HYBRID COMMAND SHAPING AND PD CONTROLLER FOR SWAY SUPPRESSION OF ROTARY CRANE SYSTEM

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

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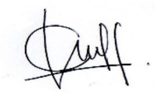

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Dedicated to my beloved family

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ABSTRACT

Crane systems were normally used for lifting, loading load from one point to others. The problem of crane systems is swing motion when payload is suddenly stopped after a fast motion. This project presents the development of input shaping with proportional derivative (PD) controller for sway suppression and trajectory tracking of rotary crane systems. The application of hybrid PD and input shaping technique can reduce the sway with better tracking responses. Firstly, PD controller is designed for angular position of rotary crane. Then, the input shaping is developed based on frequency response of PD control. The performance of the proposed controller is compared with PD-PID control scheme, in terms of time response specifications and sway reduction. The simulation results show that the PD-input shaping provide better control performance as compared to PD-PID scheme.

ABSTRAK

Sistem kren biasanya digunakan untuk mengangkat, memuatkan beban dari satu titik kepada satu titik yang lain. Masalah sistem kren yang sedia ada sekarang ialah kadar ayunan apabila muatan tiba-tiba dihentikan selepas satu usul yang cepat. Projek ini dijalankan bagi membentuk input dengan pengawal berkadar derivatif (PD) untuk memujuk penindasan dan trajektori mengesan sistem kren putar. Penggunaan hibrid PD dan input yang membentuk teknik boleh dikurangkan dengan maklum balas pengesanan yang lebih baik. Langkah pertama, pengawal PD direka untuk mengawal getaran pada tangan kren. Kemudian, membentuk input dibuat berdasarkan kekerapan respons PD kawalan. Seterusnya, prestasi yang sedia ada akan dibanding dengan hidbrid input dan skim kawalan PD-PID, keputusan ini merangkumi dari segi masa tindak balas spesifikasi dan pengurangan putaran. Menunjukkan keputusan simulasi bahawa membentuk PD-input memberikan prestasi kawalan yang lebih baik berbanding skim PD-PID.

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LIST OF SYMBOLS

θ	Angle of the arm
α	Sway angle of the pendulum
r	Length of the arm
L	Length of the pendulum
m	Mass of the pendulum
Ja	Moment of inertia of the arm
Jp	Moment of inertia of pendulum
g	Gravity effect
$\dot{\theta}$	Hub velocity
K_p	Porpotional gain
K_v	Derivative gain

A_c	Gain of motor amplifier
ω_n	Natural frequency
ζ	Damping ratio
t_i	Time location
A_i	Amplitude of impulse

LIST OF ABBREVIATIONS

PD	Proportional Derivative
PZS	Positive Zero Sway
PZSD	Positive Zero Sway Derivative
PZSDD	Positive Zero Sway Derivative Derivative
PID	Proportional Integral Derivative
PSD	Power Spectral Density

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Cranes are one of the priciest and regularly used on construction sites, factories, warehouse and shipyards throughout the world. All cranes use vertical suspension cables to support the payload, thereby creating the possibility of pendulum-like payload oscillation. To limit this motion- induced vibration the primary method has been utilized to train a skilled operator and to move slowly. It does not provide the most efficient operating condition but it succeed to reduce payload oscillation and thereby, increase safety. That is why, the other method which is designing the controller is applied to the crane control system. Cranes need this controller to reduce the sway and had a better performance. Furthermore, there are so many controllers that can be design to get a better performance of crane. Besides, it is easier to install and handle compare to the human operator only. For example, the human operator was attempting to drive the crane from the start location to the goal location, while avoiding the obstacles in the workspace [1]. As a result, the crane hook collided with two of the obstacles in other word called as swing motion. After the controller were install in the crane system, the operator drive the crane again but not in the swing condition.

Rotary cranes is important machinery that normally been used at construction site and shipyards to transport a materials, which is usually heavy, large and hazardous that cannot be handling by workers. In order to make work easier and smooth the operation, rotary crane have been assigned to transfer, lift and move the payload from one place to another place. But never to forget that, safety is the most important aspect to be consider while operating crane hand cranes may have some problem with their arm and pendulum when carrying and transferring the heavy loads in faster motion, which causing to sway excessively. There are many cases and incident regarding on the crane's accident. For example, from 1992 to 2006, crane related accidents in United States led to 632 worker death, an average of 43 deaths per year [2]. The incident occur due to strike by crane's load which cause by too much swing motion in lifting operation. Due to this case, effective and efficient controller are applied inti the cranes system to meet safety requirement and smooth operation. Figure 1.1 and 1.2 shows examples of two of rotary cranes.

Figure 1.1: Rotary Crane

Figure 1.2: Rotary crane

The requirement of precise sway control of rotary cranes implies that residual sway of the payload should be zero or near zero. As the performance requirements imposed by the industry become more severe, the need to understand how to model and control rotary crane becomes an issue of concern. Thus, it becomes necessary to anticipate and control such sways in order to obtain robust and fast response of rotary crane.

1.2 PROBLEM STATEMENT

Transporting the load as fast as possible from one point to one point without causing any excessive swing at the final position is the main purpose of controlling the rotary crane. However, most of the common rotary crane results are in swing motion when payload is suddenly stopped after a fast motion [3]. Accident might be happen when cranes are fail to control.

1.3 PROJECT OBJECTIVE

The objectives of this project:

i. To develop a hybrid input shaping and PD controller for rotary crane systems.
ii. To investigate the effectiveness of the proposed controllers in term of input trackin capability, sway reduction and time response specifications.

1.4 PROJECT SCOPE

The scopes of this project:

i. Modelling of a rotary crane
    - Modelling is needed to represent the system that will be focused in order to do an analysis and further work
ii. To develop the PD controller that can control the angular position control of rotary crane arm.
iii. To design the positive input shaping controller which consist of positive zero sway (PZS), positive zero sway derivative (PZSD), and positive zero sway derivative-derivative (PZSDD)
iv. Simulation studies
    - For simulation studies, MATLAB 2014 is used for design purpose before it been transferred for experimental studies.

1.5 THESIS OUTLINE

This section will give an outlines of the structure of the thesis. This thesis will consist of five chapters including this chapter. The following is an explanation for each chapter:

Chapter 2 discusses the previous work that been done around the world about the crane, in term of control method, modelling and controlling the crane. Literature that been done will cover, for instance, modelling, control algorithm design and others.

Chapter 3 explanation on methodology of this project. In this chapter, each step in the starting from modelling of the rotary crane was explained.

Chapter 4 consists of simulation results and results analysis. Comparison between each input shaping derivative order and PID was done.

Lastly, Chapter 5 summarizes the overall conclusion for this thesis and a few suggestion and recommendation for future development.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Rotary cranes are invaluable as machines for lifting the loads in factories, construction sites, and harbours and so on. The fundamental motions of a rotary crane are load lifting, rotation, and boom hoisting. The load sway grows from such the centrifugal force that rotary motion induces. As the shipping cost is related to a ship's anchorage time, it is desirable to minimize the anchorage time by immediately eliminating sway at the end of a load transfer. In the worksite, it relies on the experience and skill of the operator, but it is obvious that the operator is too nervous and the working efficiency is low. An automatic operating system is desired so that the work can be completed safely and rapidly.

2.2 TYPE OF CRANE AND PROBLEMS

Cranes can roughly be divided into three categories based upon their primary dynamic properties and the coordinate system that most naturally describes the location of the suspension cable connection point. The first category, bridge cranes, operate in Cartesian space, as shown in Figure 2.1 and Figure 2.2. The trolley moves along a bridge, whose motion is perpendicular to that of the trolley. Bridge cranes that travel on a mobile base are often called gantry cranes. Bridge cranes are common in factories, warehouses, and at shipyards.

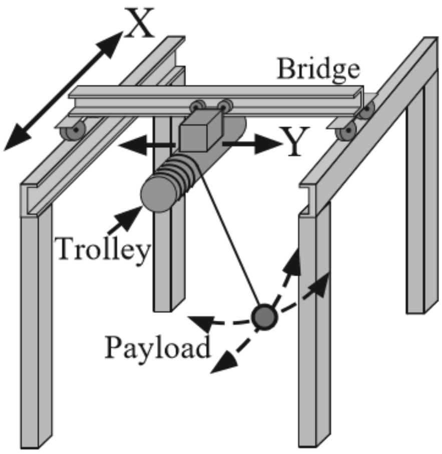

Figure 2.1: Bridge crane

Figure 2.2: Bridge crane sketch

The second major category of cranes is boom cranes, shown in Figure 2.3 and Figure 2.4 [4]. Boom cranes are naturally described in spherical coordinates, where a boom rotates about axes both perpendicular and parallel to the ground. In the figure, ψ is the rotation about the vertical Z axis, and θ is the rotation about the Y axis. The payload is supported from a suspension cable at the end of the boom. Boom cranes have the primary advantage of supporting loads in compression. As a result, they are typically more compact than bridge or tower cranes with similar load carrying capacities. Boom cranes are commonly found at building construction sites. Their compact nature also lends well to being mounted on a mobile base. Boom cranes are often mounted on trucks, tracked vehicles, and ships.

Figure 2.3: Boom crane

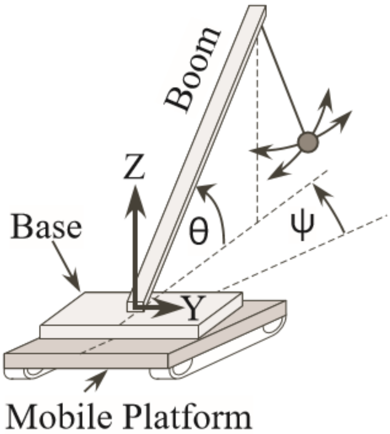

Figure 2.4: Boom crane sketch

The third major category of cranes is tower cranes, like the ones shown in Figure 2.5 and Figure 2.6. Tower cranes are most naturally described by cylindrical coordinates. A horizontal jib arm rotates around a vertical tower. The payload is supported by a cable from the trolley, which moves radially along the jib arm. Tower cranes are commonly used in the construction of multi-story buildings and have the advantage of having a small footprint-to-workspace ratio. Primary disadvantages of tower and boom cranes, from a control design viewpoint, are the nonlinear dynamics due to the rotational nature of the cranes, in addition to the less intuitive natural coordinate systems for human operators.

