility of other types of cranes. With this great power of the fixed crane also comes a great potential danger that will cause a very serious injury or death. When using such a crane on a construction site, or any other type of site, and a load drops from it, it is almost impossible to stop the load from hitting the ground or anyone in its path. The worker must be wear protective clothing and safety gear, such as safety glasses, a hard hat, and steel-toed shoes to avoid the serious injury due to an accident. They are several different types of fixed crane like gantry crane, overhead crane, tower crane, rotary crane, jib crane and telescopic crane.

Gantry crane are very common in factories, where they are designed to move the material or equipment along the factory floor as the product is slowly assembled. The gantry crane may also be used to move the parts around, typically along the assembly line as the components are assembled. Each gantry crane is able to lift only one material with a maximum amount and cannot be exceeded. It is not easy to move a heavy weight on the end. The operator must be aware to handle this crane to avoid an accident.

Figure 1.6: Gantry Crane

Other type of fixed cranes commonly used in construction is overhead crane which is permanently fixed in place overhead for moving huge volumes of material and heavy material which cannot be moved easily by hand. These cranes are also used at ports all over the world, to carry container or material from the ships or to transfer into the ship. These cranes tend to be quite large, very expensive, and ca with a movable bridge that carries a hoisting mechanism and travels on a fixed runway structure.

Rotary crane also included in the group of fixed crane. They are two types of rotary crane; boom crane and tower crane are common industrial structures that are used in building construction, factories, and harbors. These designed to move or transport very large material. With the size of these cranes becoming larger and the motion expected to be faster, the process of controlling them became difficult without using automatic control methods. In general, the movement of cranes has no prescribed path. A tower crane is used in the construction of tall buildings. Tower cranes are fixed to the ground during the construction period.

Figure 1.7: Overhead Crane

Figure 1.8: Tower Crane

A jib crane is a type of crane where a horizontal member, supporting a moveable hoist, is fixed to a wall or to a floor-mounted pillar. Jib cranes are usually used in industrial premises and on military vehicles. The jib may swing through an arc, to give additional lateral movement, or be fixed. Similar cranes, often known simply as hoists, were fitted on the top floor of warehouse buildings to enable goods to be lifted to all floors.

A telescopic crane is one of the fixed cranes. It has a boom that consists of a number of tubes fitted one inside the other. A hydraulic or other powered mechanism extends or retracts the tubes to increase or decrease the total length of the boom. These types of booms are often used for short term construction projects, rescue jobs, lifting boats in and out of the water. The relative compactness of telescopic booms makes them adaptable for many mobile applications, often of short duration.

Figure 1.9: Jib Crane

Figure 1.10: Telescopic Crane

1.1.2 Gantry Crane

Gantry crane is used in most demanding environments where very heavy equipment and machines have to be lifted. It is usually used to loads in areas which have restricted access. We can easily locate a gantry crane at factories to lift loads and equipment which ordinary cranes might not be able to lift.

This types of cranes in-corporate a trolley, which meaning in a horizontal plane. The payload is attached to the trolley by a cable, whose length can be varied by a hoisting mechanism. The load with the cable is treated as a one-dimensional pendulum with one-degree-of-freedom sway. There is another version of these cranes, which can move also horizontally but in two perpendicular directions. The analysis is almost the same for all of them because the two-direction motions could be divided into two uncoupled one-direction motions.

Gantry Crane is used to lift heavy objects with the help of a hoist which is fixed in trolley. The hoist can move horizontally on a rail which is fixed under the beam. Gantry cranes have wheels on the foot of the crane which allows it to traverse. The wheels of the crane rest on a supporting beam which is fixed parallel to the factory wall or any other large building. Some gantry cranes are fixed and are used to move railway cargo.

Figure 1.11: Gantry Crane at factory

Most companies use gantry crane to lift objects which are very heavy. Shipping industry find gantry crane useful as gantry crane are used to lift heavy objects like ship engines which has to be moved over to the ship. Gantry crane is not only used for lifting heavy objects but also used in small workshops to lift automobile engines for automotive companies.

The biggest benefit of gantry crane is that they don't need tracks as they have rubber tires. Workstation gantry crane is also used to move small items in factory area. Most gantry cranes used at workstation are stationary when equipment and items are loaded and mobile when items and equipment are unloaded.

Figure 1.12: Gantry Crane at port

1.1.3 Incidents Involving Gantry Crane

Gantry crane has a lot to help the people in the workplace, especially in the process of lifting or moving the heavy or large loads. However, the operator must use that crane in the right way such as do not use your gantry to lift more than their rated capacity to avoid an accident which can cause serious injury or death.

There are many cases and incident regarding on the crane's accidents. For example, in July 2007, a worker at Nucor Steel Corp.'s Marion, Ohio, facility was killed after being yanked into a crane. He had been suspended in a harness 30-40ft above the ground while working on the mill's air conditioning system. The harness reportedly became tangled in the crane's shaft causing the man to be pulled into the crane. In February 2008, at AK Steel Corp. Coshocton, Ohio, the worker, David Wemtz, was killed while performing maintenance work. He was crushed by a steel coil that was being lowered by a gantry crane [1].

In March 2008, a crane operator, Jason Lee Blackmon, fell 40ft to his death at Gerdau Ameristeel Corp.'s Jackson, Tennessee, facility. Reportedly he had been on a platform about to board the crane during a shift change when the crane failed to come to a complete stop, as it is required to do when a worker boards the crane [1].

In May 2008, Russell Payne, a millwright at Arcelor Mittal USA's Burns Harbor, Indiana, facility died when he was caught between two steel beams and crushed. The crane caught one beam and dragged it to another. Reportedly the crane operator had thought that Payne had moved out of the area, and attempted to put the crane back in place via remote control [1].

1.1.4 Gantry Crane Safety

Operating a gantry crane can prove a difficult and dangerous if the operator do not use that crane properly. To avoid the accidents at workplace during using the gantry crane, the operator must follow some procedure:

a) Do not move or lift the overweight of load.
b) The hoist rope is not wrapped around the load.
c) Slings, load chains and other lifting devices are securely seated on the hook.
d) The hoist is located directly above the load to be lifted.
e) The load is properly secured and balanced. This can be checked as the load is lifted slightly. Reposition the sling if required.

1.2 Problem Statement

Almost every industry uses a gantry crane for its material handling applications. These gantry cranes are mostly equipped with cabled hoisting mechanism, which are prone to the load sway problems. When a human operator attempts to maneuver payloads using a gantry crane, oscillations induced into the payload by the motion of the trolley can be significant. These oscillations make it difficult to manipulate the payload quickly and with positioning accuracy. Furthermore, when the workspace is cluttered with obstacles, the oscillations can create significant safety issues, especially when then payload or obstacles are of a hazardous nature.

Many control strategies based on the classic or modern control techniques have been proposed and tested in the laboratory level for the control of the crane system, such as PID controller, adaptive control, optimal control, and nonlinear control. However, from the practical point of view, real-time control requires some simplification of the experimental model, and human intervention is always necessary for this type of control. Another issue relating to the case of conventional control is the robustness problem. Due to this problem, project of the control delayed feedback signal of a modeling gantry crane system will be investigated.

1.3 Objective of Project

The main objective of this project is to study the performance of the controller to reduce the sway angle of the rope for a two-dimensional gantry crane system.

1.4 Project Scopes

They are several scopes of this project;

i. The two-dimensional crane system consists of a cart, rope, payload, actuator as well as controller.

ii. The control technique to be implemented to control the sway angle of the rope is Delayed Feedback Signal (DFS).

iii. The control signal for DFS controller requires only one position sensor and uses only the current output of this sensor and the output τ second in past.

iv. There are only two control parameter, k and τ that need to be set.

v. Simulation has been carried using Simulink for several critical time delays and for various gains.

vi. For comparative the performance of the system, the parameter for mass of the load, length of the rode and the initial point of release load are set up with the various value.

1.5 Thesis Outline

Thesis is orderly organized into 5 chapters. Each chapter will be elaborated in details.

Chapter 1 explains an overview of the crane which it cover the type of crane, the gantry crane, incident involving the gantry crane and gantry crane safety. It also outlines the problem statement, objective and scope of the project.

Chapter 2 discusses the previous work that been done around the world about the crane, in term of dynamic modeling, or designing the crane system. Literature that been done will cover, for modeling, crane control approaches, and the delayed feedback signal as a controller.

Chapter 3 will be focused on methodology of this project. In this chapter, each step in the work methodology flow chat starting from modeling of the gantry was explained.

Chapter 4 consists of experimental results and results analysis. Comparison the performance of the control for the different value of the parameter mass of the load, length of the rode and the initial point of release load will be discussed.

Chapter 5 discusses the overall conclusion and future recommendation for future development.

CHAPTER 2

LITRETURE REVIEW

2.1 Dynamic Modeling of Gantry Crane System

The model of gantry crane system with its payload is consider in this work is shown in Figure 2.1. From that figure, x is represents the horizontal position of the movement cart, *l* is the length of the rope. The angle θ is for the sway angle, M is for mass of cart and m is the mass of payload. The cart is considering move in two-dimensional plane x-y plane.

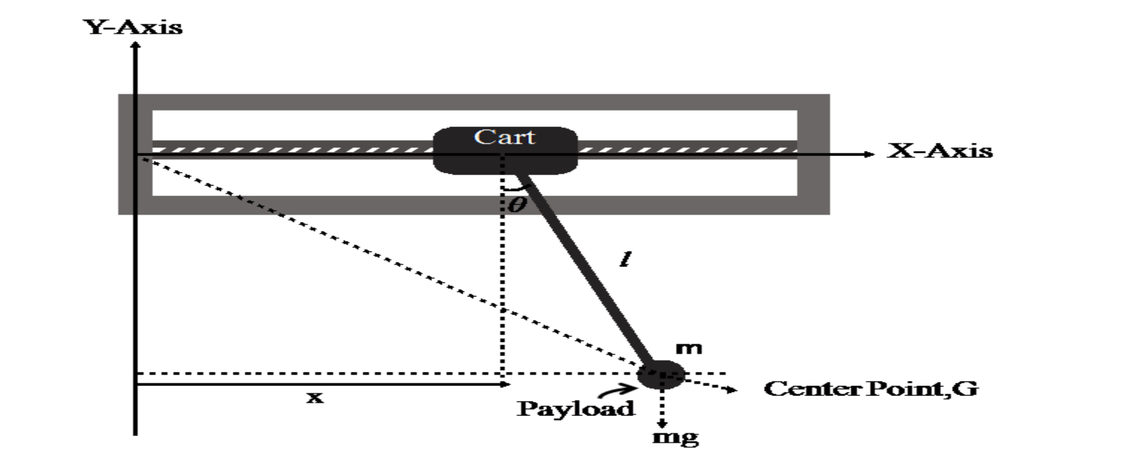


Figure 2.1 Modeling of Gantry Crane System

When operate the payload, the oscillations induced into the payload by the motion of the cart and it can be significant. These oscillations make it difficult to manipulate the payload quickly and with positioning accuracy. Furthermore, when the workspace is cluttered with obstacles, the oscillations can create significant safety issues, especially when the payload is of a hazardous nature.

By referring [2], to investigate the system on the modeling of the gantry crane, considered the Eular-Lagrangre formulation to derive the equation of motion of the gantry crane. The kinetic energy of the system can thus formulated as

$$T = \frac{1}{2}M\,\dot{x}^2 + \frac{1}{2}m(\dot{x}^2 + \dot{l}^2 + l^2\dot{\theta}^2 + 2\dot{x}\,\dot{l}\,sin\theta + 2\dot{x}\,l\dot{\theta}\,cos\theta) \qquad ...(2.1)$$

Then, the potential energies of the system are given by

$$U = -mglcos\theta \qquad ...\ (2.2)$$

Let the generalized forces corresponding to the generalized displacements $q = \{x, \theta\}$ be $F = \{F_X, 0\}$. Constructing L = T – U and using Lagrangian's equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \left(\frac{\partial L}{\partial \dot{q}_j}\right) = F_j \qquad j = 1,2 \qquad ...\ (2.3)$$

So, the equation of motion was summarized

$$F_x = (M + m)\ddot{x} + ml(\ddot{\theta}\ cos\ \theta - \dot{\theta}^2\ sin\ \theta\ ) + 2m\dot{l}\dot{\theta}\ cos\ \theta + m\ddot{l}\ sin\ \theta \qquad ...(2.4)$$

$$l\ddot{\theta} + 2\dot{l}\dot{\theta} + \ddot{x}\,cos\ \theta + g\ sin\ \theta = 0 \qquad ...(2.5)$$

Then, the model of uncontrolled system in steady state can be represented

$$\dot{x} = Ax + Bu$$

$$y = Cx \qquad ...(2.6)$$

With the vector $x = [x \quad \dot{x} \quad \theta \quad \dot{\theta}]$

Matrices A and B are given

$$A = \begin{vmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{mg}{M} & 0 & 0 \\ 0 & -\frac{(M+m)g}{Ml} & 0 & 0 \end{vmatrix} \qquad B = \begin{vmatrix} 0 \\ 0 \\ \frac{1}{M} \\ -\frac{1}{Ml} \end{vmatrix}$$

$$C = \begin{vmatrix} x & \dot{x} & \theta & \dot{\theta} \end{vmatrix} \qquad D = \begin{vmatrix} 0 \end{vmatrix} \qquad \text{...(2.7)}$$

2.2 Crane Control Approaches

Crane was designed for the lifting, lowering and horizontal movement of a load with a hoisting mechanism in a short time to load reach to its destination faster without swinging. During the operation, the load must be free in swaying. The operation must be stopped until the swing dies out when the swing over a limit. Otherwise, it can cause accidents.

Many researchers try to overcome this problem with develop control algorithms to automate crane operations. However, most of the researches are not suitable for practical implementation. Due to this problem, most industrial cranes still depend on operators compare with using automated crane, who sometimes fail to reduce the swing. Accidents can happen if we do not solve this problem which can cause serious injury or death. In addition, the nature of the crane environment, which is often unstructured in shipyards and factory floors which caused most industrial crane not using an automated crane because it is difficult to operate that crane. The control algorithm should be able to overcome with these conditions. By referring [3], they concentrate on reviewing the general approaches used in the crane control.

In operation of crane, they are five steps. The first step is gripping the loads. Then, the loads will be lift. Next step is moving the loads from point to point. Then, the loads are lowering before it is ungripping. A full automation of these processes is possible and has been described clearly through [4]. The process takes a long time is the step to move the load from one point to another point and requires a skillful operator to accomplish it. Most researchers now are trying to find the most suitable method to facilitate the process of moving load with reduces the swing. They are two approaches for crane automation.

The first approach, the operator is kept in the loop and modifies the dynamic of the load to make his job easier. First way is to add damping by feeding back the load swing angle and its rate or by feeding back a delayed of the swing angle [5,6]. This feedback adds another way which it generated by the operator. A second way is to remove this frequency from the input by adding the filter to avoid exciting the load near its natural frequency [7]. This shows time delay between the operator action and the input to the crane. This delay may confuse the operator. A third way is to add a mechanical absorber to the structure of the crane [8]. Implementing this method requires a considerable amount of power, which makes it impractical.

In the second approach, the operation is completely automated by removing the operator from the loop. The various techniques can be done for this operation. The first technique is based on generating trajectories to transfer the load to its destination with minimum swing. These trajectories are obtained by either input shaping or optimal control techniques. The second technique is based on the feedback of the position and the swing angle. The third technique is based on dividing the controller design problem into two parts: an anti-swing controller and a tracking controller. Each one is designed separately and then combined to ensure the performance and stability of the overall system.

Feedback control is well-known to be less sensitive to disturbances and parameter variations. Hence, it is an attractive method for crane control design.
[9] developed a controller, which feeds back the trolley position and speed and the load swing angle.

The feedback gains are calculated by trial and error based on the root-locus technique. Later, he improved his controller by changing the trolley velocity gain according to the error signal [9]. Through this approach, the system damping can be changed during transfer of the load. Initially, damping is reduced to increase the velocity, and then it is increased gradually.

Consequently, a faster transfer time is achieved. However, the nominal feedback gains are obtained by trial and error. This makes the process cumbersome for a wide range of operating conditions. [10] employed feedback control with adaptive gains, which are calculated based on the pole-placement technique.

Since the gains are fixed during the transfer operation, his control algorithm can be best described as gain scheduling rather than adaptation. [11] developed a compensator with its zeros designed to cancel the dynamics of the pendulum. This controller was tested on a physical crane model. It produced good results except that the system was underdamped.

Therefore, the system response was oscillatory, which implies a longer transfer time. [12] developed a linear feedback controller using full-state feedback. The controller gains are tuned according to the cable length. However, if the cable length changes in an unqualified way, degradation of the system performance occurs. In addition, the tuning algorithm was not tested experimentally.

2.3 Delayed Feedback Signal (DFS) Controller

The block diagram used in these simulation is shown in figure 2.2.

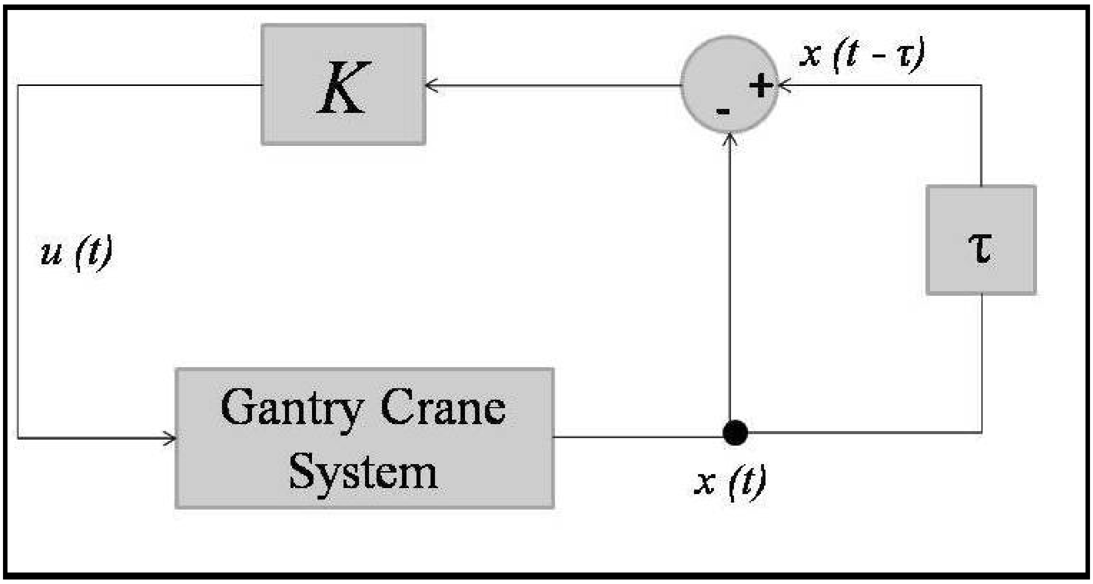


Figure 2.2 Delayed Feedback Signal(DFS) controller structure

The control signal is calculated based on delayed position feedback

$u(t) = k\,[\,y(t) - y(t - \tau)\,]$

but $y = Cx$

so, $u(t) = k[C(x) - C(x - \tau)]$ ...(2.8)

substitute (2.8) in (2.6),

$x = Ax + Bk\,[\,C(x) - C(x - \tau)\,]$

$= Ax + kBC(x) - kBC(x - \tau)\,]$...(2.9)

Taking (2.9) in Laplace Transform

$$sIx(s) = Ax(s) + kBC(x) - kBC(1 - e^{-s\tau})x(s) \quad \ldots(2.10)$$

The stability of the system given by equation (2.10) depends on the roots of the characteristic equation given by

$$\Delta(s,\tau) = |\, sI - A + kBC\,(1 - e^{-s\tau}) \quad \ldots(2.11)$$

Equation (2.11) is transcendental and results in an infinite number of characteristic roots [13]. Several approaches to solve the equation before this can be found in [13, 14].

To determining the critical values of the time delay τ that result in characteristic roots of crossing the imaginary axes by using the approach using the approach develop in [14]. The equation (2.11) is writing in form

$$\Delta(s,\tau) = P(s) + Q(s)\, e^{-s\tau} \quad \ldots(2.12)$$

P(s) and Q(s) are polynomials in s with real coefficients with deg(P(s)=n>deg(Q*(s)*) where n is the order of the system.

Let s= jω, and separate the polynomials P(s) and Q(s) into real and imaginary parts. Then replacing $e^{-j\omega\tau}$ into cos($\omega\tau$) - jsin($\omega\tau$). So,the equation (2.12) will be form in

$$\Delta(j\omega,\tau) = P_R(\omega) + jP_I(\omega) + (Q_R(\omega) + jQ_I(\omega)(\cos(\omega\tau) - j\sin(\omega\tau)) \quad \ldots(2.13)$$

The characteristics of s are changed to jω because to find the critical time delay that leads to marginal stability. If equation (2.13) has positive real roots the characteristic equation $\Delta(s,\tau) = 0$ on the imaginary axis for some values of $\tau \geq 0$. A solution of $\Delta(j\omega,\tau) = 0$ exists if the magnitude $|\Delta(j\omega,\tau)| = 0$. Taking the square of the magnitude of $\Delta(j\omega,\tau)$ and setting it to zero lead to the equation below.

$$P_R^2 + P_I^2 - (Q_R^2 + Q_I^2) = 0 \quad \ldots(2.14)$$

Then , setting the real and imaginary parts of equation (2.14) to zero , the system will be get in two equations.

$$\sin(\beta) = \frac{(-P_R Q_I + P_I Q_R)}{(Q_R{}^2 + Q_I{}^2)} \quad \text{and}$$

$$\cos(\beta) = \frac{(-P_R Q_R + P_I Q_I)}{(Q_R{}^2 + Q_I{}^2)}$$

The critical values of time delay can be determined as follows:in equation (14), if a positive root, ω_c, the corresponding time delay τ can determined by solving the system of two equations as:

$$\tau_k = \frac{\beta}{\omega} + \frac{2k\pi}{\omega} \quad \text{with } k = 0,1,2,...$$

where $\beta \in [0 \;\; 2\pi]$. The root loci of the closed-loop system are crossing the imaginary axis of the s-plane at these time delays. This crossing can be from either stable to unstable or from unstable to stable. In order to investigate the above method , the time delayed feedback controller is applied to the gantry crane system.

The Delayed Feedback Signal (DFS) controller should have only one position sensor and uses only the current output of this sensor and the output τ second in past to control signal for. The parameter, k and τ needs to be set.

CHAPTER 3

METHODOLOGY

3.1 Work Methodology

Methodology is a work progress which it usually constructs in a flow chart. It also can be a fast review of works which takes a period of time to complete it. For this project, there are several steps to finish the project besides the reviewing and study before starting the experiment. In term of work methodology, it can be summarized as in Figure 3.1.

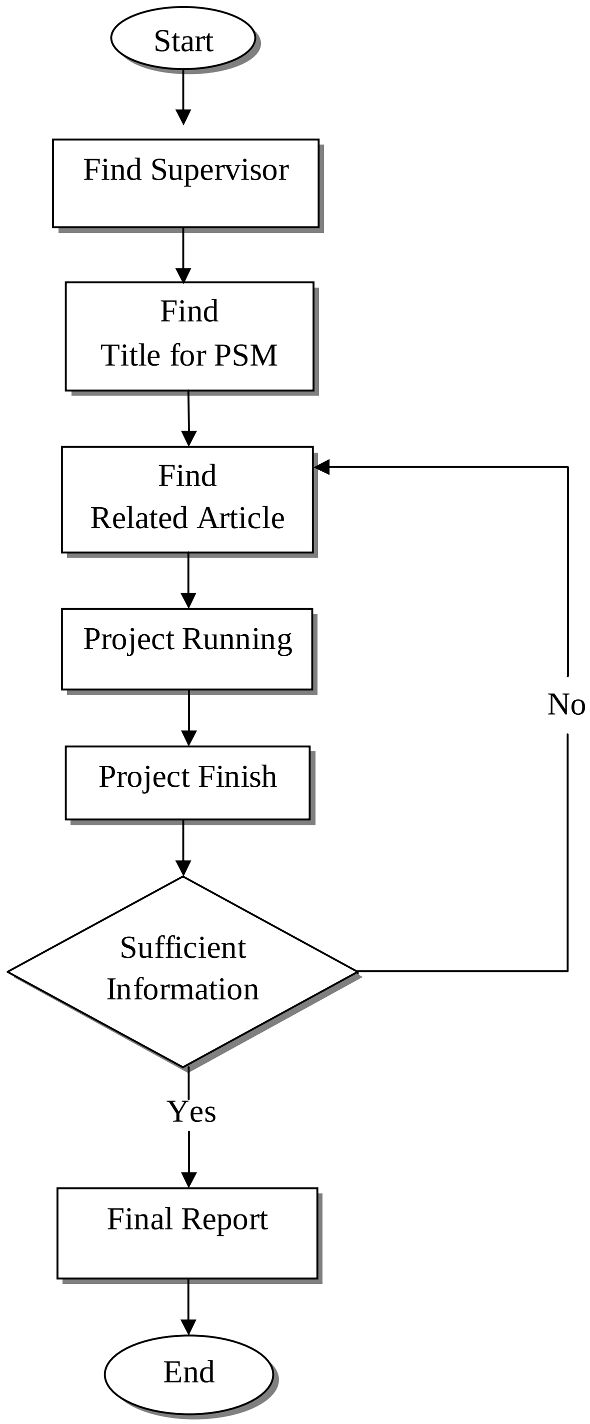
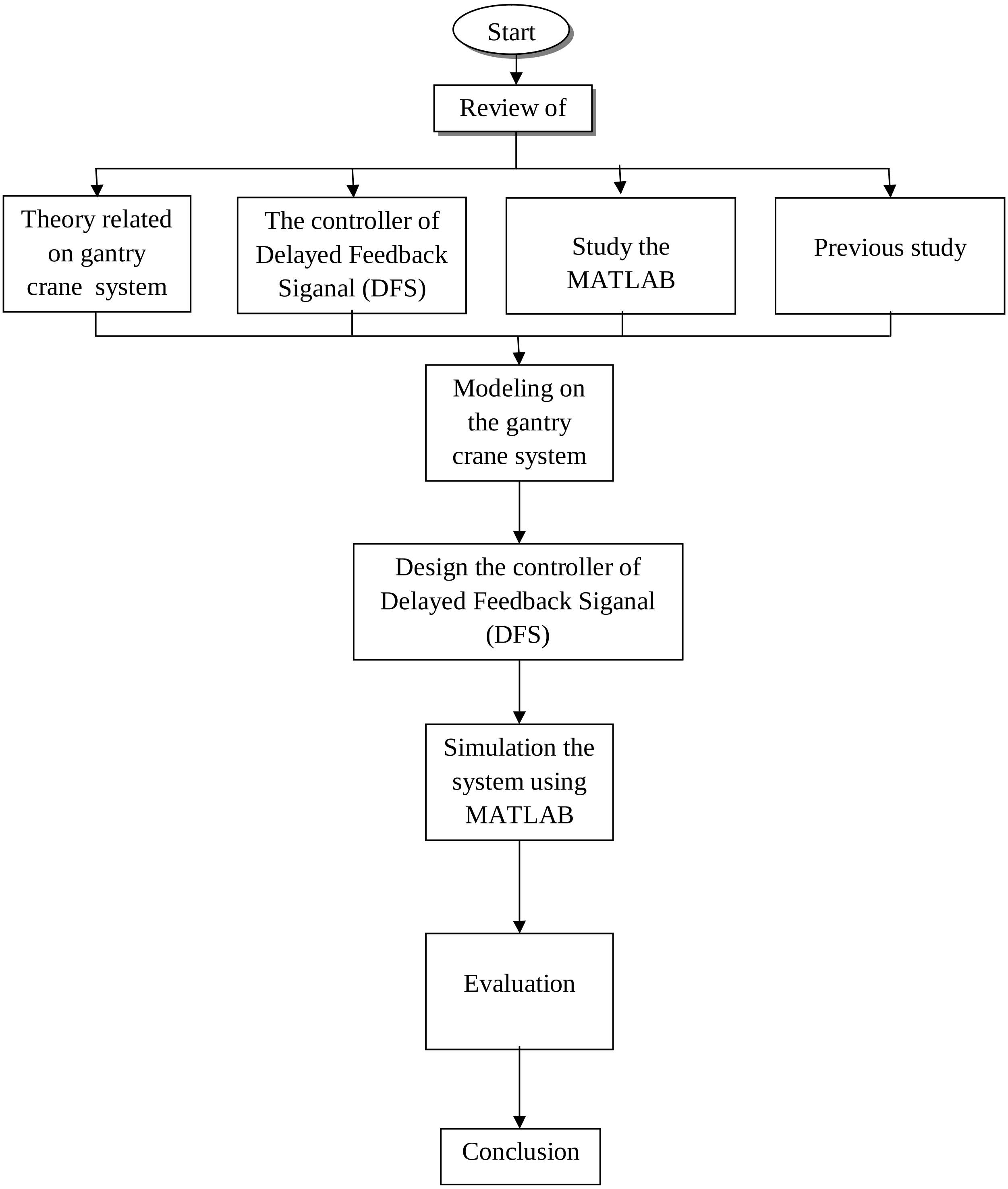


Figure 3.1: Work methodology

3.2 Project Flowchart



3.3 Simulation of Gantry Crane System Using DFS Controller

Computer simulations have been carried using MATLAB. The system is simulated to compare the performance between the system under Delayed Feedback Signal (DFS) and the system without controller.

3.3.1 Analysis the Modeling of Gantry Crane System

To develop this project, the first step to do is analysis the system for modeling of the gantry crane especially involves the dynamic characteristic of the system. By analyzing the dynamic system, it can predict the problem before a system is built. A system analysis the dynamics refer to a situation which is changing together with time that means the subject of the system dynamics includes much of the engineering science basic to the established disciplines, such as mechanical, electrical and others. For this case, the system dynamics will be confined on mechanical system. In order to deal with the dynamic system problem, all of its components involved in that system must be recognized and review, so that the mathematical model of the equation will be formulated.

The mathematical model is one method of the modeling. The mathematical model should include the details that can be describe the systems in term of equation without making it too complex which this way usually use the mathematical solution such as ordinary, linear, differential equations with constant coefficients as a basic for the derivation of the system's dynamics model. By using the set of equation that been formulated, the dynamic behavior of the system can be investigated which will show the relation between the input and output of the system. The solution can be found in various methods, whether using graphical technique, numerical method, and operational block diagram of the system or purely mathematical solution [15]

The mathematical equation can be derived from the gantry crane model by considering the dynamics of the system by analyzing the following characteristics: kinematics and kinetics. Kinematics [16] is the study which related to predict unknown information about an object's motion if other information is known. Kinetics [17] is the analysis of the forces causing the aspects of motion. By using these characteristics, the mathematical equation can be derived in two ways, which will give the same results.

To derive the equation for this case, the kinetics characteristic has been chosen. Consider the free body diagram which is shown in Figure 3.2 and Figure 3.3:

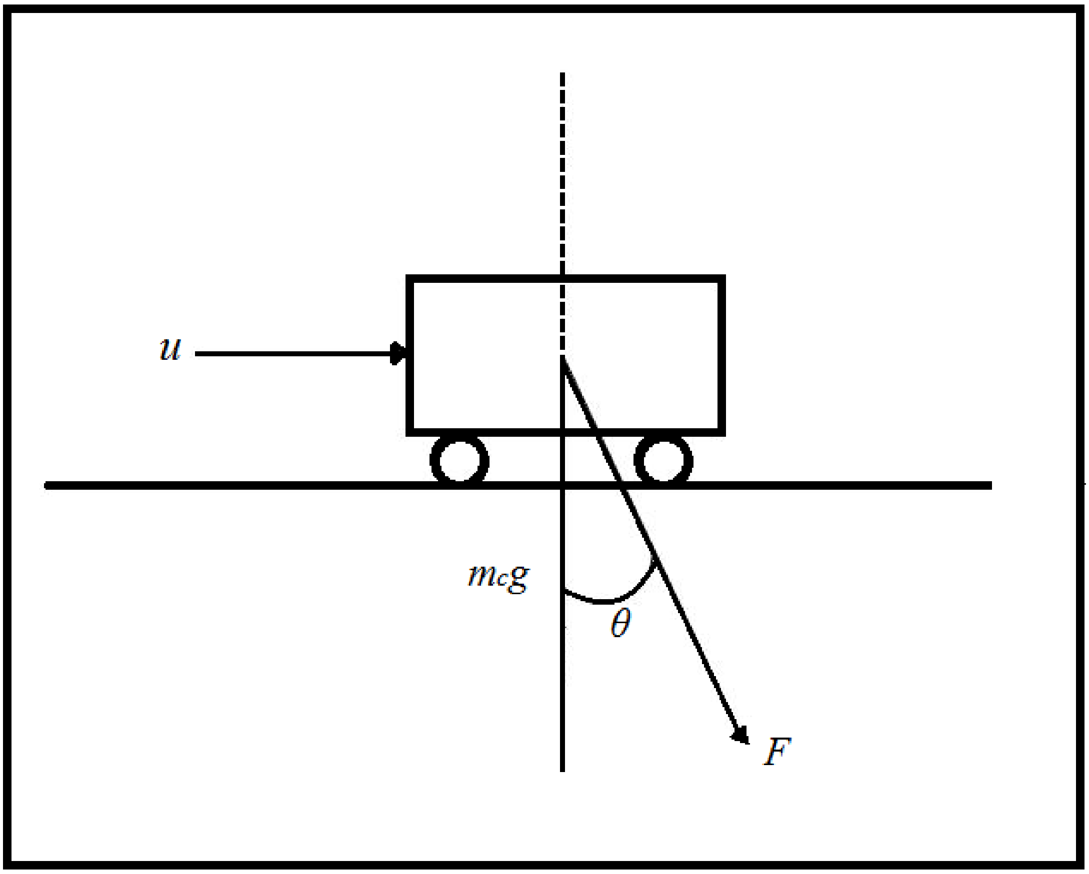


Figure 3.2: Cart’s free body diagram

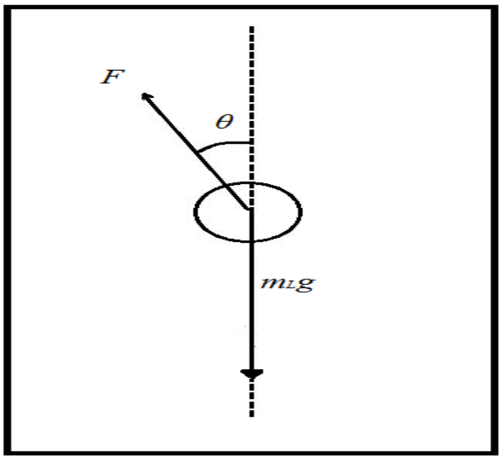


Figure 3.3: Load's free body diagram

Note that *F* is assuming to be the longitudinal force cause by the bar which the bar is assumed to be thin and less mass. Using kinetics characteristics, which relates between force and acceleration, the following equation can be derived:

i) Cart for move in horizontal:

$$M\frac{d^2x_1}{dt^2} = u + F\sin\theta \qquad \text{... (4.1)}$$

ii) Cart for move in vertical:

$$F\cos\theta + Mg = 0 \qquad \text{... (4.2)}$$

iii) Load for move in horizontal:

$$m\frac{d^2(x_1 + l\sin\theta)}{dt^2} = -F\sin\theta \qquad \text{... (4.3)}$$

iv) Load for move in vertical:

$$m\frac{d^2(l\cos\theta)}{dt^2} = -F\cos\theta + mg \qquad \text{... (4.4)}$$

From equation (4.1) and (4.3)

$$M\frac{d^2x_1}{dt^2} = u - m\frac{d^2(x_1 + l\sin\theta)}{dt^2}$$

$$M\frac{d^2x_1}{dt^2} + m\frac{d^2(x_1 + l\sin\theta)}{dt^2} = u \qquad \text{... (4.5)}$$

From equation (4.3) and (4.4)

$$m\frac{d^2(l\cos\theta)}{dt^2} = \frac{\cos\theta}{\sin\theta}.m\frac{d^2(x_1 + l\sin\theta)}{dt^2} + mg$$

$$m\frac{d^2(l\cos\theta)}{dt^2}.\sin\theta - m\frac{d^2(x_1 + l\sin\theta)}{dt^2}.\cos\theta = mg\sin\theta \qquad \text{... (4.6)}$$

but,

$$\frac{d^2(x_1 + l\sin\theta)}{dt^2} = \ddot{x}_1 + l\ddot{\theta}\cos\theta - l\dot{\theta}^2\sin\theta \qquad \text{... (4.7)}$$

$$\frac{d^2(l\cos\theta)}{dt^2} = -l\ddot{\theta}\sin\theta - l\dot{\theta}^2 - \cos\theta \qquad \text{... (4.8)}$$

From the equation (4.5), (4.6), (4.7) and (4.8),

$$(m + M)\ddot{x}_1 + ml(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) = u \qquad \text{... (4.9)}$$

$$m\ddot{x}_1\cos\theta + ml\ddot{\theta} = -mg\sin\theta \qquad \text{... (4.10)}$$

$$\ddot{x}_1\cos\theta + l\ddot{\theta} = -g\sin\theta \qquad \text{... (4.11)}$$

The equation can be rewrite in state space equation form from equation (4.9) and (4.10).

$$\begin{vmatrix} m+M & ml\cos\theta \\ m\cos\theta & ml \end{vmatrix} \begin{vmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{vmatrix} = \begin{vmatrix} ml\dot{\theta}\sin\theta + u \\ -mg\sin\theta \end{vmatrix} \quad \text{... (4.12)}$$

By solving the equation (4.12)

$$\begin{vmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{vmatrix} = \begin{vmatrix} \dfrac{u + m\sin\theta(l\dot{\theta}^2 + g\cos\theta)}{M + m\sin^2\theta} \\ -\dfrac{u\cos\theta + m\sin\theta(g + l\dot{\theta}\cos\theta) + gM\sin\theta}{l(M + m\sin^2\theta)} \end{vmatrix} \quad \text{... (4.13)}$$