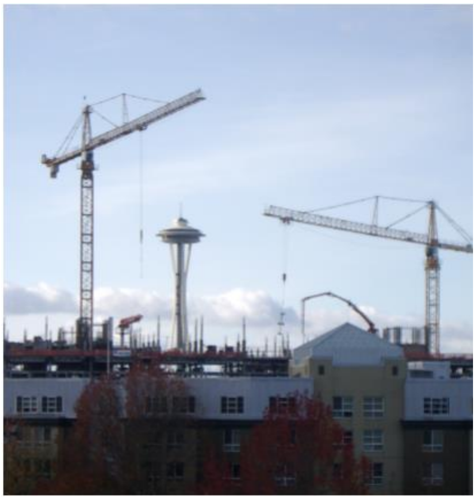

Figure 2.5: Tower crane

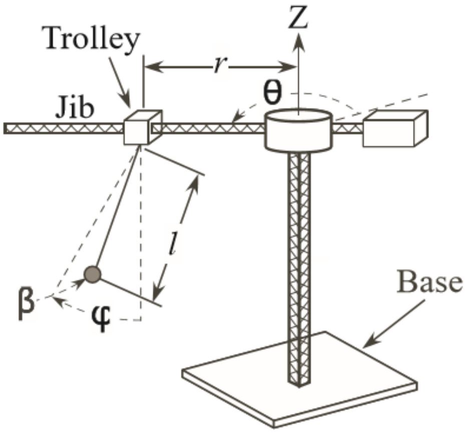

Figure 2.6: Tower crane sketch

A common characteristic among all cranes is that the payload is supported via an overhead suspension cable. While this provides the basic functionality of the crane, it also presents several challenges, the primary of which is payload oscillation. Motion of the crane will often translate to large payload oscillations. These payload oscillations have many detrimental effects including the degradation of payload positioning accuracy, increased task completion time, and decreased safety. Significant research effort has been made into reducing oscillations.

2.3 CRANE CONTROL METHOD

The vibration or sway is a significant problem in dynamical systems that are required to perform precise motion in presence of structural flexibility. Robotic arms, flexible manipulators, step motors, and crane systems are some examples for this category. In reducing the excessive sway of a rotary crane, many researches and paper work had been done in proposing the techniques to overcome the problem.

Various techniques in controlling cranes system based on open loop and closed loop systems have been proposed. For crane control, the open loop methods has been applied to the crane by many researchers [5, 6]. Unfortunate results that they got are poor because open loop strategy is sensitive to the system parameters and could not compensate for the effect of wind disturbance. While, for closed loop system also has been adopted for controlling the crane system. Hazlerigg was one of the first to propose this method [7]. Since then, many researchers have advocated feedback methods for crane control [8], For example, PD controller has been purposed for anti-swing control [5]. However, the performance not very effective to eliminate steady state error.

Furthermore, fuzzy logic controller has also been proposed for controlling the crane system by several researchers [9, 10]. In [10], the proposed fuzzy logic controllers consist of position as well as anti-sway controllers. Other than that, M.A. Ahmad, A.N.K. Nasir, N. Hambali and H. Ishak, they use input shaping and PD-type Fuzzy Logic to control the input tracking and anti-swaying control of a gantry crane system [9]. However, the fuzzy logic designed still need to struggle in finding the satisfactory rules, membership function, fuzzification and deffuzification parameter heuristically [10]. In M.I. Solihin and Wahyudi project, they use Fuzzy-tuned PID controller for anti-swing control [11]. But yet, still cannot cater the sway motion very well.

Feed-forward control techniques is another approach in controlling the crane systems. To make sure the systems sways at response modes are reduced, feed-forward control schemes are developed. Feed-forward control schemes are mainly for sway suppression and involve developing the control input through consideration of the physical and swaying properties of the system, while minimizing residual vibrations of computer controlled machines. Input shaping is a strategy to generate time-optimal shaped commands by using only a simple model, which consist of the estimates of damping ratios and natural frequencies. Hence, to reduce the residual vibration when positioning lightly damped systems are very efficient by using input shaping, besides it is a simple method. It offers several clear advantages over conventional approaches for trajectory generation [12]

i) Input shaping can be generated from simple, empirical measurements of the actual physical system; without considering the analytical model of the system. [12].

ii) The stability of the closed loop system is untouchable in any way. It simply modifies the command signal to the system so that all moves, regardless of length, are vibration free [12].

According to M.A. Ahmad, R.M.T. Raja Ismail, M.S. Ramli, A.N.K. Nasir, and N. Hambali paper's, they use feed-forward technique in reducing sway suppression.[13] The earliest incarnation of this self-cancelling command generation was developed by Smith [14] but his technique was extremely sensitive to modelling errors [15]. This new technique is named as input shaping. Input Shaping [16, 17] is a command filtering technique that dramatically used to reduces motion-induced payload oscillation by intelligently shaping the reference commands. It has been used to mitigate unwanted oscillation in cranes [18]. Using estimates of system natural frequencies and damping ratios, a series of impulses, called the input shaper, is designed. . The convolution of the input shaper and the original command is then used to drive the system. Input shaping shown to be effective for controlling oscillation of crane when the load does not undergo hoisting [19, 20].This process is demonstrated with a two-impulse input shaper and a step command. According to Sirri Sunay Gurleyuk, Ozgur Bahadir, Yunus Turkkan and Hakan Usenti which had proposed in their paper Three-Step (TS) input shaping technique. A solution space for three-impulse shaping is given including both positive negative shapers. It is shown here that ZVD and EI shapers are the special solution points in TS shaping space. The duration of the shaper less or more than ZVD's can be obtained in the defined space. Some of the new shapers give better robustness than ZVD [22]. In the input shaper, the amplitudes and time locations of the impulses are determined by solving the set of constraints [31]. Other than that, M.A. Ahmad, R.M.T. Raja Ismail, M.S Ramli, and N. Hambali in their project, they investigate the nominal characteristic trajectory following (NCTF) with presenting of input shaping [17] . However, the NCTF control is limited for position control of cart and cannot cater the sway. In Nur Sabrina's thesis, she consider a negative input shaping as a controller to control the swing of the crane system [23].

Besides that, feedback control techniques is another approach in controlling the crane systems. According to J. Yu, F.L Lewis by University of Texas, they use nonlinear feedback control in their crane system to control crane performance and sway angle [24]. The outcome from this project are amazing cause it can reduce the sway and had better performance but using nonlinear control theory needs a complicated mathematical analysis.

2.4 MODELLING AND CONTROLLING

To control a rotary crane systems or any system which quite similar to it, researchers need to consider everything not only the sway problem. Khalid L. Sorensen, William Singhose and Stephen Dickerson; the authors used, the controller which been designed not only control the sway of the cranes, it also control the load positioning [25]. Santiago et.al, the implemented algorithms solve two main problems of module assembly: 1) precision positioning of large and heavy modules, and 2) anti-swinging transportation of modules [26].

So in this project the input shaping algorithm with helps of PD controller will be used to reduce the sway and time response of a rotary crane. The positive input shaping is implemented by convolving a sequence of impulses, an input shaper, with a desired system command to produce a shaped input. And a PD controller, control the angular position the arm of the rotary crane.

2.5 SUMMARY

So far, many controllers has been designed to fix the problem of control crane system, to come out with the best among others. However, there are still cannot applied practically. Perhaps it need to look out deeper characteristic that may affect the crane control whether load swing or other than that. All of factors need to be considers to come out with the best performance of crane control systems. So that, through this project, the rotary crane will be modelled to investigate several aspects on the characteristic and dynamic of the system.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter presents the control method to control rotary crane systems, which is hybrid input shaping and PD controller for anti-swaying and input tracking control. The methodology of this research is divided into a few major sections. First of all, modelling the rotary crane model by using the Euler-Lagrange formulation [27]. Then, PD controller were develop to control angle position of rotary arm. This is then extended to incorporate the input shaping technique for swing control of the rotary crane. Lastly, analysed the result by comparing the simulation results with presenting the input shaping and without input shaping injection.

3.2 THE ROTARY CRANE SYSTEM

In order to validate our proposed control method, a mathematical model of rotary crane systems is considered. Figure 3.1 shows the rotary crane system that is used in this study. Here θ represent the horizontal angle of the arm, α is the sway angle of the pendulum, r represent the length of arm and L is the length of the pendulum.