Equation (4.13) is in nonlinear function. So, it cannot be used easily for the purpose of analysis and design but if the model is linear, it is easier. To get a linear model, linearization must be implemented to the above model. The model can be linearized if the following condition be considered: deflection angle, θ is small, and if it has small angular velocity, $\dot{\theta}$. In other words, the following condition will satisfy the aim:

$$\begin{matrix} \cos\theta \approx 1 & \sin\theta \approx \theta \\ \sin^2\theta \approx 0 & \dot{\theta} \approx 0 \end{matrix} \quad \text{... (4.14)}$$

For consider the equation (4.14) to equation (4.13), yield

$$\begin{vmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{vmatrix} = \begin{vmatrix} \dfrac{u + mg\theta}{M} \\ -\dfrac{u + mg\theta + gM\theta}{lM} \end{vmatrix}$$

$$\begin{vmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{vmatrix} = \begin{vmatrix} \dfrac{mg\theta}{M} \\ -\dfrac{mg\theta + Mg\theta}{lM} \end{vmatrix} + \begin{vmatrix} \dfrac{u}{M} \\ -\dfrac{u}{lM} \end{vmatrix}$$

$$\begin{vmatrix} \ddot{x}_1 \\ \ddot{\theta} \end{vmatrix} = \begin{vmatrix} 0 & \frac{m}{M} g \\ 0 & -\frac{m+M}{lM} g \end{vmatrix} \begin{vmatrix} x_1 \\ \theta \end{vmatrix} + \begin{vmatrix} \frac{1}{M} \\ -\frac{1}{lM} \end{vmatrix} u$$

... (4.15)

take,

$$x = \begin{vmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{vmatrix} = \begin{vmatrix} x_1 \\ \dot{x}_1 \\ \theta \\ \dot{\theta} \end{vmatrix} = \begin{vmatrix} cart.position \\ cart.velocity \\ load.angle \\ load.angle.rate \end{vmatrix}$$

... (4.16)

then, the extension of state equation (4.16) can be written as:

$$\dot{x} = \begin{vmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{vmatrix} = \begin{vmatrix} \dot{x}_1 \\ \ddot{x}_1 \\ \dot{\theta} \\ \ddot{\theta} \end{vmatrix} = \begin{vmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{mg}{M} & 0 & 0 \\ 0 & -\frac{(M+m)g}{Ml} & 0 & 0 \end{vmatrix} \begin{vmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{vmatrix} + \begin{vmatrix} 0 \\ 0 \\ \frac{1}{M} \\ -\frac{1}{Ml} \end{vmatrix} u$$

..(4.17)

the model of uncontrolled system in steady state can be represented

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du \quad \dots \quad (4.18)$$

by compare the equation (4.17) and (4.18)

$$A = \begin{vmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{mg}{M} & 0 & 0 \\ 0 & -\frac{(M+m)g}{Ml} & 0 & 0 \end{vmatrix} \qquad B = \begin{vmatrix} 0 \\ 0 \\ \frac{1}{M} \\ -\frac{1}{Ml} \end{vmatrix}$$

$$C = \begin{vmatrix} x & \dot{x} & \theta & \dot{\theta} \end{vmatrix} \qquad D = \begin{vmatrix} 0 \end{vmatrix}$$

3.3.2 Study about Delayed Feedback Signal Controller

The objective of the feedback controller is to reduce the sway angle due to disturbance effect. To eliminate the effect of disturbances, all the feedback control strategies are incorporated in the close loop system in order. Figure 3.4 show the block diagram which it uses in these simulations. The control signal is calculated based on the delayed position feedback approach described in:

$$u(t) = k(y(t) - y(t\text{-}\tau))$$

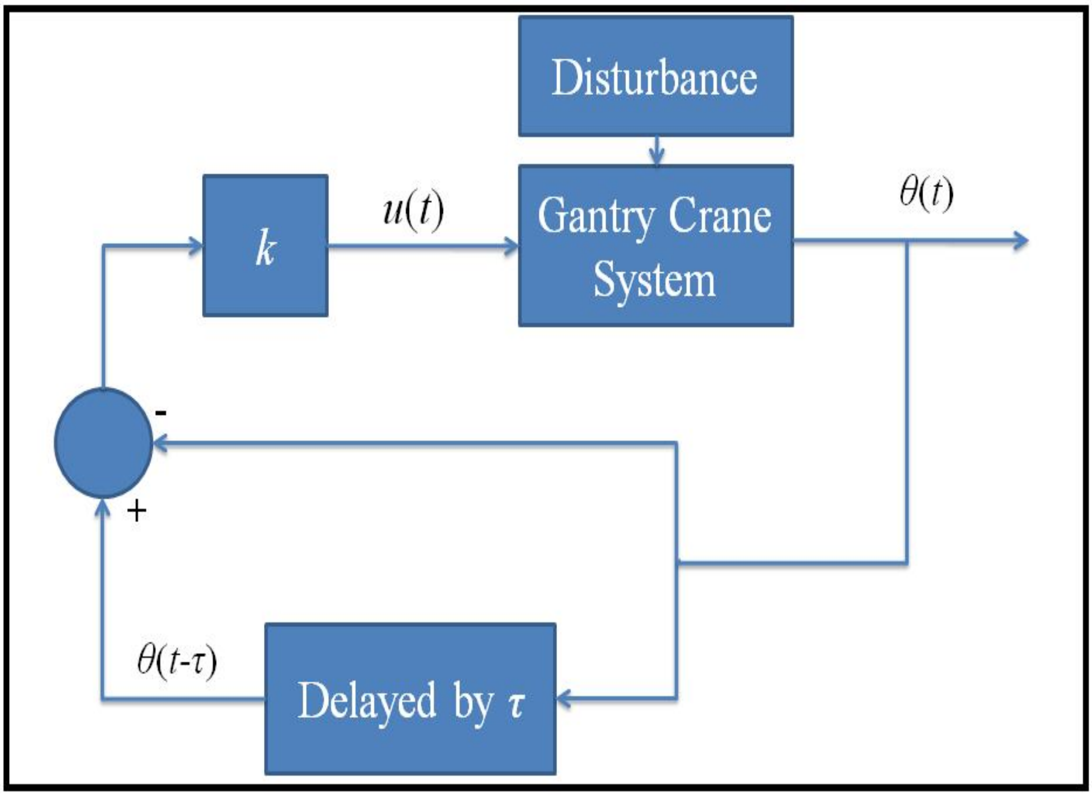


Figure 3.4: Block diagram of Delayed Feedback Signal (DFS) controller

3.3.3 Simulation of a System

The system has been built in the MATLAB Simulink environment to verify the characteristic of the model. A complete design for the block diagram in Figure 3.5 has been consider consist of the subsystem of 2D Gantry Crane, subsystem of the controller and the block diagram of the output for cart position, cart velocity, load angle and overshoot for the load angle.

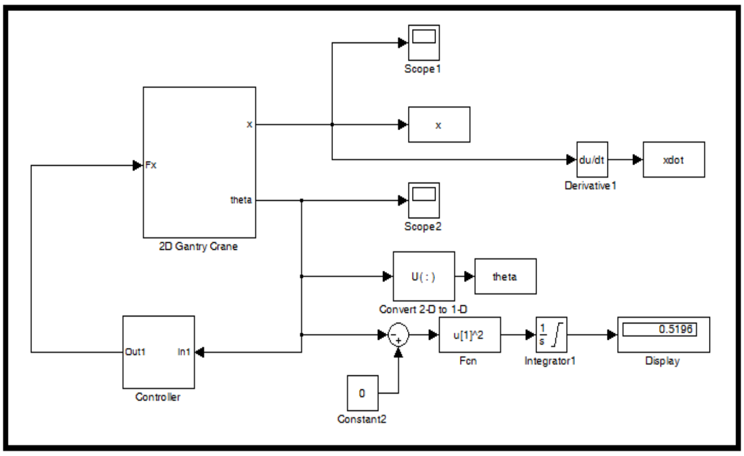


Figure 3.5: Block diagram in each system for simulation

Figure 3.6 shows the block diagram for combination of all cases while the system inside in block diagram Gantry Crane System is shown in Figure 3.7.

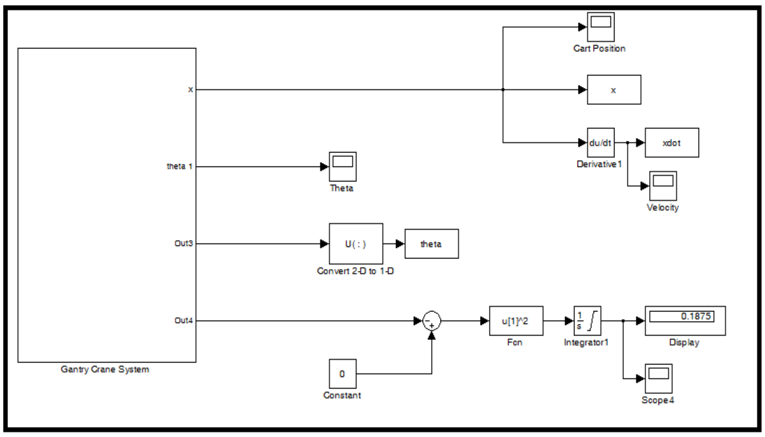


Figure 3.6: Block diagram for combination of all cases

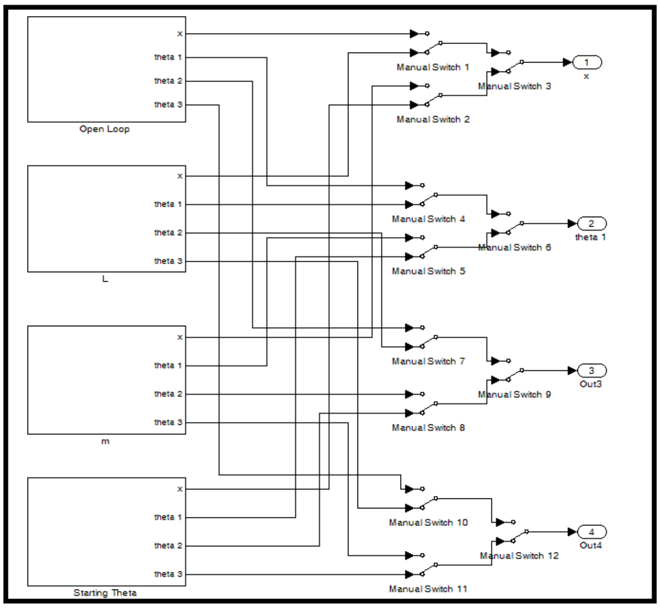


Figure 3.7: Configuration inside in block diagram Gantry Crane System

The configuration inside in block diagram in every case which it is a show in Figure 3.7 is shown in Figure 3.8.

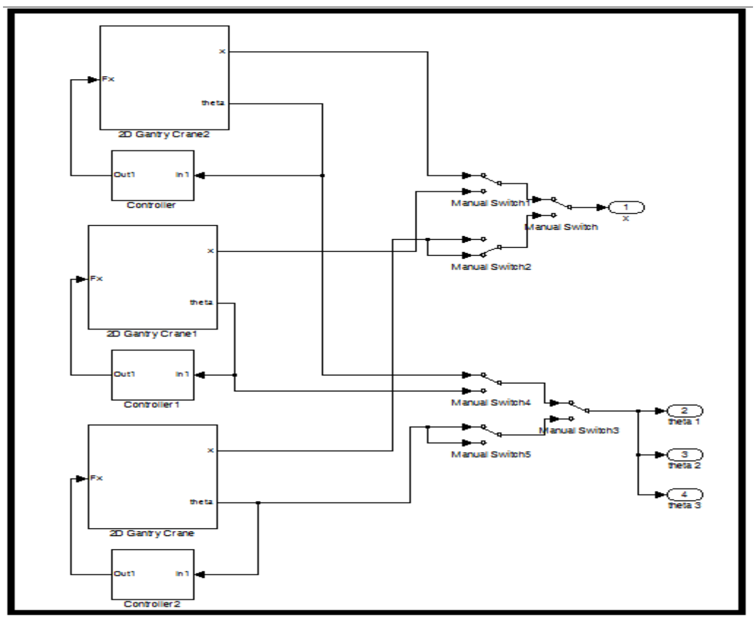


Figure 3.8: Configuration inside in each Case

Figure 3.9 shows a configuration inside the 2D Gantry Crane block which has a two main block diagram. For the Block Diagram 1, the output is cart position while for the Block Diagram 2, the output is load angle. Both of block diagrams use the same input. There are four input function for each block diagram which are 'Fx', 'theta', 'thetadot' and 'xdot'.

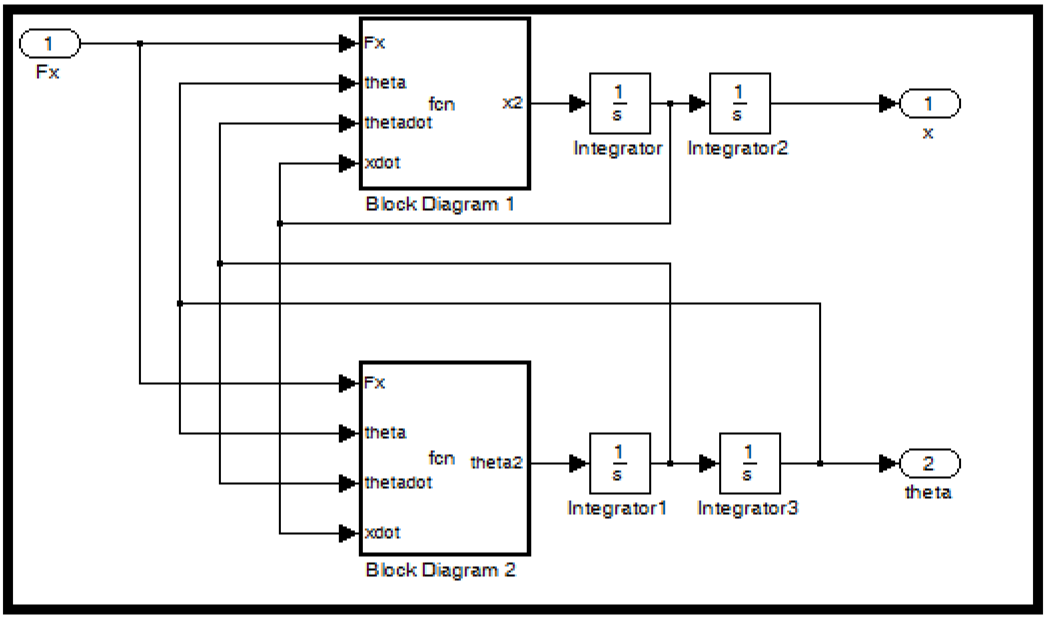


Figure 3.9: Configuration inside the 2D Gantry Crane block

A configuration inside the Controller block is shown in figure 3.10 which has a Time Delay block, Gain block, and Sum block. Time Delay block should apply specified delay to the input signal. The best accuracy is achieved when the delay is larger than simulation step size. The Gain block is placed after the Sum block. The output of the Controller block is connected to the input of the 2D Gantry Crane block.

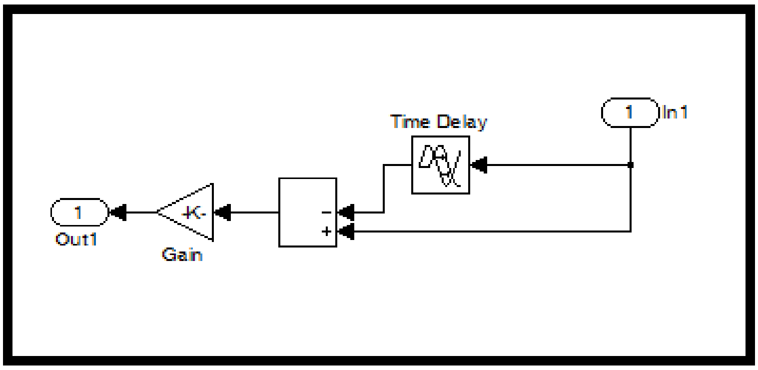


Figure 3.10: Configuration inside the Controller block.

3.3.4 Setting the Parameter of 2D Gantry Crane System

The input of the modeling of gantry crane system is moving in two dimensional x and y plane. The disturbances for this system are ignoring. In order, the time delayed feedback controller is applied to the system of 2D Gantry Crane by setting the value of parameters with double click the Block Diagram 1 and Block Diagram 2 and insert the values of parameter in the coding. The parameter value of M is for the mass of cart in kg, m is set for the mass of the load in kg, *l* is for length of rode in m, and the g is for gravitation coefficient which it is set to $9.81 m/s^2$. Figure 3.11 is shown the coding to set the value of parameter in Block Diagram 1 while the Figure 3.12 is shown coding to set the value of parameter in Block Diagram 2.

```
function x2 = fcn(Fx,theta,thetadot,xdot)
% This block supports an embeddable subset of the MATLAB language.
% See the help menu for details.

M=2.49; %kg
m=1; %kg
L=1; %m
g=9.81; %m/s^2
k=11.398; %Ns/m

x2=(-(Fx-k*xdot)*cos(theta)-g*(M+m)*sin(theta)-m*L*thetadot^2*sin(theta)*cos(theta))/(cos(theta)*(M*(cos(theta))^2-M-m))-g*sin(theta)/cos(theta)
```

Figure 3.11: Coding to set the parameter value in Block Diagram 1

```



function theta2 = fcn(Fx,theta,thetadot,xdot)
% This block supports an embeddable subset of the MATLAB language.
% See the help menu for details.

M=2.49; %kg
m=1; %kg
L=1.0; %m
g=9.81; %m/s^2
k=11.398; %Ns/m

theta2 = ((Fx-k*xdot)*cos(theta)+g*(M+m)*sin(theta)+m*L*thetadot^2*sin(theta)*cos(theta))/(m*L*(cos(theta))^2-(M+m)*L);
```

Figure 3.12: Coding to set the parameter value in Block Diagram 2

For the comparative the performance of the system, the parameter mass of the load, length of the rode and the starting load angle are set up with the three different values for each process when enter the parameter values. The other value such as mass of the cart, M and the gravitation coefficient, g must be fixed.

To compare the performance of the system for the different parameter length of the rope, the parameter for the mass of the load and starting value of load angle must be fixed while if to compare the performance of the system for the different parameter for the mass of the load, the value of parameter for length of the rode and starting value of the load angle must be fixed. The value of the parameter for the length of the rode and mass of the load must be fixed to see the performance of the system for the different value of the parameter starting load angle. The right tuning gain for all the changed values to get the most efficient performances will be finding. The graph of Power Spectrum Density (PSD), velocity ($\dot{\theta}$), load angle(θ) and cart position(x) were plotted. Table 3.1 shows the values of the parameter which is set up for the system.

Table 3.1: The value of the parameter

Case	Parameter				
	Length of the Rope, l (m)	Mass of the Cart, M (kg)	Mass of the Load, m (kg)	Starting Theta, θ (rad)	Gravitation Coefficient, g (m/s^2)
Open Loop	1	2.49	1	1.5	9.81
Case A	0.5	2.49	1	1.5	9.81
	1.0	2.49	1	1.5	9.81
	1.5	2.49	1	1.5	9.81
Case B	1.0	2.49	1	1.5	9.81
	1.0	2.49	2	1.5	9.81
	1.0	2.49	3	1.5	9.81
Case C	1.0	2.49	1	0.5	9.81
	1.0	2.49	1	1.0	9.81
	1.0	2.49	1	1.5	9.81

3.3.5 Tuning the Value of Time Delay

Then, the different value of time delay, τ is set up with the constant value of gain, k until the graph of theta shown a stable response as predicted. The block parameter to set up the value of time delay is show in figure 3.13.