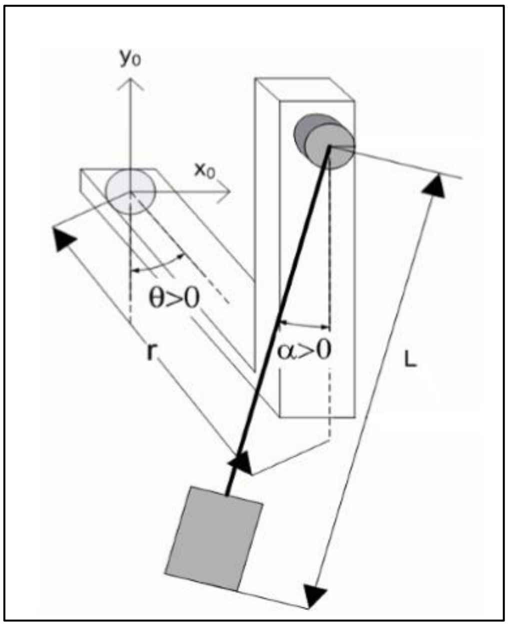

Figure 3.1: Description of the rotary crane system

3.2.1 Dynamic modelling of the rotary crane

Considering the motion of the rotary crane on a horizontal plane, the kinetic energy of the system can thus be formulated as [28]

$$T=\frac{1}{2}J_a\theta^2+\frac{1}{2}m(L\,cos\alpha(\alpha)+r\theta)^2+\frac{1}{2}m\big(L\,sin\alpha(\alpha)\big)^2+\frac{1}{2}J_p\alpha^2\ , \qquad (3.1)$$

where m is centre of mass of pendulum, J_a represent as a moment of inertia of the arm, J_p is moment of inertia of pendulum.

The potential energy of the beam can be formulated as

$$U=mgl(1-cos\,\alpha)\ , \qquad (3.2)$$

where g is gravity effect and l represent as the length of the pendulum.

Closed-form dynamic model of rotary crane is from the energy expressions in (3.1) and (3.2) are used to formulate the Lagrangian $L=T-U$. Let the generalized torques corresponding to the generalized state variables $\bar{q}$ = {θ, α} be $\bar{\tau}=\{\tau,\ 0\}$. Using Lagrangian's equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\theta}}\right)-\frac{\partial L}{\partial\theta}=\tau-B\dot{\theta}, \qquad (3.3)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\alpha}}\right)-\frac{\partial L}{\partial\alpha}=0,$$

and linearizing α=0, the equation of motion is obtained as below,

$$(J_a+mr^2)\ddot{\theta}+mLr\ddot{\alpha}=\tau-B\dot{\theta}\ , \qquad (3.4)$$

$$\frac{4}{3}mL^2\ddot{\alpha}+mLr\ddot{\theta}+mgL\alpha=0\ , \qquad (3.5)$$

3.3 HYBRID INPUT SHAPING AND PD CONTROLLER

In this project, PD controller incorporate with input shaping will develop to perform the better control system of the rotary crane.

3.3.1 Collocated PD control scheme

In the control of rotary crane systems the comman strategy involes the utilization of PD feedback of collocated sensor signals. PD controller sub-block diagram is shown in Figure 3.2 below, where K_P is porportional gain, K_V represent as derivative gain and A_C as a gain of the motor amplifier. As for the output of the block diagram are $\theta, \alpha, \dot{\theta}$ represent as hub angle, sway angle and hub velocity.

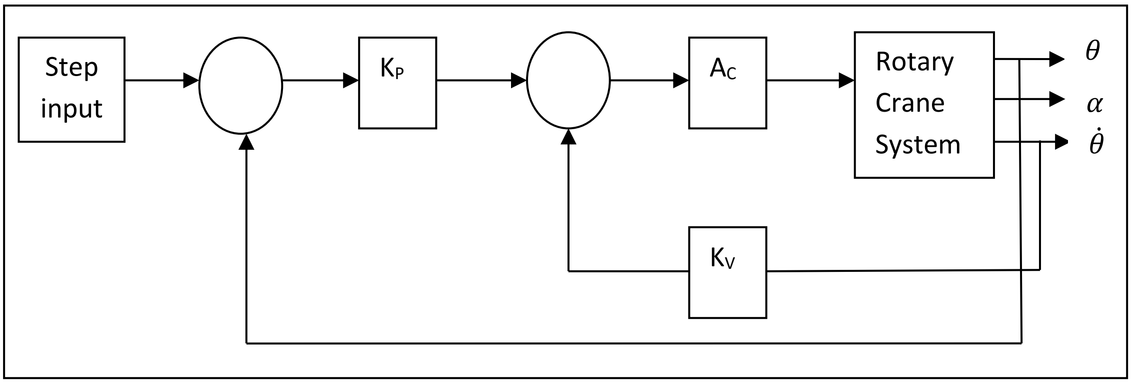

Figure 3.2: Hybrid PD control block diagram

Then, simulate the PD rotary crane and obtain sway frequency that will be used to design an input shaping later.

3.3.2 Input shaping control scheme

Input shaping technique is a feed-forward control technique that involves convolving a desired command with a sequence of impulse know as input shaper. Basically, input shaping design objective are to determine the time location and the amplitude of the impulses, so that the command shaped reduces the detrimental effects of the system flexibility. The parameters is obtain from the natural frequencies and damping ratios of the system. Therefore, by using input shaping technique the sway reduction of rotary crane system can be achieved. To ensure that the shaped command input produces the same rigid body motion as the unshaped command yields and for achieving the zero residual single-mode swaying of the system, the corresponding design relations of two impulse sequence or Zero-Sway (ZS) are [29]

$$t_1 = 0, \qquad t_2 = \frac{\pi}{\omega_d}, \qquad A_1 = \frac{1}{1+K}, \qquad A_2 = \frac{K}{1+K} \tag{3.6}$$

where

$$K = e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}} \quad , \quad \omega_d = \omega_n\sqrt{1-\zeta^2}$$

ω_n is the natural frequency and ζ represent as a damping ratio. t_1, t_2 represent as time location and A_1, A_2 are amplitude of the impulse.

Positive zero sway (PZS) shaper consists two impulse response as shown in figure below. The two impulse which are: [30]

i) Unity amplitude summation.
ii) Time optimality constraints.

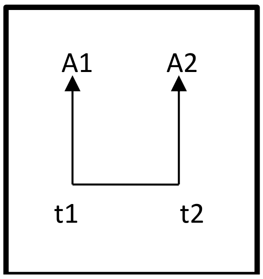

Figure 3.3: Positive zero sway

This yield is for three impulse sequence namely Zero-Sway-Derivative (ZSD) with parameter [30]

$$t_1 = 0,\ t_2 = \frac{\pi}{\omega_d},\ t_3 = \frac{2\pi}{\omega_d}$$

$$A_1 = \frac{1}{1+2K+K^2}, \quad A_2 = \frac{2K}{1+2K+K^2}, \quad A_3 = \frac{K^2}{1+2K+K^2} \tag{3.7}$$

Positive zero sway derivative (PZSD) shaper contain three impulse response as shown in figure 3.5 below. The three impulse recognize as:

i) Unity amplitude summation.
ii) Time optimal constraints.
iii) First order robustness constraint equation

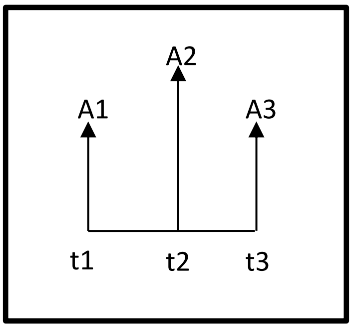

Figure 3.4: Positive zero sway derivative

This yields is for four impulse sequence namely as Zero-Sway-Derivative-Derivative (ZSDD) [29, 30]

$$t_1 = 0,\ t_2 = \frac{\pi}{\omega_d},\ t_3 = \frac{2\pi}{\omega_d}, \qquad t_4 = \frac{3\pi}{\omega_d}$$

$$A_1 = \frac{1}{1+3K+3K^2+K^3}, \qquad A_2 = \frac{3K}{1+3K+3K^2+K^3}$$

$$A_3 = \frac{3K^2}{1+3K+3K^2+K^3}, \qquad A_4 = \frac{K^3}{1+3K+3K^2+K^3} \tag{3.8}$$

Positive zero sway derivative derivative (PZSDD) shaper consists four impulse response as shown in figure below. The four impulse response are:

i) Unity amplitude summation.
ii) Time optimal constraints.
iii) Second order robustness constraint equation.

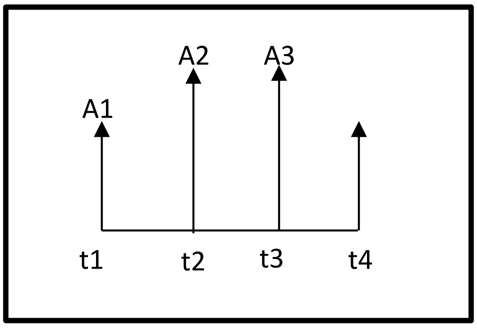

Figure 3.5: Positive zero sway derivative derivative

3.4 SIMULATION STUDIES

The simulation will undergo via MATLAB 2014 SIMULINK. The output signal will gave the preliminary result of the power spectral density, hub angle of the rotary arm and sway angle of the pendulum for all the derivatives. Then, all the result will be compare to different derivatives.

3.5 DATA COLLECTION AND ANALYSIS

The simulation result for the responses of rotary crane input will be analysed and compared between absent input shaping and present input shaping. Besides, the result also will compare with different controller which is PID to decide which is more effective to reduce sway angle of the pendulum and give a best shot when rotate.

Comparison of the specifications of the responses using a input shaping technique and PID are recorded. The specifications of the responses will considers the rise time, settling time, overshoot and the amplitude of the sway angle of the pendulum. Then, the specifications will come out which combination is the best for crane control systems for rotary crane.

3.6 SUMMARY

From the drafting at methodology here, the output will produces a better control crane system because when PD controller incorporate with hybrid command shaping can control many response which is can reduce the sway angle of the pendulum while maintaining the position of rotary arm. Through this system, industry fields can reduce the accident that occur when transferring, loading and lifting loads.

CHAPTER 4

RESULT AND ANALYSIS

4.1 INTRODUCTION

This chapter discussed the results and analysis of the proposed hybrid input shaping and PD controller for rotary crane system. The simulation studies are performed using MATLAB 2014.