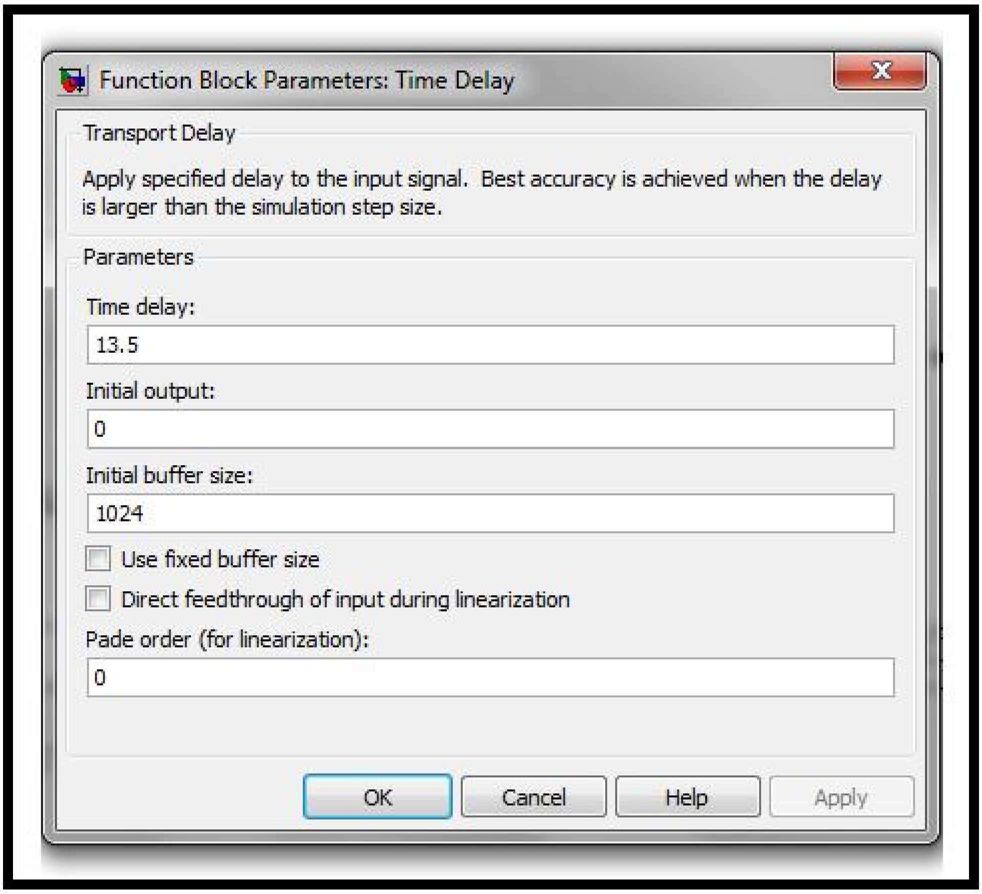


Figure 3.13: The block parameter to set up the value of time delay

3.3.6 Tuning the Value of Gain, *k*

After the system can be made critically stable by selecting the best value of τ, the value of gain k is tune. The tuning of the gain constant k, in equation (2.7) is easily achieved by starting from a small value and gradually increasing it. There exists a boundary k_1 of k_2.which is determined by the friction. If $k<k_1$ then, is not strong enough to overcome the friction of the system. If $k_1 = k_2$ the system is strong enough to overcome friction and if $k > k_1$ so the system is strong enough to swing-up the pendulum towards the inverted vertical. k_1 could be obtained analytically, however this is both difficult and unnecessary. The process of tuning value of gain k

is stop when the closed loop system is stable, and the time response seems to be better. Figure 3.14 is show the block parameter to tune the value of gain, *k*.

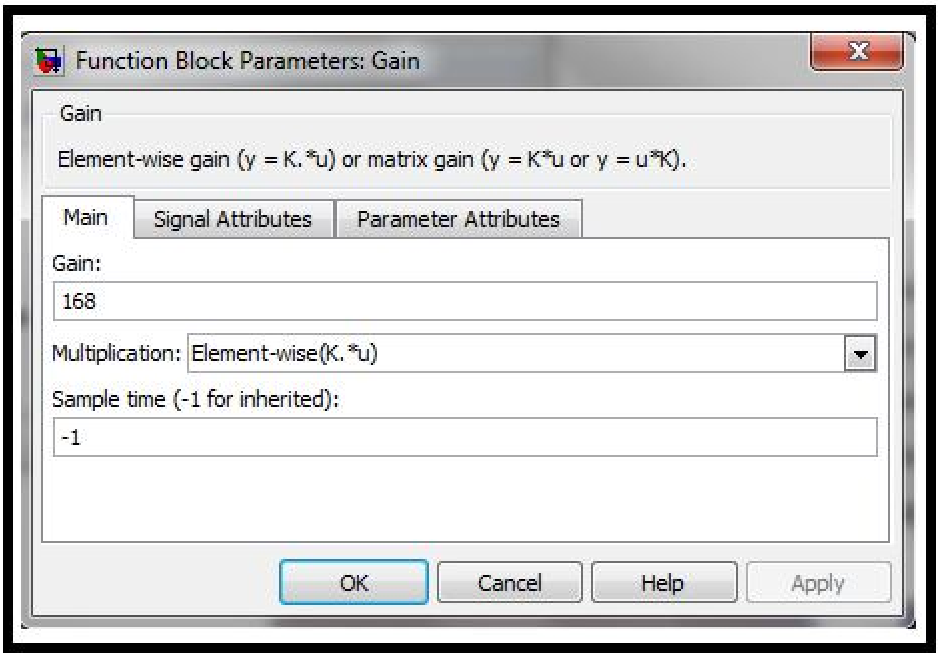


Figure 3.14: Block parameter to tune the value of gain *k*

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter contains the result and discussions for this project. All the results are obtained within simulation environment of the gantry crane system. The system responses namely sway angle of the rope, the cart position, the velocity of cart, the gain, and its Power Spectral Density (PSD) are presented. The process simulation of the system is gained by using MATLAB 7.6.0. The system responses are simulated to study the system performance under Delayed Feedback Signal (DFS) and without controller.

The first three modes of swaying frequencies of the system are considered as these dominate the dynamic of the system. To evaluate the performances of the control strategies, two criteria are used. The first criterion is the level of swaying angle reduction at a natural frequency. This is accomplished by comparing the power spectral density response of the open loop system and the system with delayed feedback signal as a controller. The second criterion is by cancellation of the disturbance. The capability of the controller to achieve zero sway angles is studied.

4.2 System without Delayed Feedback Signal Controller

The open loop responses of the free end of the sway angle of the hoisting rope were considered as the system response with disturbances effect and will be used to evaluate the performance of feedback control strategies. Figure 4.1 shows the system response of the gain value for the system (a), the sway angle of the load (b), the horizontal position of the cart (c), the velocity of the cart (d) and the power spectral of the system which its obtain from the system without controller. This result shows a response of gantry crane system without any controller. The settling time for the pendulum's swing angle is high since the pendulum is uncontrolled. The values of the parameters in mathematical equation for the model gantry crane system without controller:

Mass of the load, m = 1.00 kg

Starting angle to release the load, θ_i = 1.5 radian

Length of the rope, l = 1 m

The mass of the cart, M = 2.49 kg

The gravitation coefficient, g = 9.81 $ms^{-2.}$

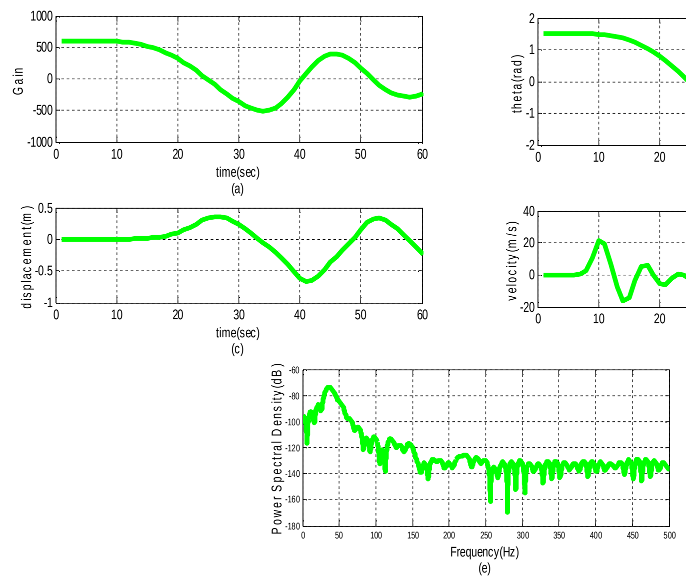


Figure 4.1: Response of the system without controller (a) Gain (b)Load Sway Angle (c) Cart Displacement (d) Cart Velocity (e) Power Spectral Density

4.3 Result the Performance for the System with Delayed Feedback Signal

To see a comparison of the use of parameters for this system, each parameter values for length of the rope, *l*, mass of the load, m, and starting point of the release the load, θ_i are set up with three different value.

4.3.1 Case A: Different Parameter for Length of the Rope

For the case A, the assumption values of the parameters in mathematical equation for the model gantry crane system are :

Mass of the load, m = 1.00 kg,
Starting angle to release the load, θ = 1.5 radian
The mass of the cart, M = 2.49 kg
The gravitation coefficient, g = 9.81 $ms^{-2.}$

The time delay for all the system for this case is setting to 13.5 sec, which the system gives a stable response when the system is tune that value for the time delay. Table 4.1 shows the gain, *k* value used for each system.

Table 4.1: Value Gain, *k*

Length of the rope, *l*	**Gain, *k***
0.5 m	213
1.0 m	89.8
1.5 m	85.2

Figure 4.2, Figure 4.3 and Figure 4.4 show the system response which it is obtain from the system for the parameter value of *l* is 0.5m, *l* is 1.0m and *l* is 1.5m. Figure 4.2(a) is a graph of gain response which it obtain when the gain is tune to 213 for the system with *l* is 0.5m. In this simulation, the response is starting at 319.5dB and reach to undershoot at t=0.5s.The response is settling at t=2.6457s. Graph in Figure 4.2(b) shows the Power Spectral Density of the system. The horizontal position for the cart is shown in Figure 4.2(c). It takes about 7.2315s to settling at 6.3m as it end position. Graph in Figure 4.2(d) show the velocity of the cart which it is reached 0ms^{-1} at t= 4.7244s. The rise time and the settling time of the cart's position and the cart's velocity are not related to the pendulum's swing angle since the controller only tuned for the pendulum's swing angle control

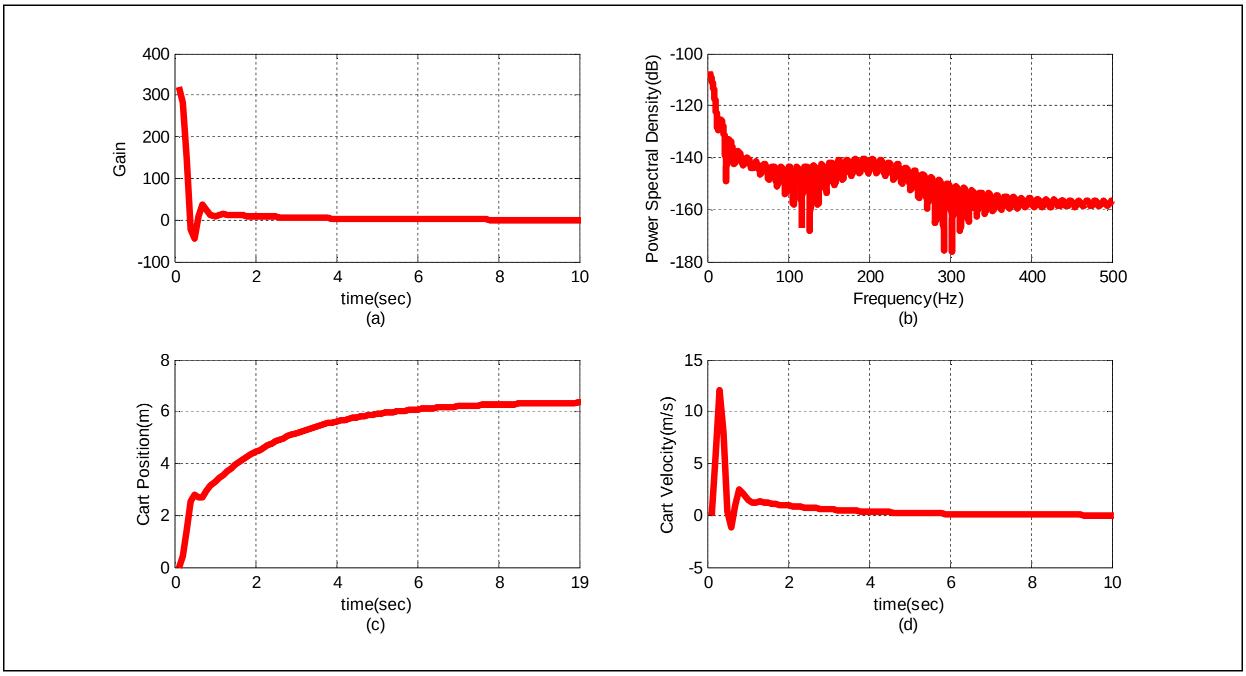


Figure 4.2: Response of the system using DFS controller for *l*=0.5m (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

The graph of gain response is shown in Figure 4.3(a) which it obtain when the system with the patameter *l* is set to 1.0m which the gain is tune to 89.8. The response is starting at 134.7dB. It reach to undershoot at t=0.9s and settling at t=2.7841s. The graph of Power Spectral Density of the system is shown in Figure

4.3 (b). The horizontal position for the cart is shown in Figure 4.3(c) which it stop from moving at 4.0307s. Since the controller only tuned for the pendulum's swing angle control, the cart is stopped moving at -0.3m. Graph in Figure 4.3(d) shows the velocity of the cart which the velocity is increase to 7.2802ms^{-1} and then decrease to -3.2194ms^{-1} before the cart velocity is achieved zero at t=3.5354s.

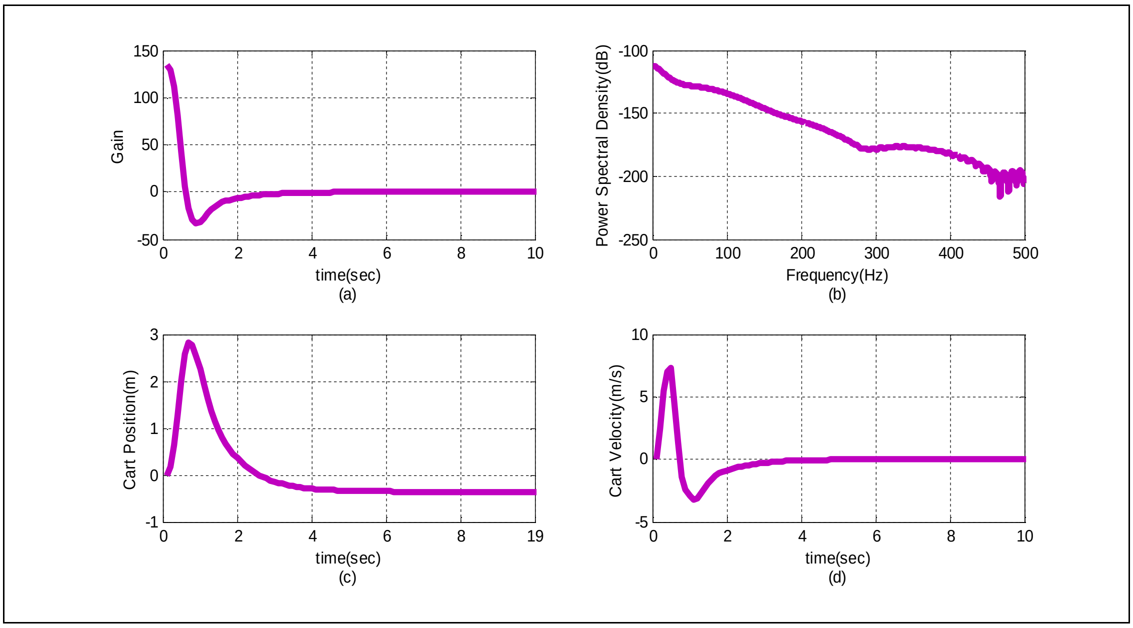


Figure 4.3: Response of the system using DFS controller for *l*=1.0m (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

Figure 4.4(a) is a graph of a gain response for the system with *l* is 1.5m which it obtain when the gain is tune to 85.2. The response is starting at 127.8dB and reach to undershoot at t=1.2s. The graph of Power Spectral Density of the system is shown in Figure 4.3 (b). The horizontal position for the cart is shown in Figure 4.3(c) while the velocity of the cart is shown in Figure 4.3(d). The settling time for cart position is at t=3.1794 while the settling time for cart velocity is at the t=3.3967s. It is shown that the cart is moving according to the sway angle of pendulum in order to the reduce the swaying motion. The velocity of the cart is directly proportional with the distance of the cart. Therefore, the velocity of response will achieve to zero when the cart is stop from moving.

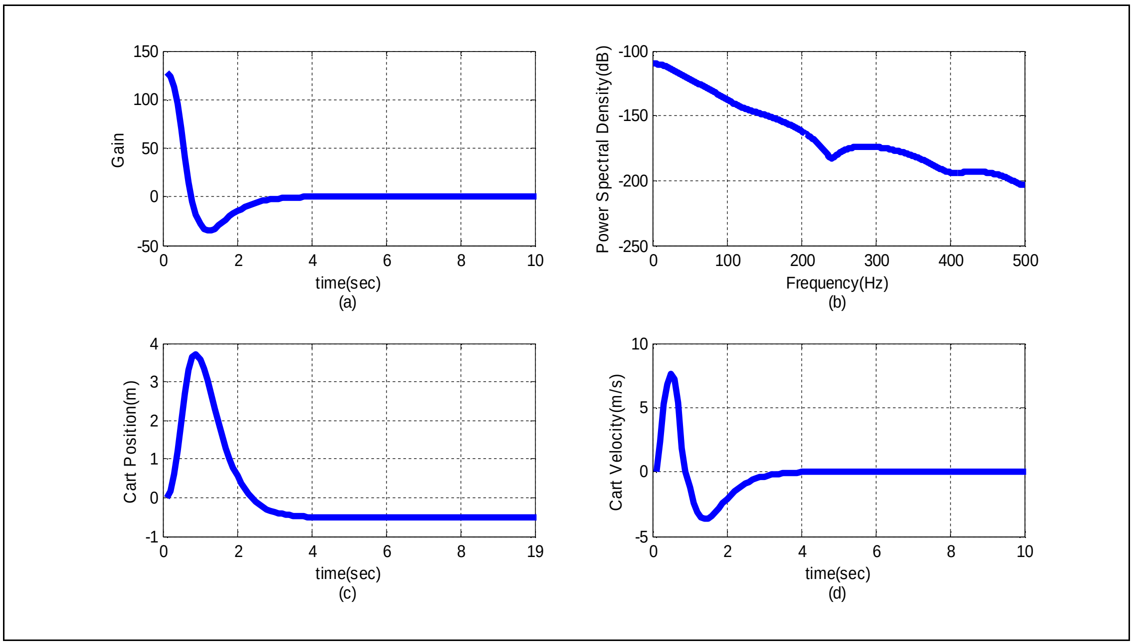


Figure 4.4: Response of the system using DFS controller for *l*=1.5m (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

Table 4.2 and Table 4.3 shows the comparative for the value rise time, t_r , and settling time, t_s of the response for position of cart and velocity of the cart for every system. From the Table 4.2, the effect of the length of the rope can be seen differently. The rise time and settling time for position of the cart keeps increasing when the length of the rope is increase.

Table 4.2: Response specification of cart position

Length of the rope, *l* (m)	**Rise time, t_r (s)**	**Settling time, t_s (s)**
0.5	4.0533	7.2315
1.0	1.8405	4.0307
1.5	0.9210	3.1794

Table 4.3 shows the response of the cart velocity for three different value parameters length of the rope. The rise time and settling time are decrease when the length of the rope is increase. The short rope takes a short time to stabilize.

Table 4.3: Response specification of cart velocity

Length of the rope, *l* (m)	**Rise time, t_r (s)**	**Settling time, t_s (s)**
0.5	0.0030	4.7244
1	1.6886×10^{-5}	3.5354
1.5	5.0188x10-7	3.2967

The Figure 4.5 shows the comparison the sway angle of the system for different parameter value of length of the rope. For response *l*=0.5m, the time response is faster to reach at minimum peak which it takes 0.5s compare to time response for *l*=1m and *l*= 1.5m. For time response *l*=1m, the time to reach at minimum peak is 0.9s while for *l*=1.5 is 1.2s. The response is undershoot for *l*=1.5m is higher to compare with *l*=0.5m and *l*=1.0m.

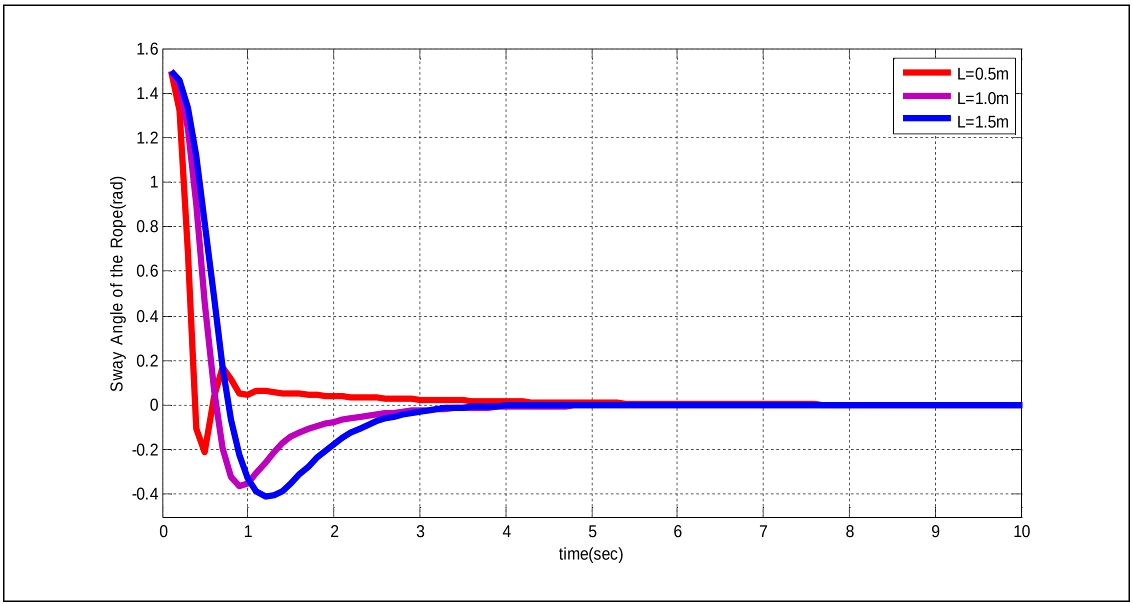


Figure 4.5: Comparison angle of sway angle of different value of *l*

4.3.2 Case B: Different Parameter for Mass of the Load

For the case B, the values of the parameters in mathematical equation for the model gantry crane system are assumption with:

Length of the rope, l = 1.00 m,

Starting angle to release the load, θ_i = 1.5 radian

The mass of the cart, M = 2.49 kg

The gravitation coefficient, g = 9.81 $ms^{-2.}$

For all the system, it gives a stable response when the time delay for this case is tuning to 13.5 sec. Table 4.4 shows the value of the gain, *k* that used for each system.

Table 4.4: Value Gain, *k*

Mass of the load, m	**Gain, *k***
1 kg	89.8
2 kg	26
3 kg	0.9

Figure 4.6, Figure 4.7 and Figure 4.8 show the system response which it is obtain from the system for the parameter value of m is 1 kg, m is 2 kg and m is 3 kg. The graph of gain response is shown in Figure 4.6(a) which it obtain when the system which the mass of the load is set to 1kg and the gain is tune to 89.8. The response is starting at 134.7dB. It reach to undershoot at t=0.9s and settling at t=2.7842s. The graph of Power Spectral Density of the system is shown in Figure 4.6 (b). Figure 4.6(c) and Figure 4.6(d) show graph of the response of horizontal position for the cart and the velocity of the cart which the velocity is increase to 7.3120ms^{-1} at t=0.5s and then decrease to -3.1296ms^{-1} at t=1.1s before the cart is stop. The settling time for cart position is at t=4.0739s while the settling time for cart velocity is at t=3.1538. Therefore, the speed response will achieve to zero when the cart is stop from moving.

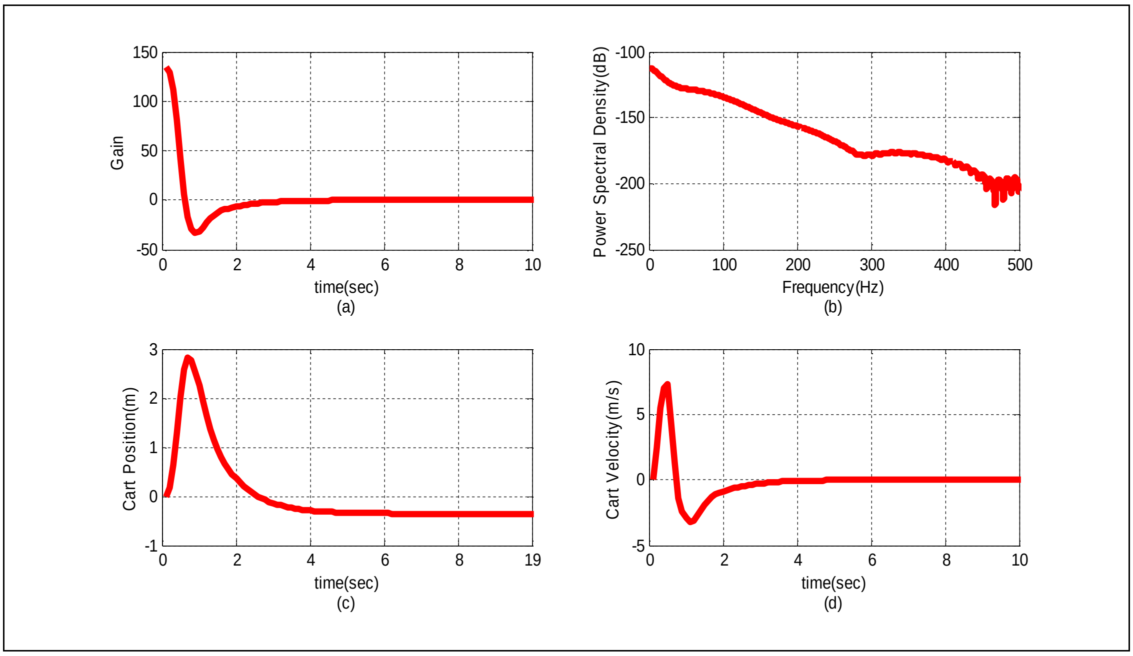


Figure 4.6: Response of the system using DFS controller for m=1 kg (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

Figure 4.7(a) is a graph of a gain response for the system with m is 2kg which it obtain when the gain is tune to 26. The initial of the the response is 39dB. The response is reach to undershoot at t=1.0s and settling at t=2.78727s. Figure 4.7(b) is a graph of Power Spectral Density of the system .The horizontal position for the cart is shown in Figure 4.7(c) which takes about 2.7962s to settling at 0.3m as it end position. Graph in Figure 4.7(d) show the velocity of the cart. The settling time for cart velocity is at the 3.0969s.

The graph of gain response is shown in Figure 4.8(a) which it obtain when the system with the patameter m is set to 3kg and the gain is tune to 0.9. In this simulation, the response is starting at 1.35dB and reach to undershoot at t=1.1s. The response is settling at t=6.5296s. Graph in Figure 4.8(b) show the Power Spectral Density of the system. The horizontal position for the cart is shown in Figure 4.8(c). It takes about 6.5095s to settling at 0.07m as it end position. Graph in Figure 4.8(d) show the velocity of the cart which it is reached 0ms^{-1} at t= 6.8440s. The rise time and the settling time of the cart's position and the cart's velocity are not related to the pendulum's swing angle since the controller only tuned for the pendulum's swing angle control.

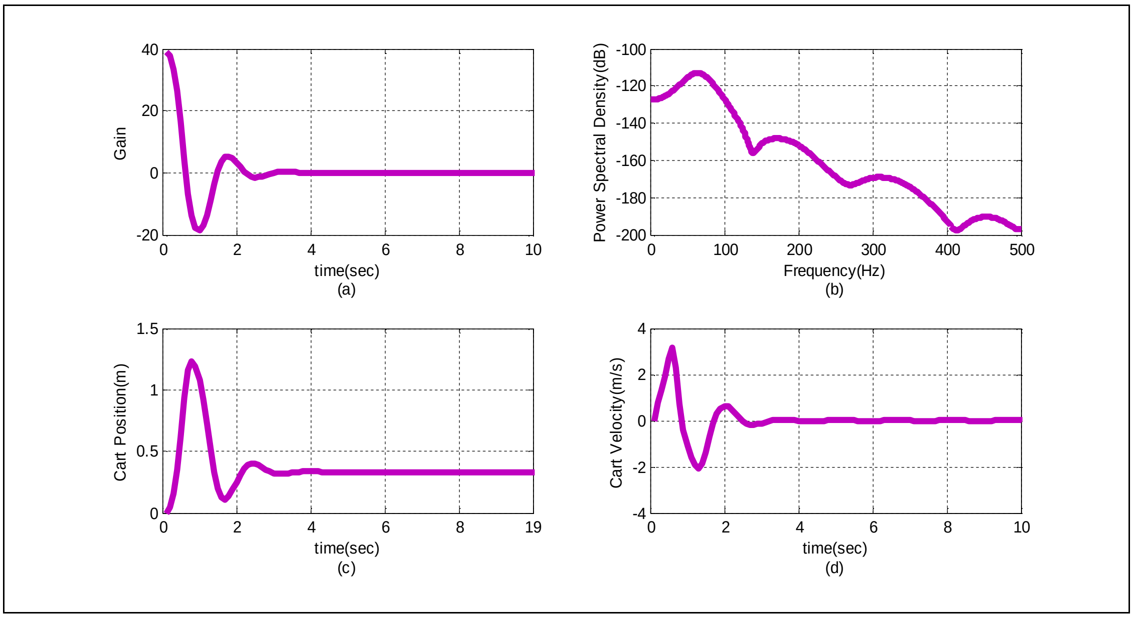


Figure 4.7: Response of the system using DFS controller for m=2kg (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

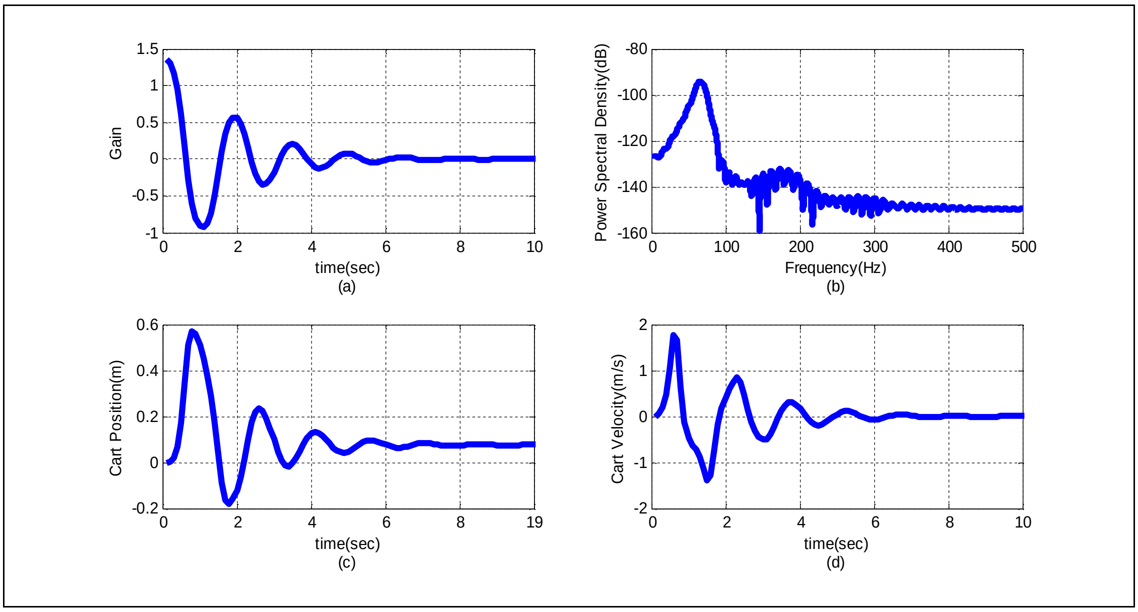


Figure 4.8: Response of the system using DFS controller for m=3kg (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

From the Table 4.5, the rise time and settling time for position of the cart for the different value of the mass of the load. The responses of the cart velocity for different value parameter of mass of the load are show in Table 4.6.

Table 4.5: Response specification of cart position

Mass of the load, m (kg)	**Rise time, t_r (s)**	**Settling time, t_s (s)**
1	1.8405	4.0308
2	1.9355	2.7962
3	1.7537	6.5095

Table 4.6: Response specification of cart velocity

Mass of the load, m (kg)	**Rise time, t_r (s)**	**Settling time, t_s (s)**
1	1.6505×10^{-5}	3.5318
2	1.1098×10^{-7}	3.0969
3	4.6838×10^{-4}	6.8440

The Figure 4.9 shows the comparison the sway angle of the system for different parameter value of mass of the load. For response m=1kg, the time response is faster to reach at minimum peak that is 0.9 s compare to time response for m=2kg and m= 3kg. For time response m=2kg, the time to reach at minimum peak is 1.0s while for m=3kg is 1.1s. The response is undershoot for m=3kg is higher to compare with m=1kg and m=2kg.

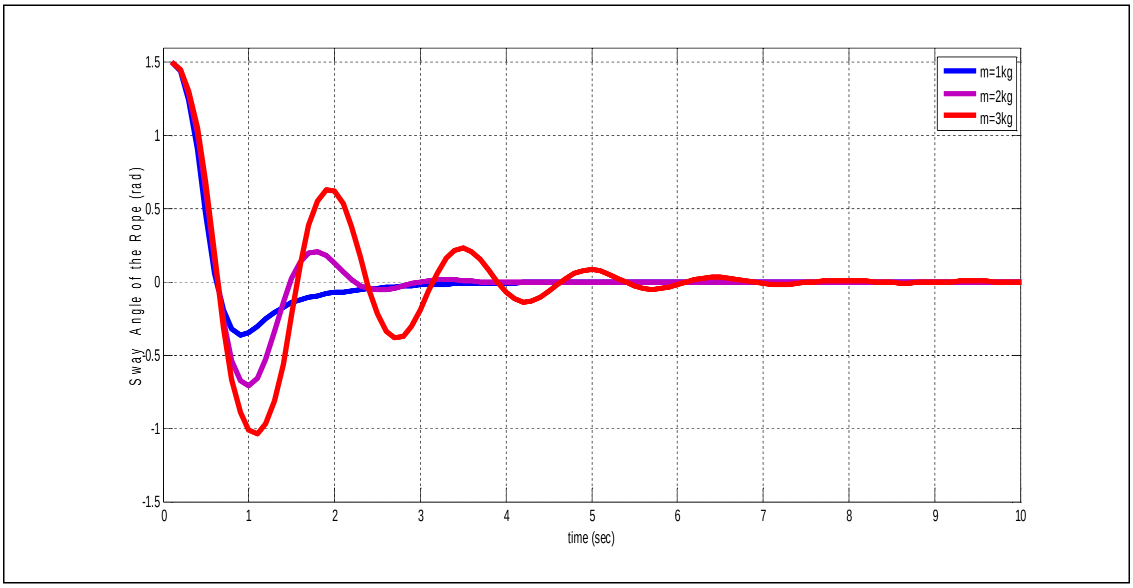


Figure 4.9: Comparison angle of sway angle of different value of m

4.3.3 Case C: Different Parameter for Starting Theta to Release the Load

The value of the parameter in mathematical equation for the model gantry crane system in case C:

Mass of the load, m = 1.00 kg,

Length of the rope, *l* = 1 m

The mass of the cart, M = 2.49 kg

The gravitation coefficient, g = 9.81 $ms^{-2.}$

The system gives a stable response when the time delay is tune to 13.5 sec for all the system. Table 4.7 shows the gain, *k* value used for each system.

Table 4.7: Value Gain, *k*

Starting angle to release the load, *θi*	**Gain, *k***
0.5 rad	70.5
1.0 rad	74.7
1.5 rad	89.8

The graph of gain response is shown in Figure 4.10(a) which it obtain when the system when the angle of load is release at 0.5rad and the gain is tune to 70.5. The response is starting at 32.25dB and reach to undershoot at t=0.9s. The graph of Power Spectral Density of the system is shown in Figure 4.10 (b). The horizontal position for the cart is shown in Figure 4.10(c) while the velocity of the cart is show in Figure 4.10(d). The cart is takes about 3.0305s to settling at -0.7m as it end position. Graph in Figure 4.10(d) show the velocity of the cart which the velocity is fluctuate before the cart velocity is achieved at $0ms^{-1}$ at t=3.1483.