4.2 SIMULATION RESULTS

Control scheme for sway suppression and input tracking capability of rotary crane is presented in this study. First, collocated PD control is designed. Then, it is extended to incorporate input shaping with different derivatives for control sway to the system. The collocated PD control tracking performance is applied based on [27] where K_P is deduced as 0.0323, K_V is 0.0067 and A_C deduced as 1.969. This closed-loop parameters with the PD control is used to control the position of rotary arm. The input shaper is designed based on the swing angle frequencies and damping ratios of the rotary crane system. Through the unshaped unit step reference input of rotary crane under a collocated PD controller the value of natural frequencies were obtained. Then, the unit step reference input of input shaper were designed and applied to the system in closed loop as shown in Figure 4.1. All the simulation is undergo in 5 seconds.

In order for the rotary crane to follow a trajectory at 90˚, the unit step command is required. All the analysis to the unshaped unit step reference input were done in time-domain and frequency-domain (spectral density). Then, all the characteristic of the response which is power spectral density (dB), hub angle of the rotary arm and the sway angle of the pendulum were compared.

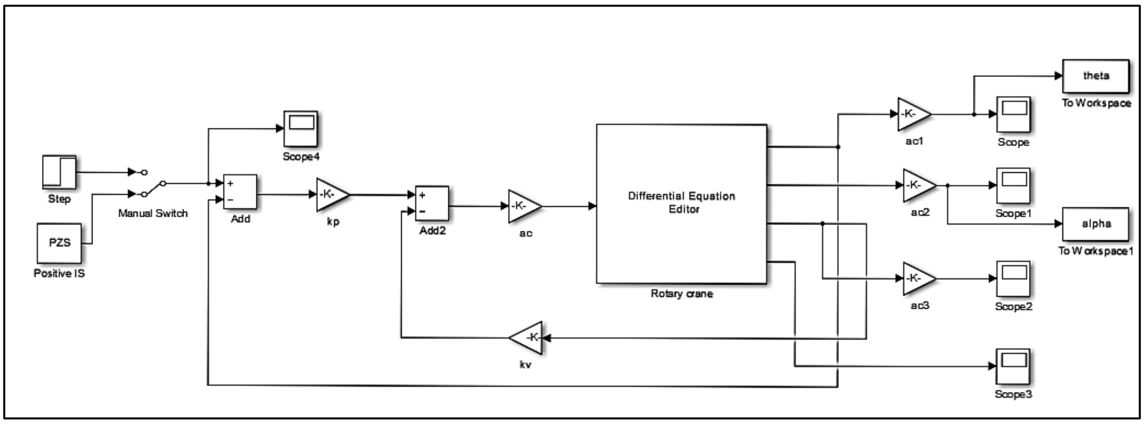

Figure 4.1: Simulink model of rotary crane with hybrid input shaping and PD control

4.2.1 Result of PD controller

Figures 4.2, 4.3, and 4.4 show the response of a rotary crane system with PD controller.

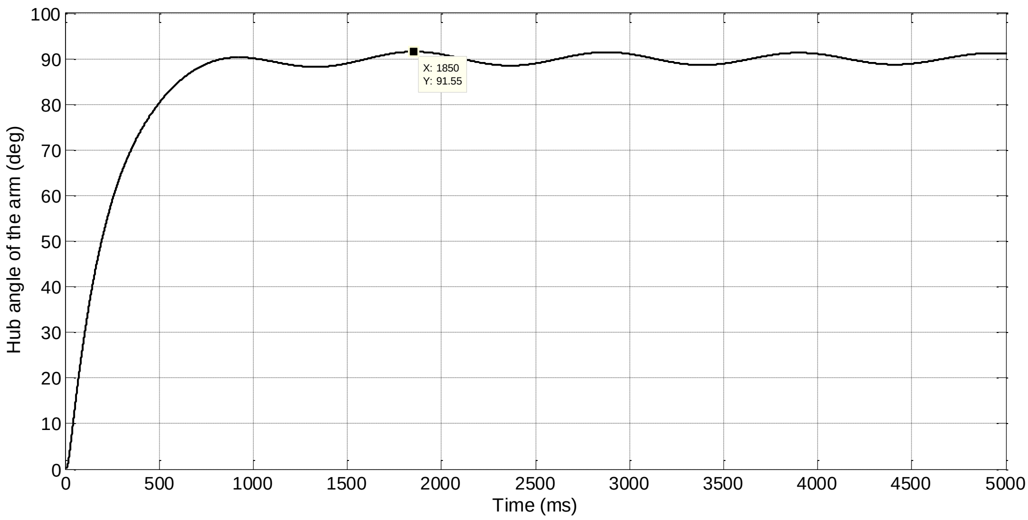

Figure 4.2: Hub angle of the arm for PD controller

As we can see in the figure above, it is very oscillate which is unstable systems. The rise time and settling time for this controller are 0.374 and 0.718. Although, it achieved a fast response crane system, it has overshoot which is 1.47. That's mean it is not good for crane system. Accident maybe can occur during transferring load process.

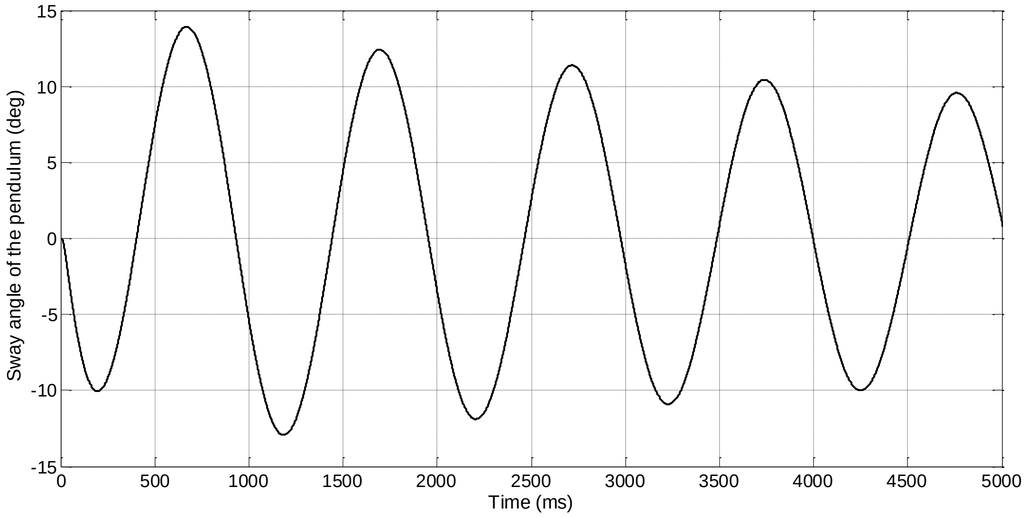

Figure 4.3: Sway angle of pendulum for PD controller

The minimum sway for PD controller is -12.92 while the maximum value is 13.9. There too much oscillate which is not good because accident maybe appear. As we can see, the sway angle take a long time to be stable.

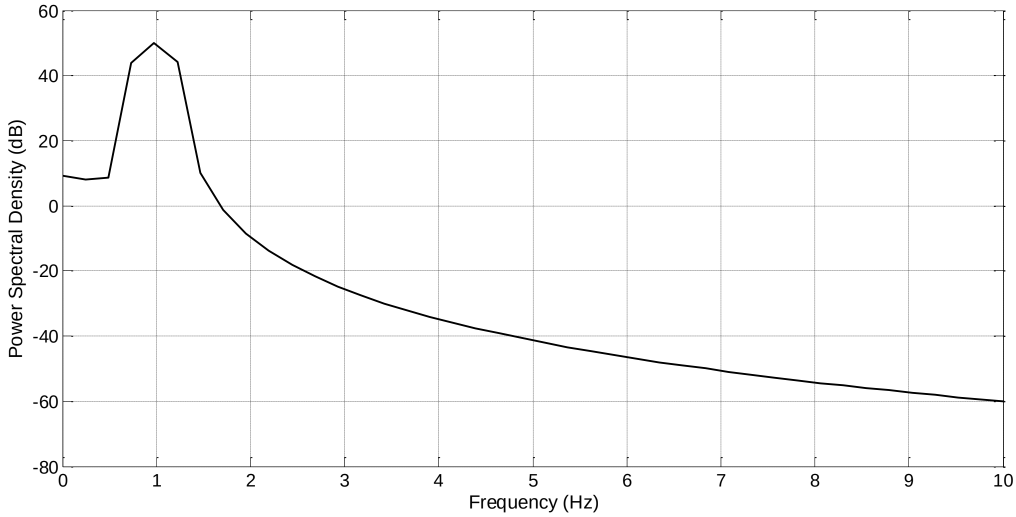

Figure 4.4: Power spectral density for PD controller

For power spectral density, the sway frequency of the rotary crane system was obtained as 0.9766 Hz.

4.2.2 Result of PD-PZS controller

Figures 4.5, 4.6, 4.7 and 4.8 shows the results of a rotary crane system after PZS being injected to the system. A significance of the technique can be seen through the reduction of each value of the parameter evaluated which is hub angle of the arm, sway angle of the pendulum and the power spectral density.