Figure 4.11(a) is a graph of a gain response for the system with initial angle in release the load is 1.0rad and the gain is tune to 74.7. In this simulation, the response is starting at 74.7dB and reach to undershoot at t=0.8s.The response is settling at t=2.7032s. Graph in Figure 4.11(b) show the Power Spectral Density of the system. The horizontal position for the cart is shown in Figure 4.11(c). It takes about 3.1553s to settling at -1.7m as it end position. Graph in Figure 4.11(d) show the velocity of the cart which the velocity is fluctuate before it is stop. The rise time and the settling time of the cart's position and the cart's velocity are not related to the pendulum's swing angle since the controller only tuned for the pendulum's swing angle control

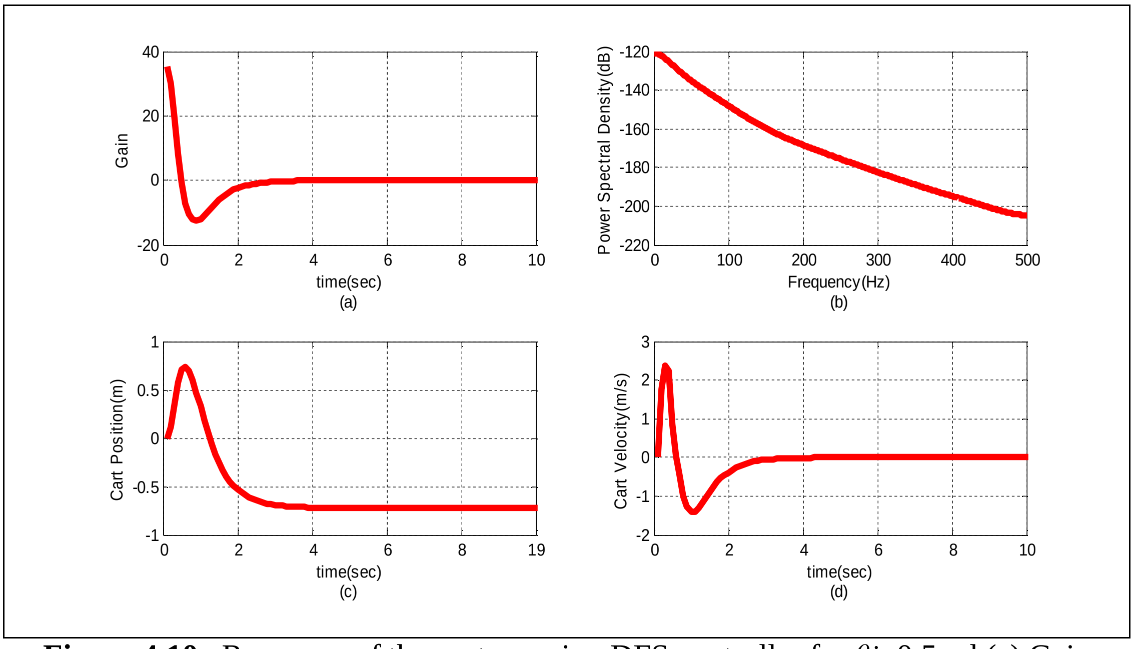


Figure 4.10: Response of the system using DFS controller for θi=0.5rad (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

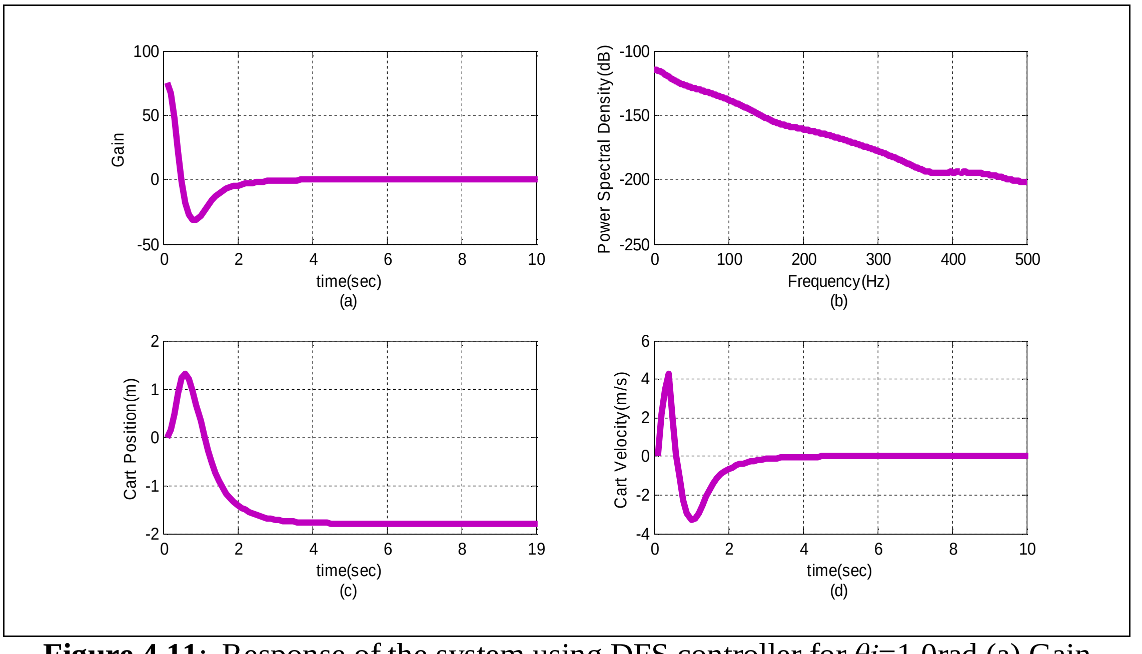


Figure 4.11: Response of the system using DFS controller for θi=1.0rad (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

Figure 4.12(a) is a graph of a gain response for the system with its initial in release the load at 1.5rad and the gain is tune to 89.8. The response is starting at 134.7dB and reach to undershoot at t=0.9s. The graph of Power Spectral Density of the system is shown in Figure 4.12 (b). The horizontal position for the cart is shown in Figure 4.12(c) while the velocity of the cart is show in Figure 4.12(d). The settling time for cart position is at 4.0306s while the settling time for cart velocity is at the 3.5465s. It is shown that the cart is moving according to the sway angle of pendulum in order to the reduce the swaying motion. The velocity of the cart is directly proportional with the distance of the cart. Therefore, the velocity of response will achieve to zero when the cart is stop from moving.

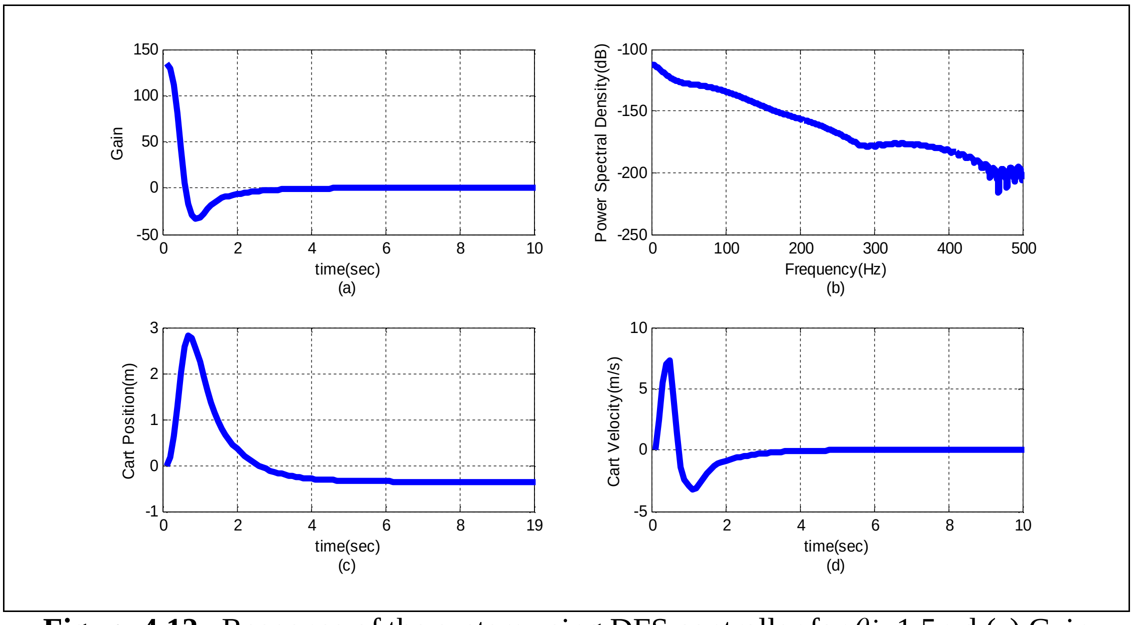


Figure 4.12: Response of the system using DFS controller for *θi*=1.5rad (a) Gain (b) Power Spectral Density (c) Cart Displacement (d) Cart Velocity

Table 4.8 and Table 4.9 shows the comparative for the value rise time, t_r , and settling time, t_s of response position of cart and velocity of the cart of the system for every system. The rise times and settling time for the cart position and cart velocity are increasing simultaneously with the increasing of the starting theta to release the load .

Table 4.8: Response specification of cart position

Starting angle in release the load, θi (rad)	Rise time, t_r (s)	Settling time, t_s (s)
0.5	1.2248	3.0305
1	1.3195	3.1553
1.5	1.8406	4.0306

Table 4.9: Response specification of cart velocity

Starting angle in release the load, θi (rad)	Rise time, t_r (s)	Settling time, t_s (s)
0.5	2.2410×10^{-7}	3.1483
1	1.1074×10^{-6}	3.2912
1.5	1.6490×10^{-5}	3.5465

The Figure 4.13 shows the comparison the sway angle of the system for different parameter value of starting to release the load. For response θi =0.5rad, the time response is faster to reach at minimum peak that is 0.8s compare to time response for θi =1.0rad and θi = 1.5rad. For time response the θi = 1.0rad, the time to reach at minimum peak is 0.9s while for θi = 1.5rad is 0.9s. The response is undershoot for θi = 0.5rad is higher to compare with θi = 1.0rad and θi = 1.5rad

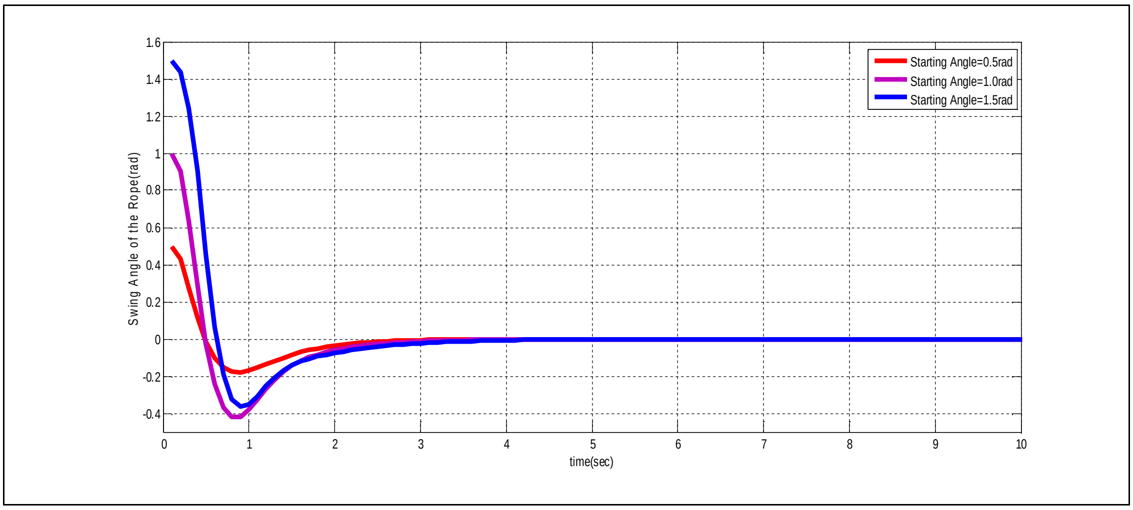


Figure 4.13: Comparison angle of sway angle of different value of θi

4.4 Analysis of the Performance for the System

For all the results obtain after doing the simulation, the analysis of the performance for the system in every case in terms of the level of the sway angle of the hoisting rope response and the Power Spectral Density of the sway angle response.

4.4.1 Case A: Different Parameter for Length of the Rode

Figure 4.14(a), Figure 4.15(a) and Figure 4.16(a) show the result for the level of the sway angle while the Figure 4.14(b), Figure 4.15(b) and Figure 4.16(b) show the results for Power Spectral Density (PSD) of the sway angle of the different hoisting rope.

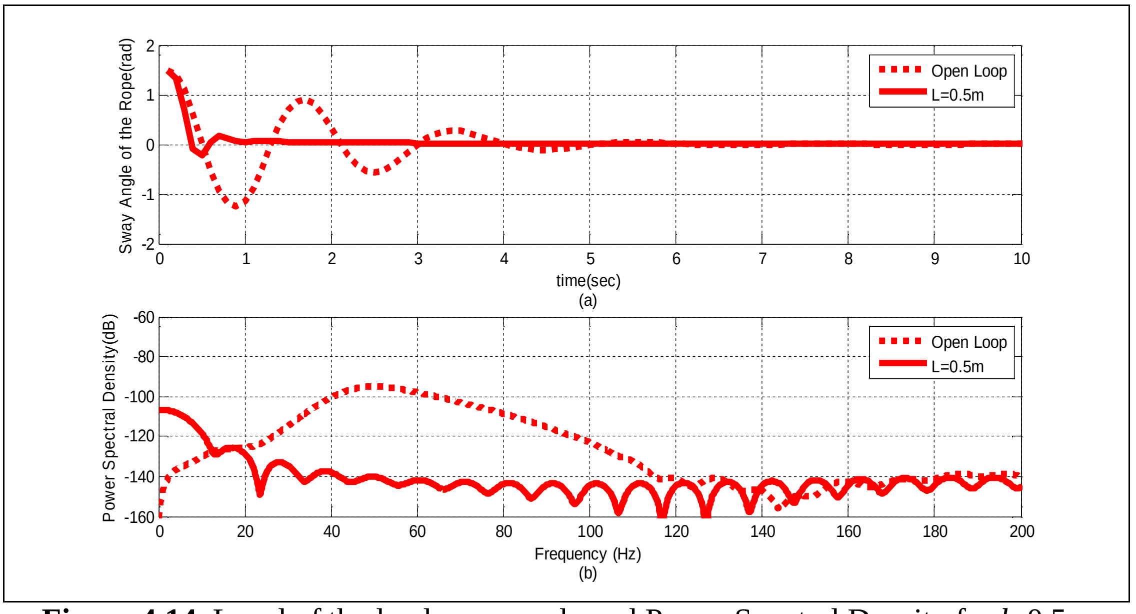


Figure 4.14: Level of the load sway angle and Power Spectral Density for l=0.5m

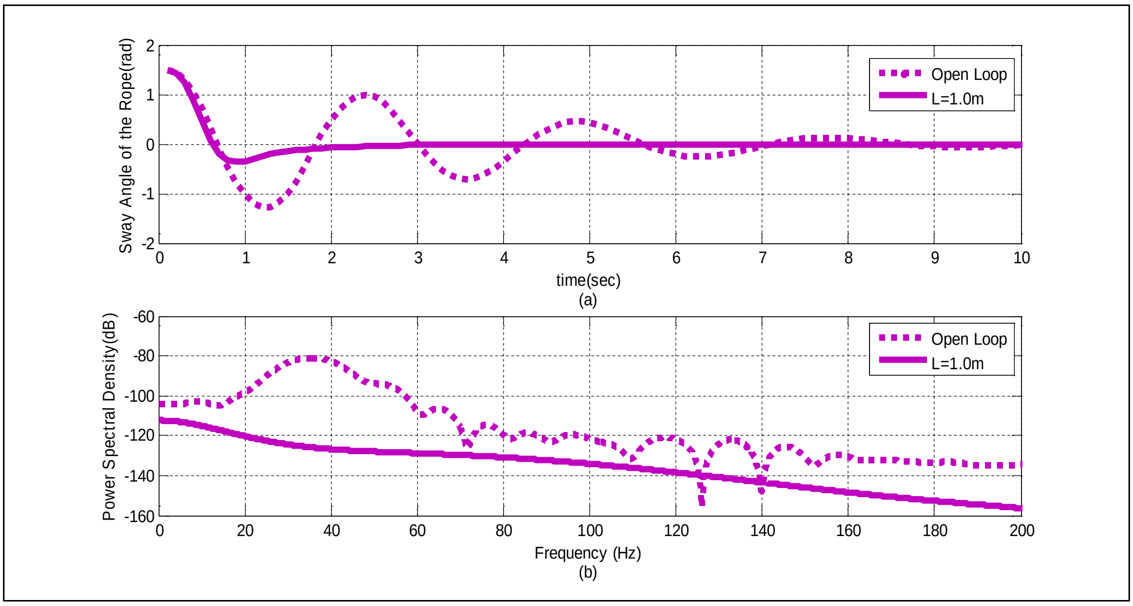


Figure 4.15: Level of the load sway angle and Power Spectral Density for *l*=1.0m

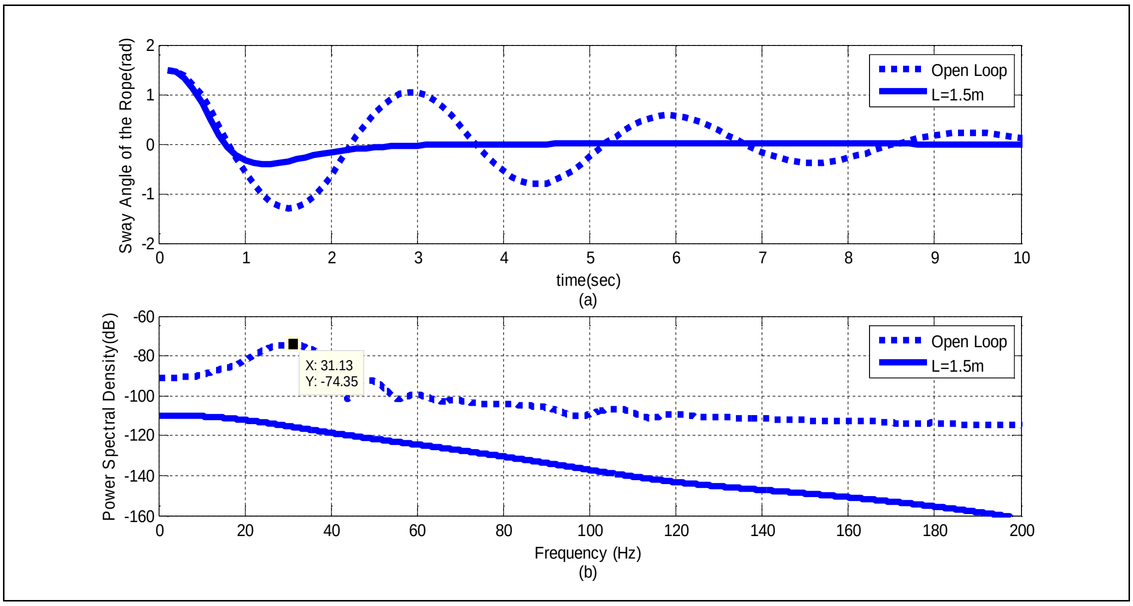


Figure 4.16: Level of the load sway angle and Power Spectral Density for *l*=1.5m

Table 4.10 summarized the specification of the response of the load sway angle. For the comparative to be clear, the result of the specification is shown in Figure 4.17. By comparing each system which have different of parameter length of rope, *l*, the value of *l* =0.5m showed a lowest value of the level swing reduction.

So, the shortest rope may produce a good result. This is because, the longest rope will produce the slowest response of the system since the energy is transferred through the rode and also considering the gravitational effect. In term of rise time and the settling time of the swing angle, for *l* =0.5m showed the smallest rise time and the smallest settling time. That's mean the level of swing angle is achieved 0rad at t=2.6456. Therefore, *l* =0.5m has the fastest response compare to *l* =1m and *l* =1.5m. So, the performance of the shortest rope is better than the longest rope because it take a short time to reduce the sway angle and fast acting. Since the controller is applied only to control the pendulum, the response of the cart position can be ignored.