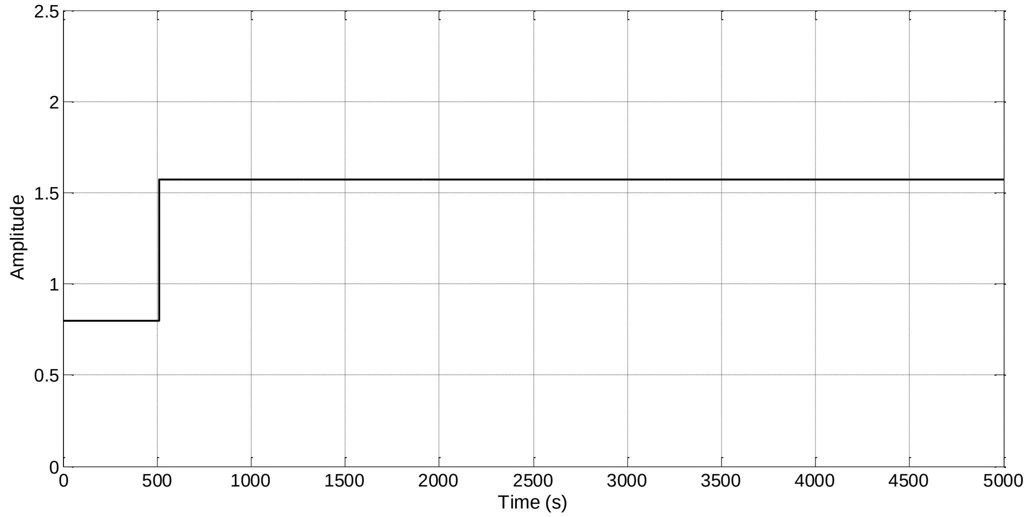

Figure 4.5: Shaped input for PD-PZS

Regarding this shaped input, all the parameters is inserted as

$t_1 = 0,$ $t_2 = \frac{\pi}{\omega_d},$ $A_1 = \frac{1}{1+K},$ $A_2 = \frac{K}{1+K}$

$$PZS = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & \frac{\pi}{\omega_d} \end{bmatrix}$$

The value of $K, \omega_d, t_2, A_1, A_2$ are 0.9691, 6.1383, 0.5120, 0.5079 and 0.4921.

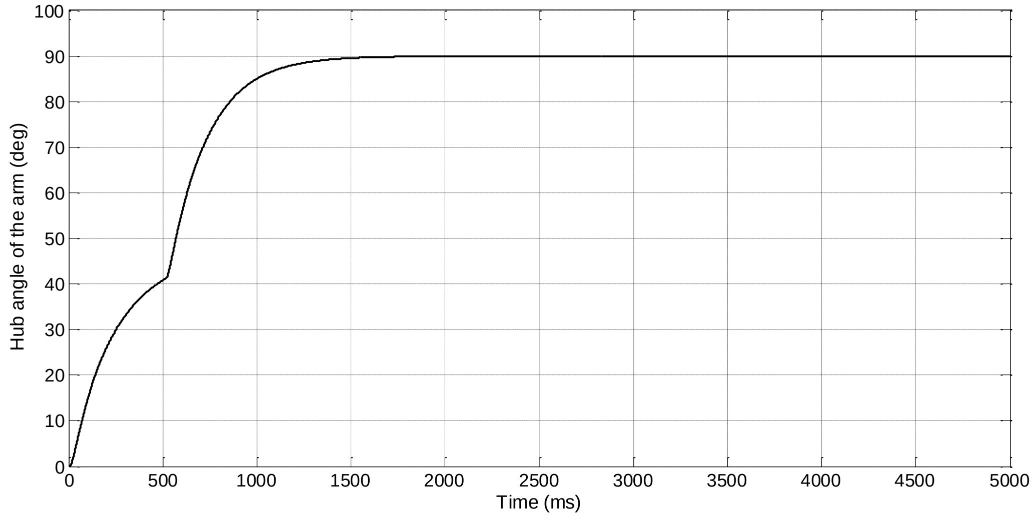

Figure 4.6: Hub angle of the arm for PD-PZS

Through the graph above, the rise and settling time are 0.736 and 1.216. And got 0.00 for overshoot. This shown that input shaping are affect the crane system to be more stable.

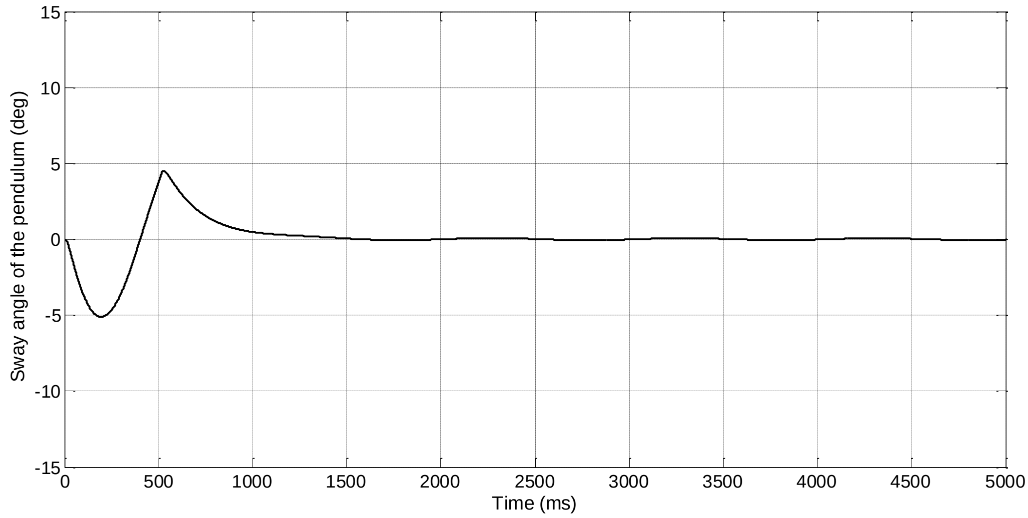

Figure 4.7: Sway angle of the pendulum for PD-PZS

Regarding the graph above, the maximum sway angle of the pendulum after injected with input shaper is 4.508 at 0.53 second and for the minimum sway is -5.091 at 0.189 second. The crane system almost reduce the sway angle of the pendulum.

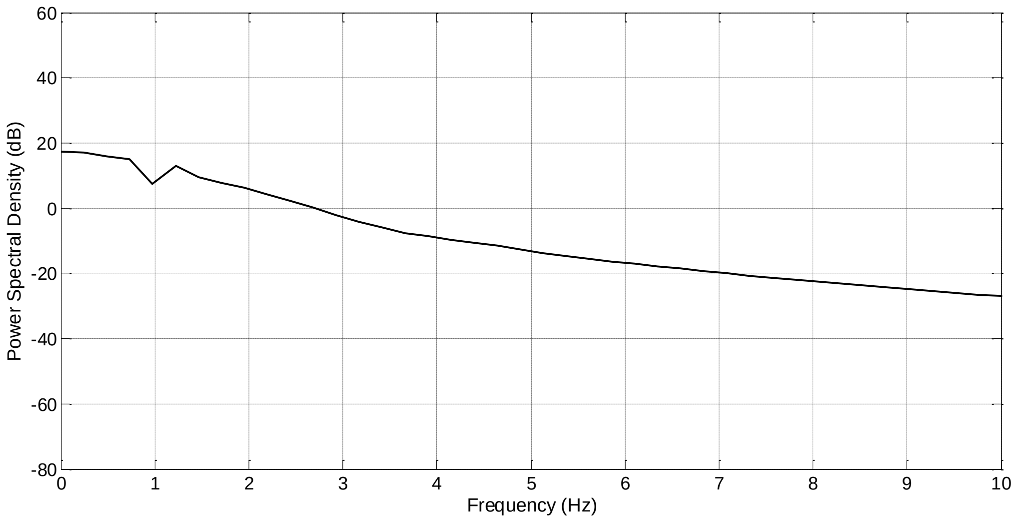

Figure 4.8: Power spectral density (dB) for PD-PZS

This power spectral density graph show that at 0.9766 the frequencies variation are weak. That is mean at this frequency swing motion are occurred.

4.2.3 Results of PD-PZSD controller

As shown in the Figures 4.9, 4.10, 4.11, and 4.12 the sway angle of the pendulum has more reduction after PZSD being injected to the system. The power spectral density and hub angle of the arm also showed a significance performance through its value reduction.

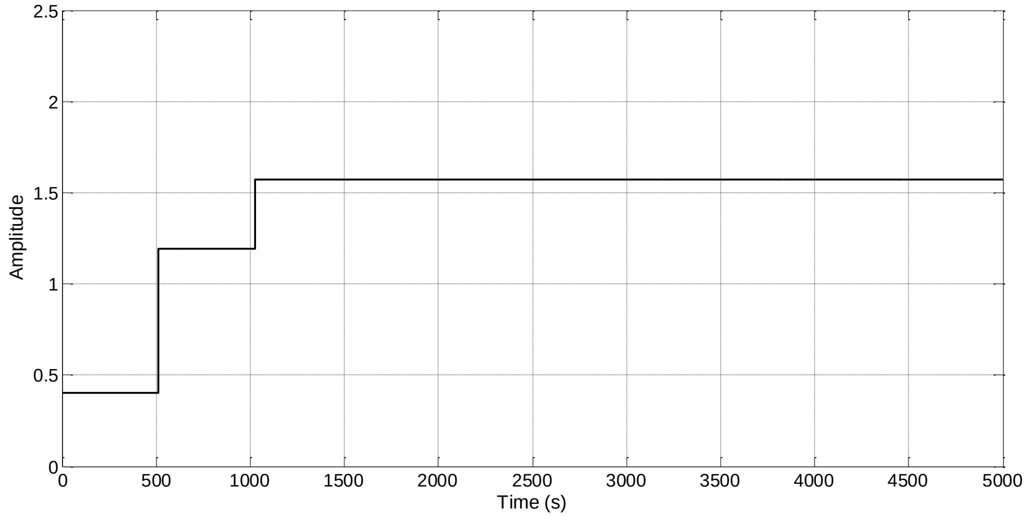

Figure 4.9: Shaped input for PD-PZSD

As relate at chapter 3 before, the shaped input are produce throughout this process;

$$t_1 = 0, \qquad t_2 = \frac{\pi}{\omega_d}, \qquad t_3 = \frac{2\pi}{\omega_d}$$

$$A_1 = \frac{1}{1+2K+K^2}, \qquad A_2 = \frac{2K}{1+2K+K^2}, \qquad A_3 = \frac{K^2}{1+2K+K^2}$$

$$PZSD = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+2K+K^2} & \frac{2K}{1+2K+K^2} & \frac{K^2}{1+2K+K^2} \\ 0 & \frac{\pi}{\omega_d} & \frac{2\pi}{\omega_d} \end{bmatrix}$$

The value of amplitude, A are 0.2579, 0.4999 and 0.2422. And the value of t_1, t_2, t_3 are 0, 0.5120 and 1.0240.

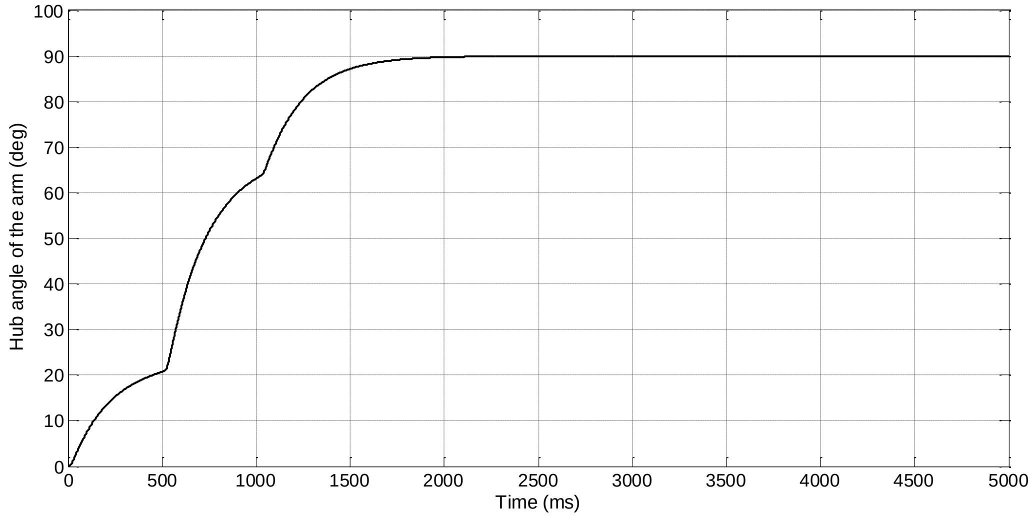

Figure 4.10: Hub angle of the arm for PD-PZSD

Based on the graph above, the rise and settling time for PD-PZSD controller are 1.117 and 1.594. And got 0.00 for overshoot.

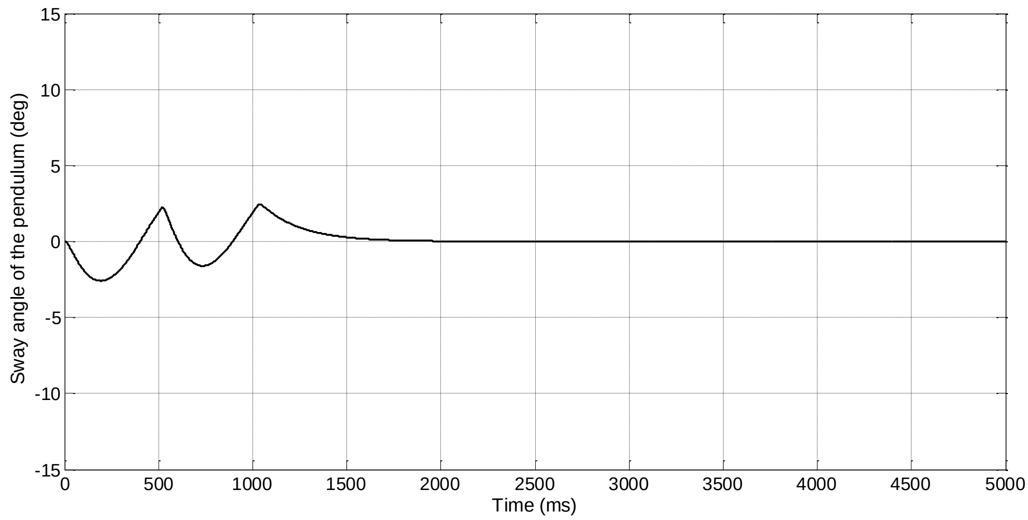

Figure 4.11: *Sway angle of the pendulum for PD-PZSD*

From the graph above, we can see the reduction of overshoot. The maximum and minimum value that we got from PD-PZSD controller are 2.36 and -2.578. The val-ue are close to zero sway.

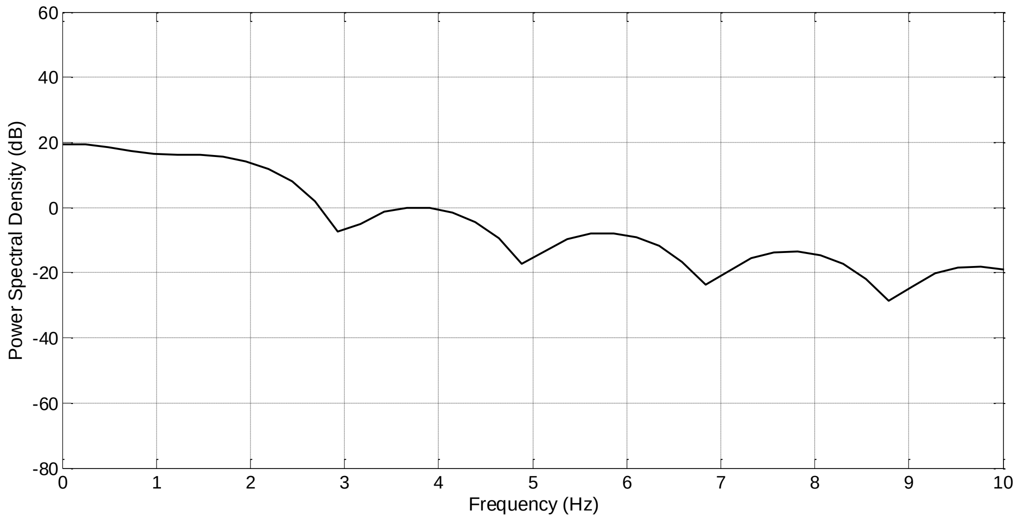

Figure 4.12: Power spectral density (dB) for PD-PZSD controller

The power spectral density for sway frequency at 0.9766 is 16.5 dB. This shown the reduction of the swing motion compare to PD controller.

4.2.4 Result of PD-PZSDD controller

Figure 4.13, 4.14, 4.15 and 4.16 showed the results of hub angle of the arm, the sway angle of the pendulum, and power spectral density with PD-PZSDD shaper.

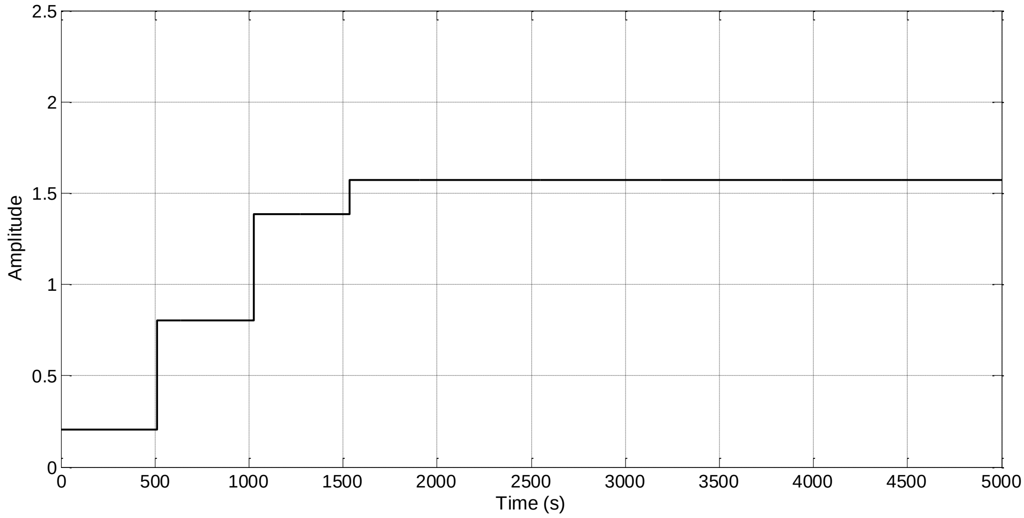

Figure 4.13: Shaped input for PD-PZSDD

From previous chapter, all the parameters has been inserted in the formula;

$$t_1 = 0, \qquad t_2 = \frac{\pi}{\omega_d}, \qquad t_3 = \frac{2\pi}{\omega_d}, \qquad t_4 = \frac{3\pi}{\omega_d}$$

$$A_1 = \frac{1}{1 + 3K + 3K^2 + K^3}, \qquad A_2 = \frac{3K}{1 + 3K + 3K^2 + K^3}$$

$$A_3 = \frac{3K^2}{1 + 3K + 3K^2 + K^3}, \qquad A_4 = \frac{K^3}{1 + 3K + 3K^2 + K^3}$$

$$PZSD = \begin{bmatrix} A_i \\ t_i \end{bmatrix}$$

$$= \begin{bmatrix} \frac{1}{1+3K+3K^2+K^3} & \frac{3K}{1+3K+3K^2+K^3} & \frac{3K^2}{1+3K+3K^2+K^3} & \frac{K^3}{1+3K+3K^2+K^3} \\ 0 & \frac{\pi}{\omega_d} & \frac{2\pi}{\omega_d} & \frac{3\pi}{\omega_d} \end{bmatrix}$$

The value of amplitude; A_1, A_2, A_3, A_4 are 0.1310, 0.3888, 0.3690 and 0.1192. And the value of time impulse are t_1, t_2, t_3, t_4 are 0, 0.5120, 1.0240 and 1.5360.