Table 4.10: Specification response of the load sway angle

Length of the rope, *l* (m)	**Rise time, t_r (sec)**	**Settling time, t_s (sec)**
0.5	1.8209	2.6456
1.0	3.3520	2.7841
1.5	4.2213	2.9574

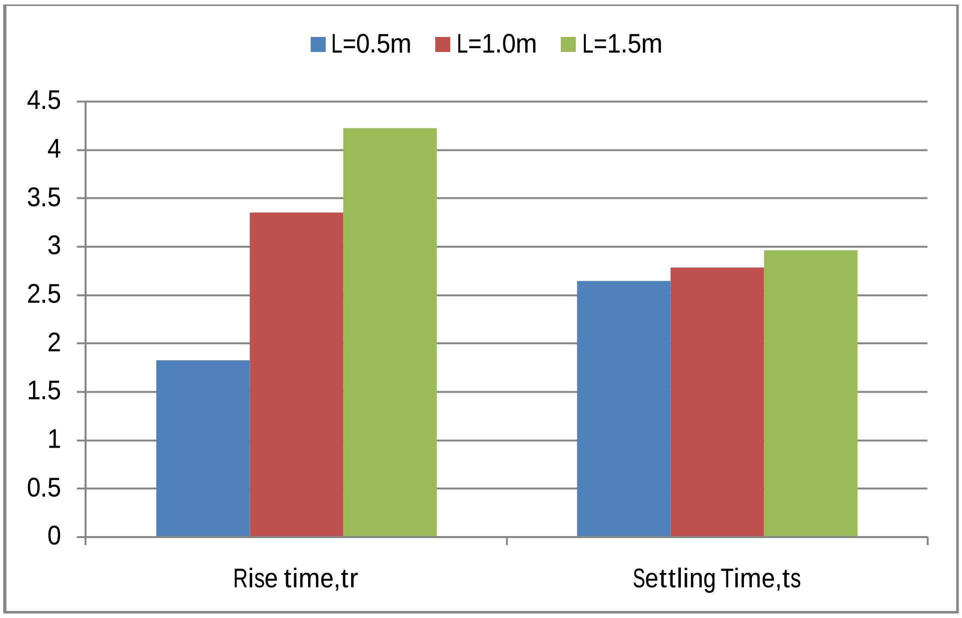


Figure 4.17: Comparison the time response of the system

The result of the attenuation level between controlled and uncontrolled system is shown in Table 4.11, Table 4.12 and Table 4.13 and then summarized in a Figure 4.18. For all system, the level of sway reduction is decreased from mode 1 to mode 3. It proved that the error is already reduced during mode 1. But there is still some error from the system. Therefore, the controller is still reducing the error during mode 2 and then during mode 3. During mode 3, sway reduction is only small value compare to other mode. It is because there is only small error left during mode 3. Therefore, the sway reduction level is decrease from mode 2.

Table 4.11: Attenuation Level for system *l*=0.5m

Mode	Frequency (Hz)	Power Spectral Density (dB)		Attenuation of Sway Angle (dB)
		With Controller	Without Controller	
1	50.54	-94.00	-140.3	45.31
2	119.00	-140.7	-147.3	6.6
3	129.40	-140.9	-146.2	5.3

Table 4.12: Attenuation Level for system *l*=1.0m

Mode	Frequency (Hz)	Power Spectral Density (dB)		Attenuation of Sway Angle (dB)
		With Controller	Without Controller	
1	35.28	-80.92	-125.8	44.88
2	65.06	-106.4	-129.2	22.80
3	76.29	-114.6	-130.3	15.70

Table 4.13: Attenuation Level for system *l*=1.5m

Mode	Frequency (Hz)	Power Spectral Density (dB)		Attenuation of Sway Angle (dB)
		With Controller	Without Controller	
1	30.15	-74.30	-115.2	40.9
2	48.58	-92.08	-121.2	29.12
3	59.81	-99.47	-124.4	24.93

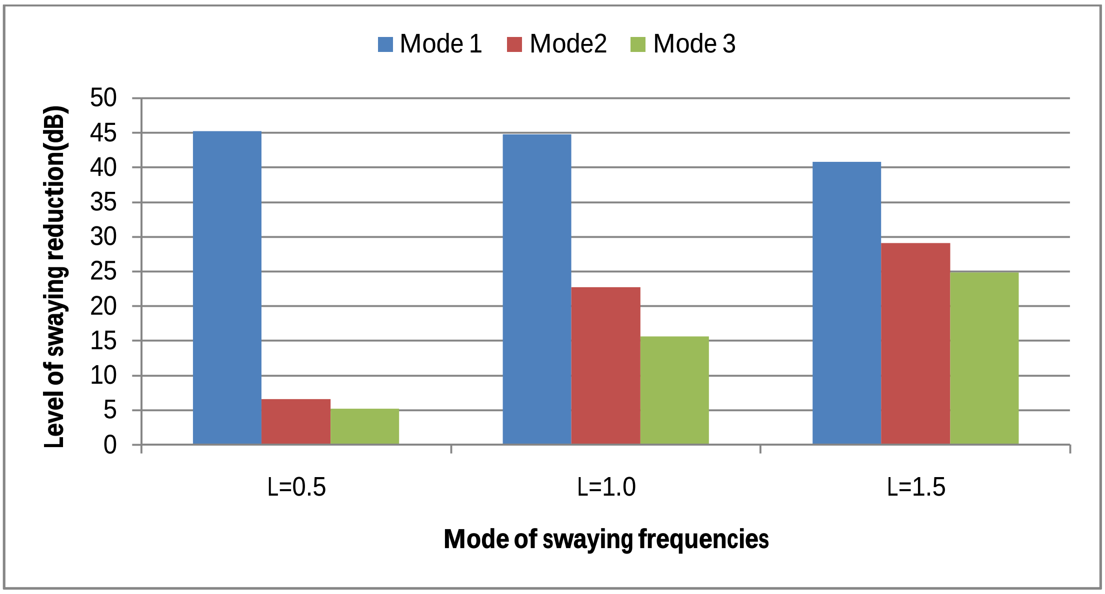


Figure 4.18: Level of sway reduction

4.4.2 Case B: Different Parameter for Mass of the Load

The results for the level of the sway angle of the different mass of the load are show in Figure 4.19(a), Figure 4.20(a) and Figure 4.21(a).

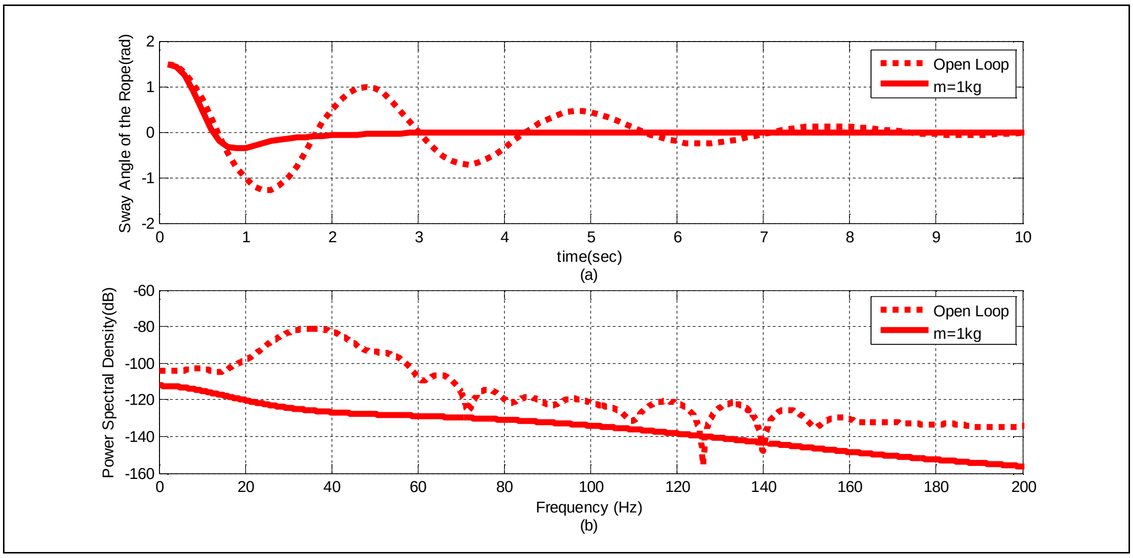


Figure 4.19: Level of the load sway angle and Power Spectral Density for m=1kg

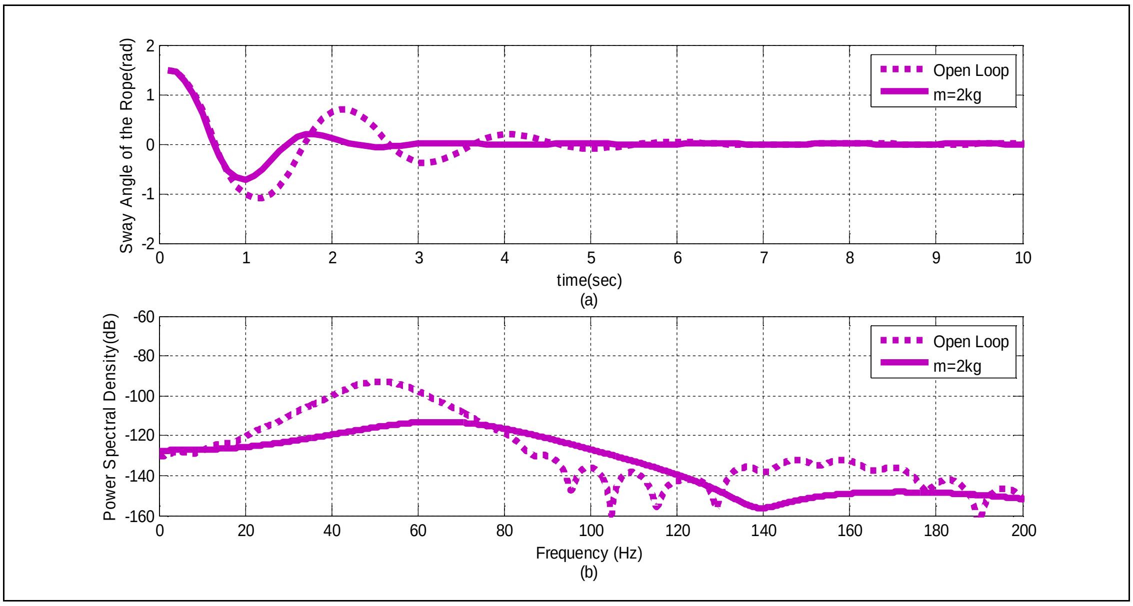


Figure 4.20: Level of the load sway angle and Power Spectral Density for m=2kg

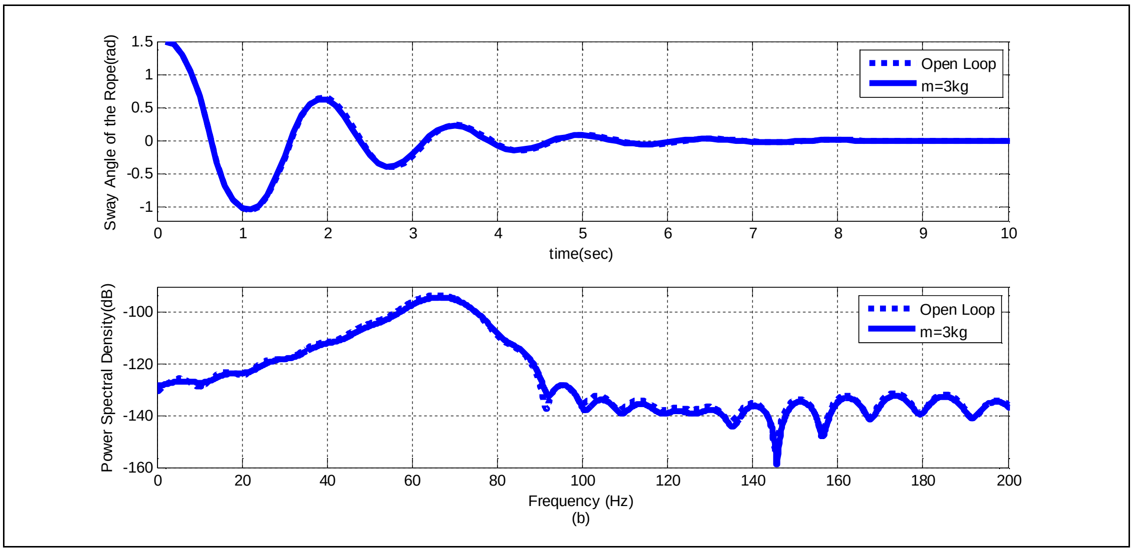


Figure 4.21: Level of the load sway angle and Power Spectral Density for m=3kg

Table 4.14 summarized the specification of the response of the load sway angle. For the comparative to be clear, the result of the specification is shown in Figure 4.22 which it shows that the heaviest load required a high rise time and settling time compare to the lightest load. So, the heaviest give a slow response to achieve a steady state due to its inertia. All the systems give zero percent of the percentage of the overshoot due to the good controller is use. So, the performance of the lightest load is better than the heaviest load because it take a short time to reduce the sway angle and fast acting.

Table 4.14: Specification response of the load sway angle

Mass of the load, m (kg)	**Rise time, t_r (sec)**	**Settling time, t_s (sec)**
1	3.3353	2.7842
2	3.3944	2.7873
3	3.3945	6.5256

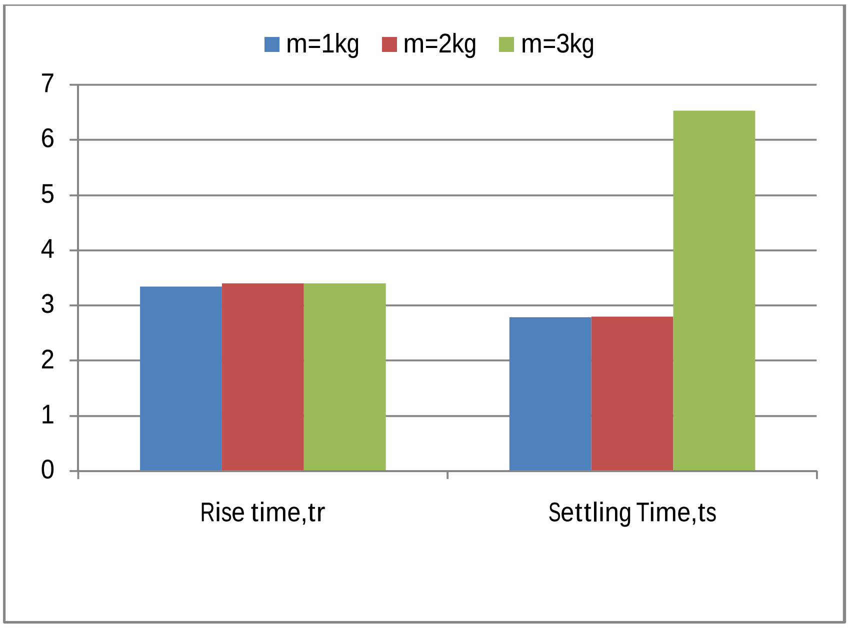


Figure 4.22: Comparison the time response of the system

Figure 4.19(b), Figure 4.20(b) and Figure 4.21(b) show the result for Power Spectral Density (PSD) of the sway angle of the different mass of the load. The result of the attenuation level is shown in Table 4.15, Table 4.16 and Table 4.17 and then summarized in Figure 4.23. For all system, the level of sway reduction is decreased from mode 1 to mode 3. It proved that the error is already reduced during mode 1. But there is still some error from the system. Therefore, the controller is still reducing the error during mode 2 and then during mode 3. During mode 3, sway reduction is only small value compare to other mode. It is because there is only small error left during mode 3. Therefore, the sway reduction level is decrease from mode 2. From that figure, it is showed that the higher performance is achieved with lightest load. The heavy loads cause high inertia which will increase the energy to the load. So, it will be take a time to reduce the sway angle.

Table 4.15: Attenuation Level for system m=1kg

Mode	Frequency (Hz)	Power Spectral Density (dB)		Attenuation of Sway Angle (dB)
		With Controller	Without Controller	
1	35.28	-80.92	-125.8	44.88
2	65.06	-106.4	-129.2	22.80
3	76.29	-114.6	-130.3	15.70

Table 4.16: Attenuation Level for system m=2kg

Mode	Frequency (Hz)	Power Spectral Density (dB)		Attenuation of Sway Angle (dB)
		With Controller	Without Controller	
1	51.55	-92.9	-115.5	22.6
2	99.73	-132.1	-152.8	20.7
3	158.9	-132.2	-149.2	17

Table 4.17: Attenuation Level for system m=3kg

Mode	Frequency (Hz)	Power Spectral Density (dB)		Attenuation of Sway Angle (dB)
		With Controller	Without Controller	
1	104	-132.2	-133.9	1.7
2	113.3	-134.0	-135.5	1.5
3	137	-136.7	-137.7	1.0

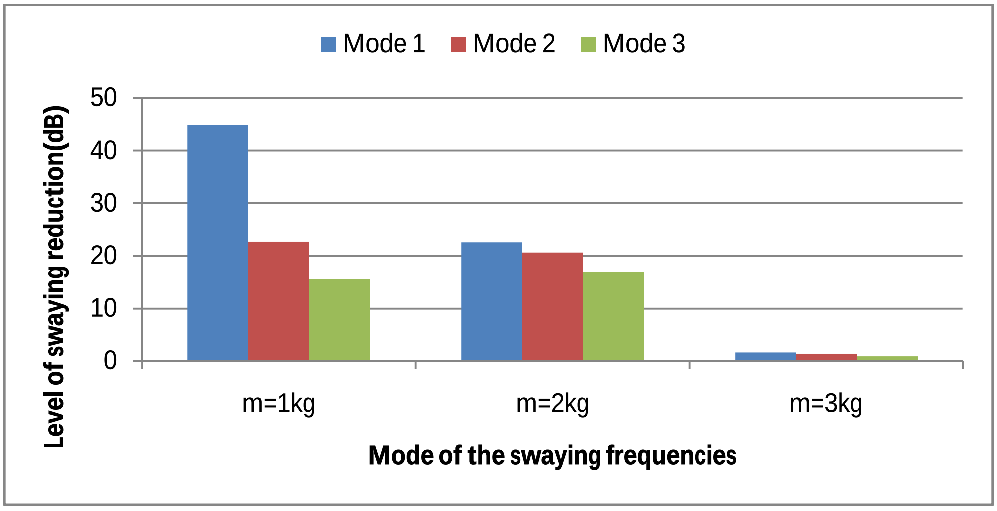


Figure 4.23: Level of sway reduction

4.4.3 Case C: Different Parameter for Starting Theta to Release the Load

The results for the level of the sway angle of the different mass of the load are show in Figure 4.24(a), Figure 4.25(a) and Figure 4.26(a).