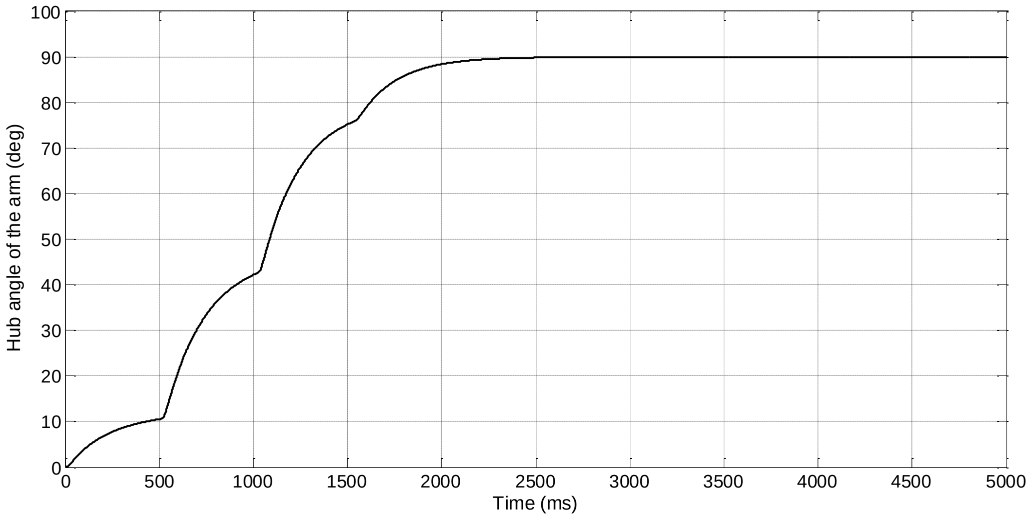

Figure 4.14: Hub angle of the arm for PD-PZSDD

The graph above shown the rise time of the PD-PZSDD control is 1.381 and the settling time is 1.976. Overshoot for this controller is 0.00.

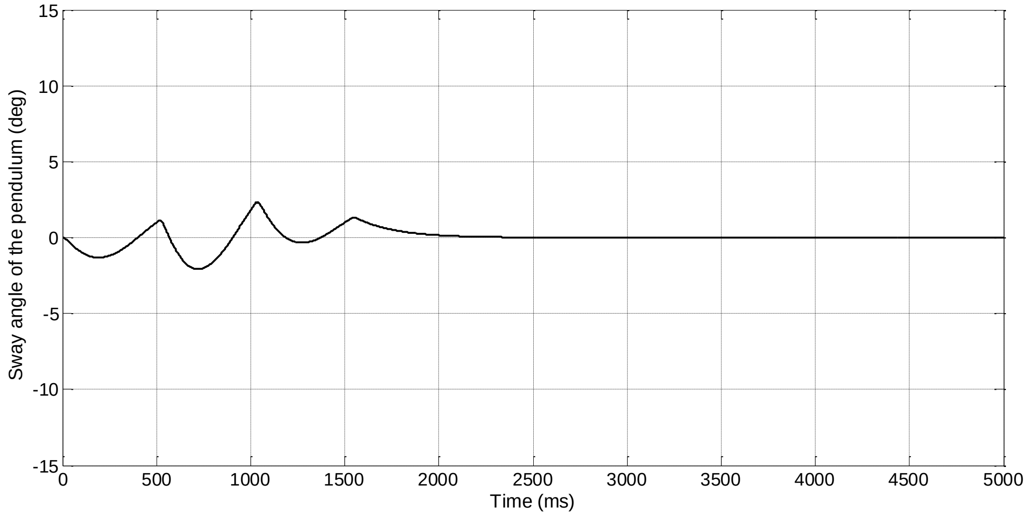

Figure 4.15: *Sway angle of the pendulum for PD-PZSDD*

From the graph, we can see the maximum and minimum value of the sway angle of the pendulum which is 2.312 and -2.066. This control system has better performance compare to PD controller before injecting of input shaper.

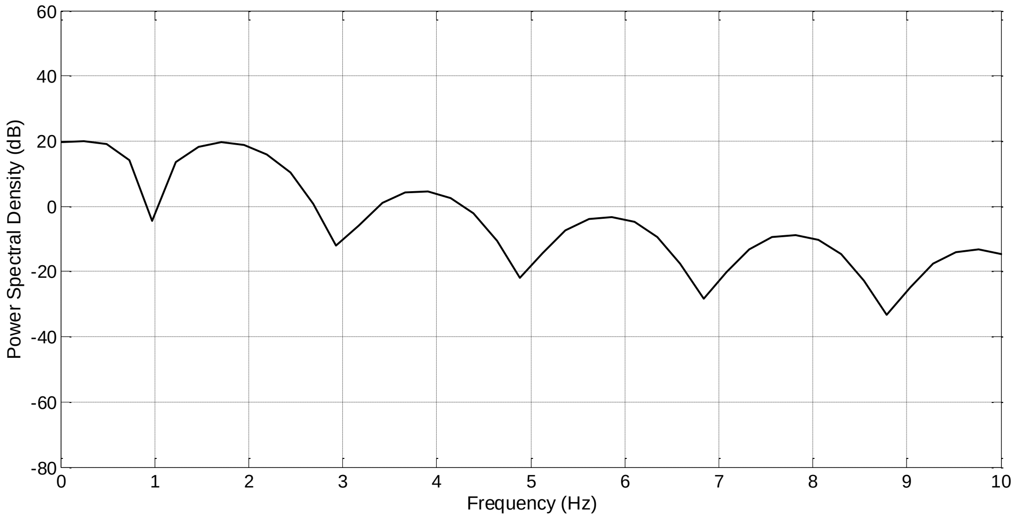

Figure 4.16: Power spectral density for PD-PZSDD

The graph above show the power spectral density at 0.9766 is -4.401.

4.3 OTHER COMPARISON

In this project, the result of the hybrid input shaping and PD controller also be compare with other controller which is PD-PID. This simulation of the Simulink diagram using MATLAB were done as Figure 4.17 below.

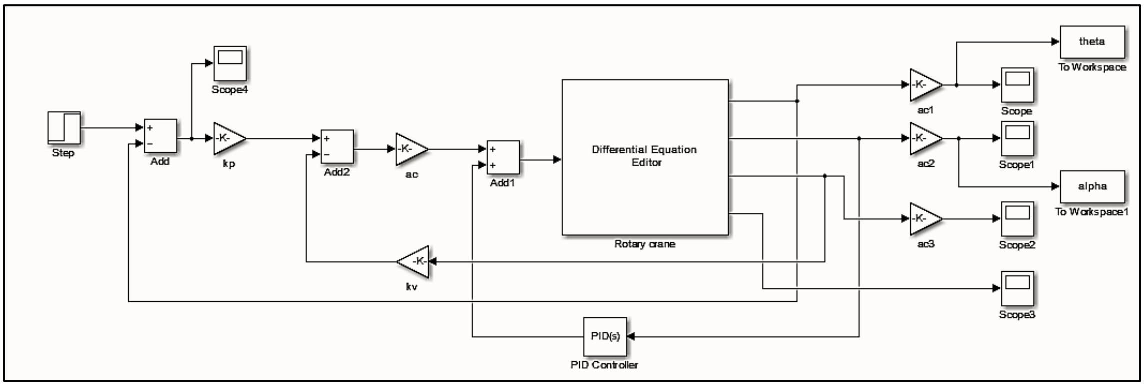

Figure 4.17: Simulink model of rotary crane with PD-PID controller

In designing the PID controller, the PID must be tuning to get the best performance for rotary crane system.

4.3.1 Result of PD-PID controller

Figure 4.18, 4.19 and 4.20 show the result of hub angle of the arm, sway angle of the pendulum and the power spectral density of PD-PID controller.

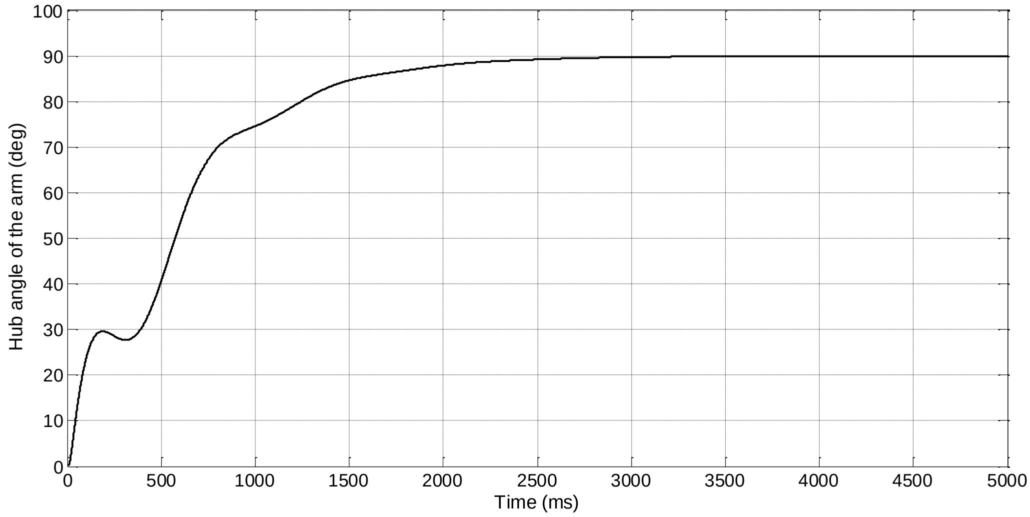

Figure 4.18: Hub angle of the arm for PD-PID

Regarding the graph above, the rise time for PD-PID controller is at 0.864 second while the settling time is at 2.072. The overshoot still 0.00 percent.