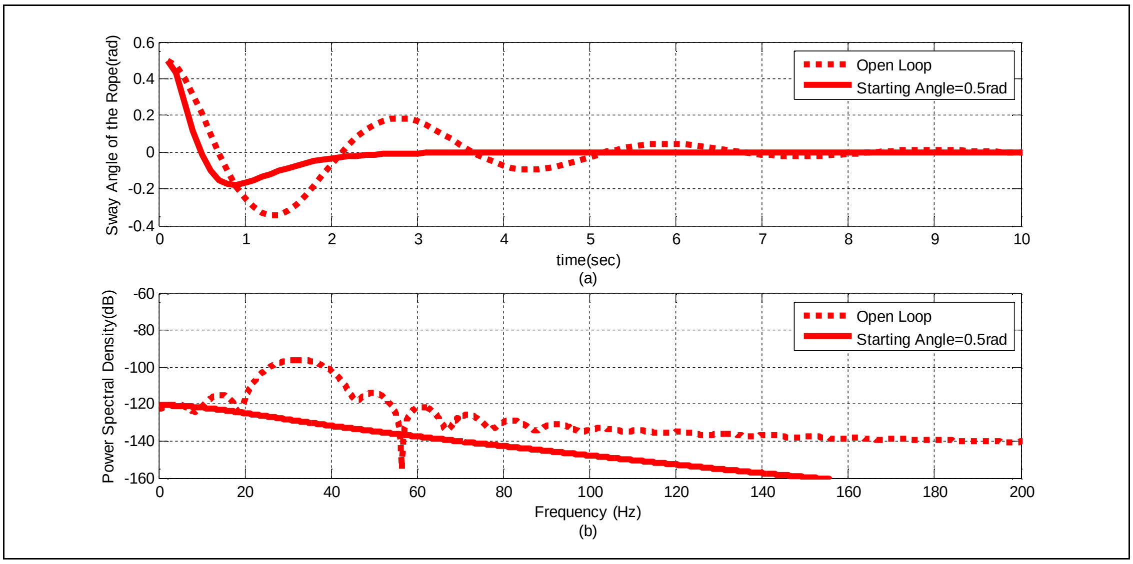


Figure 4.24: Level of the load sway angle and Power Spectral Density for starting angle in release the load is 0.5 rad

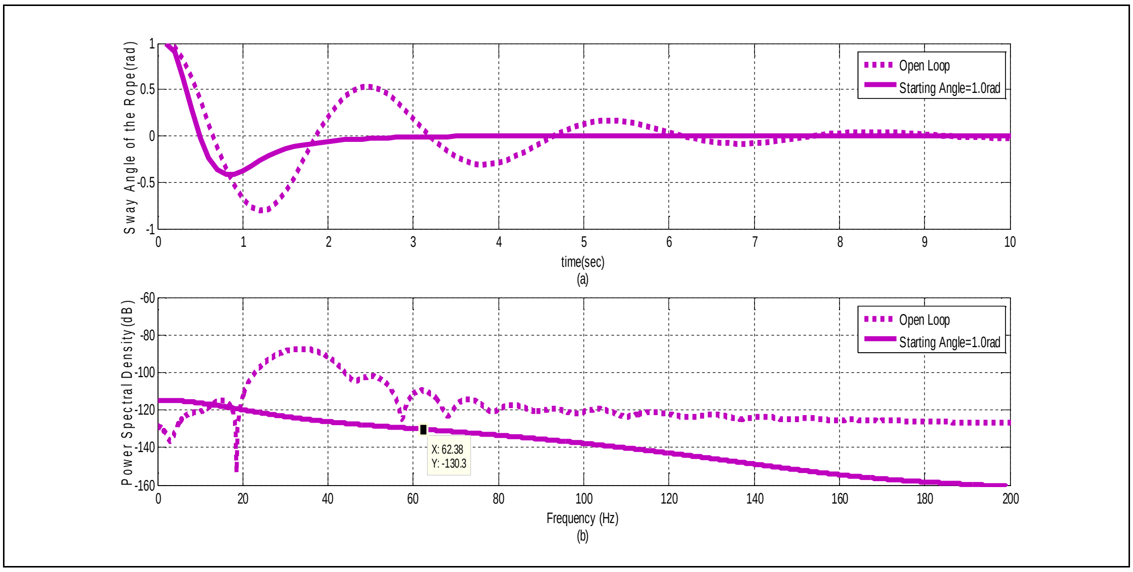


Figure 4.25: Level of the load sway angle and Power Spectral Density for starting angle in release the load is 1.0 rad

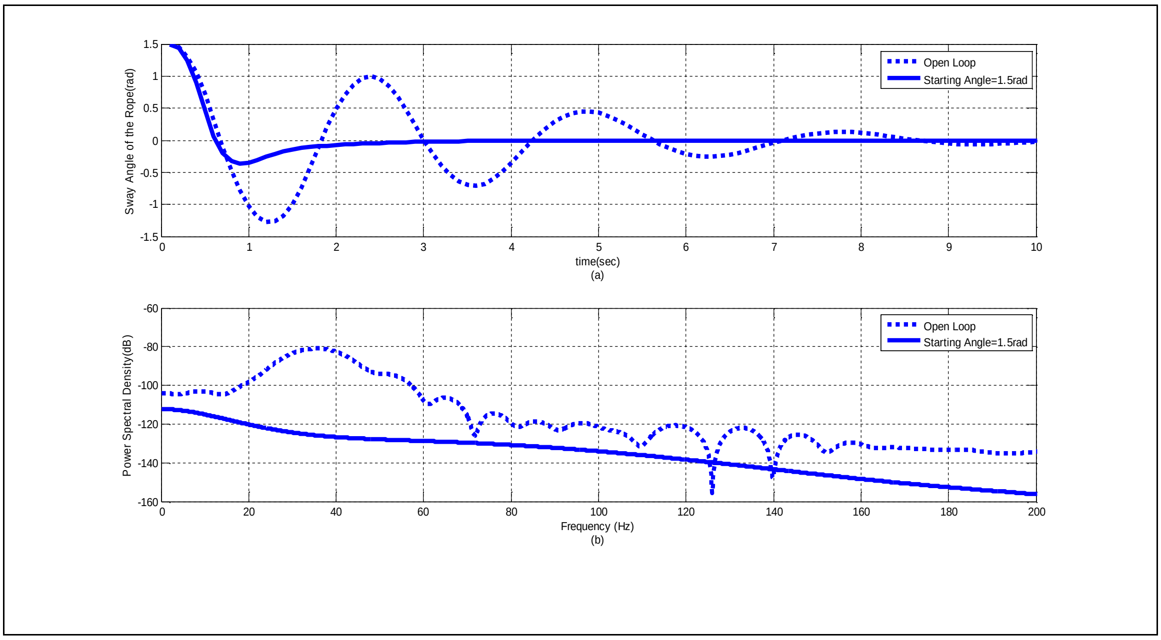


Figure 4.26: Level of the load sway angle and Power Spectral Density for starting angle in release the load is 1.5 rad

The specification of the response of the load sway angle is summarized in Table 4.19. The result of the specification is shown in Figure 4.27 which it shows that the highest point for the release of the load required a low value of the rise time and settling time compare to the lowest point due to its kinetic energy in the load. For the highest point, the pendulum has the highest momentum and kinetic energy. So, the performance of the lowest point in the release of the load better than the highest point for the release of the load because it take a short time to reduce the sway angle and fast acting.

Table 4.18: Specification response of the load sway angle

Starting theta to release the load, θi (rad)	Rise time, t_r (sec)	Settling time, t_s (sec)
0.5	2.7995	2.6915
1.0	2.8919	2.7032
1.5	3.3336	2.7839

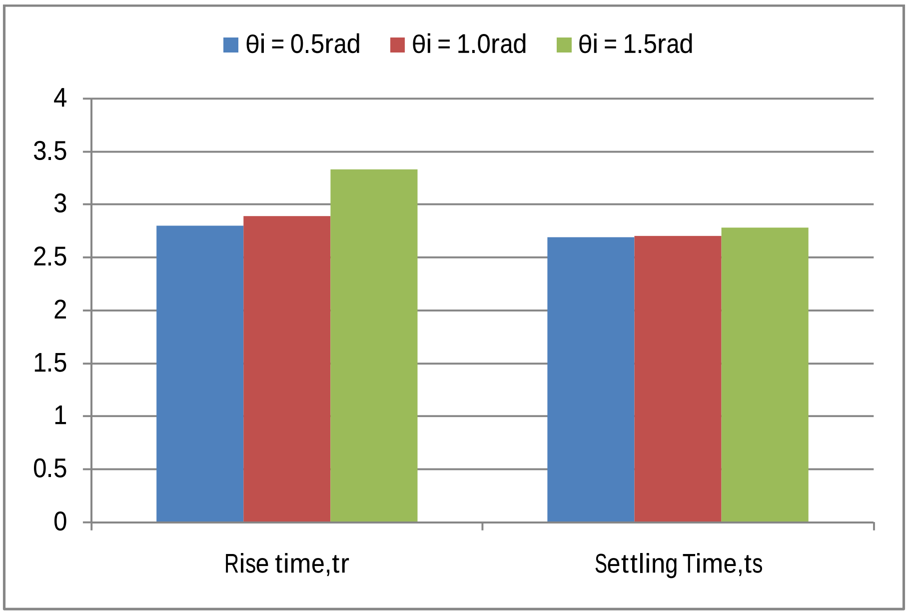


Figure 4.27: Comparison the time response of the system

Figure 4.24(b), Figure 4.25(b) and Figure 4.26(b) show the result for Power Spectral Density (PSD) of the sway angle of the starting point to release the load. The result of the attenuation level is shown in Figure 4.28 which it summarized from the Table 4.19, Table 4.20 and Table 4.21. For all system, the level of sway reduction is decreased from mode 1 to mode 3. It proved that the error is already reduced during mode 1. But there is still some error from the system. Therefore, the controller is still reducing the error during mode 2 and then during mode 3. During mode 3, sway reduction is only small value compare to other mode. It is because there is only small error left during mode 3. Therefore, the sway reduction level is decrease from mode 2.

Table 4.19: Attenuation Level for system for starting angle in release the load is 0.5 rad

Mode	**Frequency (Hz)**	**Power Spectral Density (dB)**		**Attenuation of Sway Angle (dB)**
		With Controller	**Without Controller**	
1	32.35	-95.98	-129.1	33.02
2	50.29	-114.2	-134.8	20.6
3	60.91	-121.4	-137.7	16.3

Table 4.20: Attenuation Level for system for starting angle in release the load is 1.0 rad

Mode	**Frequency (Hz)**	**Power Spectral Density (dB)**		**Attenuation of Sway Angle (dB)**
		With Controller	**Without Controller**	
1	33.69	-87.41	-124.6	37.19
2	50.54	-102.1	-128.3	26.2
3	62.38	-109.7	-130.3	20.6

Table 4.21: Attenuation Level for system for starting angle in release the load is 1.5 rad

Mode	Frequency (Hz)	Power Spectral Density (dB)		Attenuation of Sway Angle (dB)
		With Controller	Without Controller	
1	35.28	-80.92	-125.8	44.88
2	65.06	-106.4	-129.2	22.80
3	76.29	-114.6	-130.3	15.70

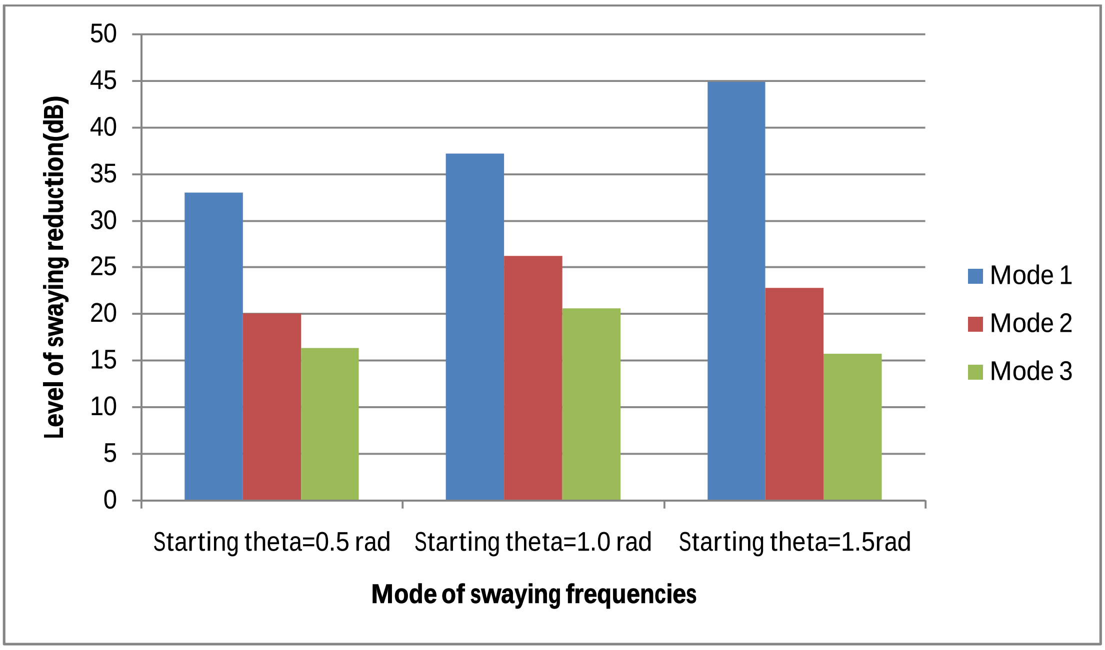


Figure 4.28: Level of sway reduction

Table 4.22 summarized the comparison of the rise time and settling time for each system in every case.

Table 4.22: Comparison of rise time (Tr) and settling time (Ts) for each system in every case.

Case	Parameter	Cart Position, (m)		Cart Velocity, (m/s)		Load Sway Angle	
		Tr(s)	**Ts(s)**	**Tr(s)**	**Ts(s)**	**Tr(s)**	**Ts(s)**
	L = 0.5m	4.0533	7.2315	0.0030	4.7244	1.8209	2.6456
Case A	**L = 1.0m**	1.8405	4.0307	$1.6886\text{x}10^{-5}$	3.5354	3.3520	2.7841
	L = 1.5m	0.9210	3.1794	$5.0188\text{x}10^{-7}$	3.2967	4.2213	2.9574
	M = 1kg	1.8405	4.0308	$1.6505\text{x}10^{-5}$	3.5318	3.3353	2.7842
Case B	**M = 2kg**	1.9355	2.7962	$1.1098\text{x}10^{-7}$	3.0969	3.3944	2.7873
	M = 3kg	1.7537	6.5095	$4.6838\text{x}10^{-4}$	6.8440	3.3945	6.5256
	θi= 0.5rad	1.2248	3.0305	$2.2410\text{x}10^{-7}$	3.1483	2.7995	2.6915
Case C	**θi =1.0rad**	1.3195	3.1553	$1.1074\text{x}10^{-6}$	3.2912	2.8919	2.7032
	θi = 1.5rad	1.8406	4.0306	$1.6490\text{x}10^{-5}$	3.5465	3.3336	2.7839

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

At the end of this project, the application and high performance using Delayed Feedback Signal (DFS) for control of a gantry crane system is successfully developed. The Delayed Feedback Signal (DFS) controller should have only one position sensor and uses only the current output of this sensor and the output τ second in past to control signal. The parameter, k and τ needs to be set.

To see a comparison of the use of parameters for this system, each parameter values for length of the rope, l, mass of the load, m, and starting point of the release the load, θ_i are set up with three different value. The performance of every system is compared. For the different parameter of length of the rope, the higher performance is achieved with the shortest length of the rope because the energy in longest rope is high compare to the shortest rope. So, it will take a time to reduce the angle. For the different parameter of mass of the load, the higher performance is achieved with the heaviest load. The heavy loads cause high inertia which will increase the energy to the load. So, the time will be longer to reduce the sway angle. For the different parameter of starting point in release the load, the higher performance is achieved with the highest starting point in release the load. The highest point in release the load cause the kinetic energy is increased. So, more time is required to reduce the sway angle.

5.2 Recommendation

Based on this project, there are three recommendations for the future works:

i. The robust and scale gantry crane is used which is preferable to use in the experiment study.
ii. The feedback control can replace feed-forward approaches because the feedback control is less sensitive to disturbances and parameter variation. A sensor will be needed for measuring the position and the load swing angle if using the feedback control in the future experiment.
iii. For the future application, it is recommended to use the system that has a vibration.

REFERENCE

[1] www.hoistmagazine.com

[2] M.A Ahmad, 2009, “Swat Reduction on Gantry Crane System using Delayed Feedback Signal and PD –type Fuzzy Logic Controller: A comparative Assessment.

[3] Rahman, E.M.A., Nayfeh, A.H., Masoud, Z.N., 2003. Dynamic and Control of Crane: a Review, *Journal of Vibration and Control*, 9(7), 863-908.

[4] Vaha, P., Pieska, A., and Timonen, E., 1988, “Robotization of an offshore crane,” in Robots: Coming of Age, Proceedings of the 19th ISIR International Symposium, pp.637–648.

[5] Masoud, Z. N., Nayfeh, A. H., Henry, R. J., and Mook D. T., 2002, “Sway reduction on container cranes using delayed feedback controller,” in Proceedings of the 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, CO, AIAA-2002-1279.

[6] Henry, R. J., Masoud, Z. N., Nayfeh, A. H., and Mook, D. T., 2001, “Cargo pendulation reduction on ship–mounted cranes via boom-luff angle actuation,” Journal of Vibration and Control 7, 1253–1264

[7] Robinett, R. D., Parker, G. G., Feddma, J., Dohrmann, C. R., and Petterson, J., 1999, “Sway control method and system for rotary crane,” USA Patent No 5908122, June.

[8] Balachandran, B., Lee, Y. Y., and Fang, C. C., 1999, “A mechanical filter concept for control of non-linear crane-load oscillation,” Journal of Sound and Vibration 228(3), 651–682.

[9] Ridout, A. J., 1989a, “Anti-swing control of the overhead crane using linear feedback” Journal of Electrical and Electronics Engineering 9(1/2), 17–26.

[10] Salminen, R., Marttinen, A., and Virkkunen, J., 1990, "Adaptive pole placement control of a piloted crane," in Proceedings of the IFAC 11th Trienmal World Congress, Tallinn Estonia, USSR, pp. 313–318.

[11] Hazlerigg, A. D. G., 1972, "Automatic control of crane operations," in Proceedings of the 5th IFAC World Congress, Paris, France, pp. 11–13.

[12] Hurteau, R. and Desantis, R. 1983, "Microprocessor-based adaptive control of a crane system," in Proceedings of the IEEE Conference on Decision and Control Including The Symposium on Adaptive Processes, New York, NY, Vol. 2, pp. 944-947.

[13] M.Ramesh, S Narayam, "Controlling chaotic motions in two-dimensional airfoil using time delayed feedback," J.Sound Vibration 239(5)(2001) 1037-1049.

[14] Z.H Wang and H.Y.Hu, "Stability Switches of Time-Delayed Feedback Dynamic Systems with unknown Parameters," Journal of Sound and Vibration, vol 233, No 2,pp.215-233,2000.

[15] Zairulazha, Z., (March, 2005). "Modelling and Vibration Control of a Gantry Crane", Universiti Teknologi Malaysia, Master Thesis.

[16] M.Weldon, T.Peacock, G.B Jacobs, M.Helv and G Haller, 2008 "Experimental and numerical investigation of kinematic theory of the unsteady separation" Journal Fluid mechanical, vol 611,pp.1-11.

[17] R.C Hibbeler, 1995Engineering Mechanics, "Dynamics Seventh Edition USA", Prentice Hall.