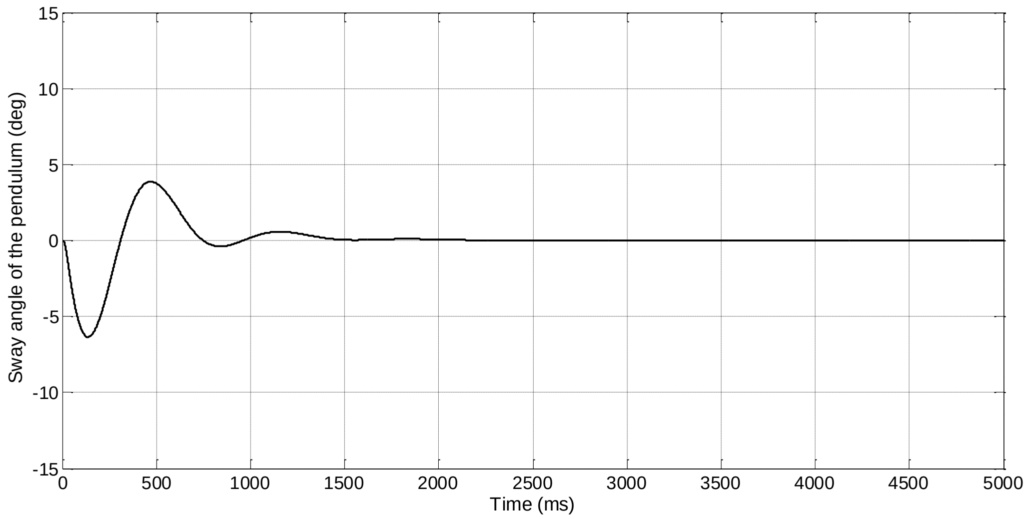

Figure 4.19: Sway angle of the pendulum for PD-PID

Graph above tell us that, the maximum and minimum value for PD-PID controller are 3.867 and -6.349. It is bigger values for maximum and minimum compare to PD-input shaper.

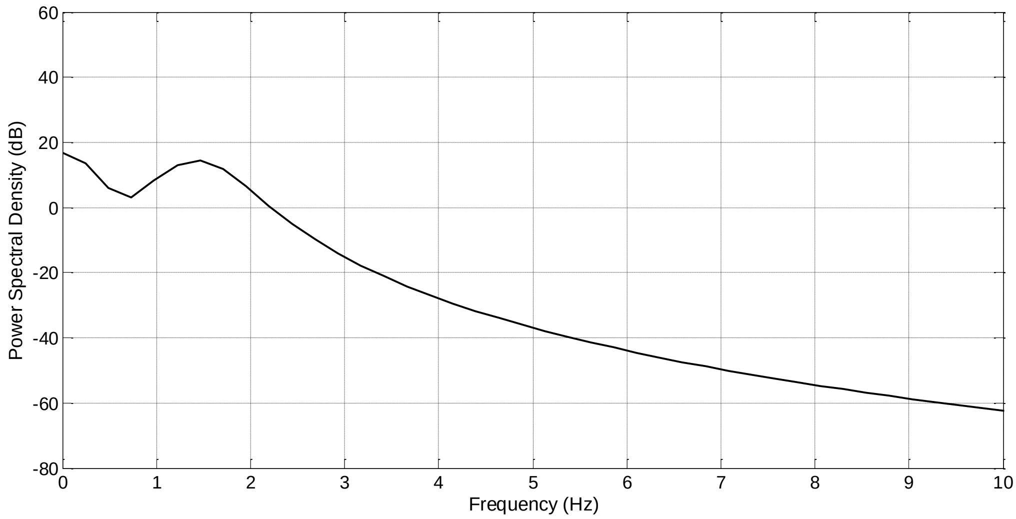

Figure 4.20: Power spectral density for PD-PID controller

4.4 COMPARATIVE ASSESSMENT

All the element will compare between the different of input shaping and PID controller

4.4.1 Comparison of hub angle of the rotary arm

Figure 4.21 below shows the system response of hub angle of the arm to the controllers. The specification response of hub angle which is rise time, setting time and overshoot of the system time response were summarized in Table 4.4.

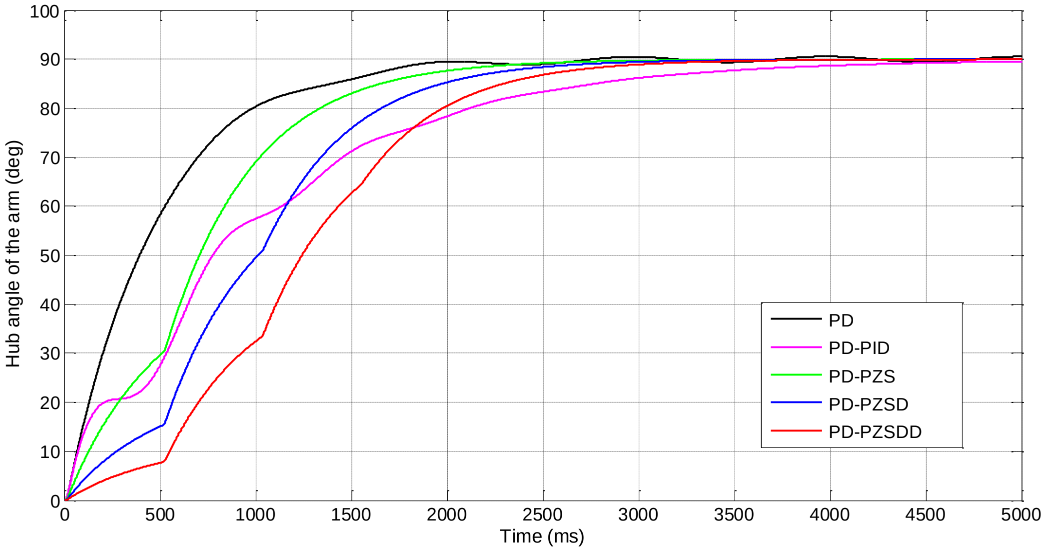

Figure 4.21: Comparison of hub angle

From the graph above it show 5 controller which is the black in colour is PD, the pink one is PD-PID, green and blue colour represent as PD-PZS and PD-PZSD. While the red one is PD-PZSDD.

The Table 4.1 below show the steady-state value of the angle arm can reach. We can see all the controller show a good response and the steady-state error for each controller are; for PD-PZS 0.33, PD-PZSD 0.62, PD-PZSDD 1.22 and PD-PID is 4.05.

Table 4.1: Hub angle of the arm with different controller

Input shaping	**Hub angle of the arm (deg)**
PD-PZS	89.67
PD-PZSD	89.38
PD-PZSDD	88.78
PD-PID	85.95

4.4.2 Comparison of sway angle of the pendulum

Figure 4.22 shows the sway angle response of the system after input shaping being injected to the system. It is noted that the sway angle were significantly reduced when the positive input shaping were inject.

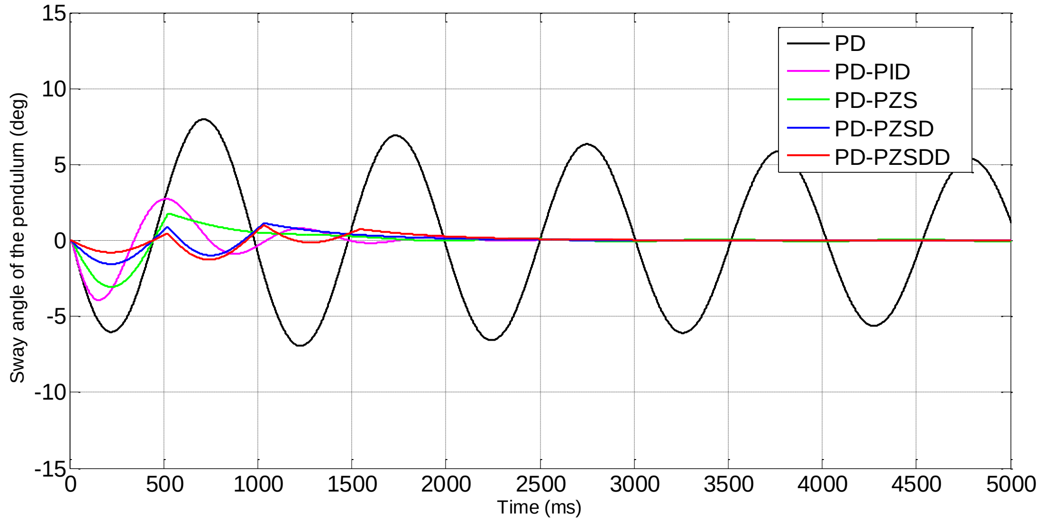

Figure 4.22: Comparison of sway angle of the pendulum

From the graph above, it's clearly state that PD controller oscillate too much. But it has been better when input shaping were inject, same goes to the result of PD-PID.

For the table 4.2 below, its show the maximum value of sway angle of the pendulum. The sway of crane system has been reduce compare to PD controller. The best sway reduce are PD-PZSDD followed by PD-PZSD, PD-PZS and lastly PD-PID.

Table 4.2: Sway angle of the pendulum with different derivatives

Input shaping	Sway angle of the pendulum (deg)
PD-PZS	1.745
PD-PZSD	1.106
PD-PZSDD	0.9661
PD-PID	2.735

4.4.3 Comparison of power spectral density

From the Figure 4.23 and Table 4.3, the values of power spectral density obtain after injecting positive input shaping keeps reducing with the addition of the derivatives. These values then will be compared with the value of the magnitude of PSD before positive input shaping been injected to the system to get the attenuation of level of sway.

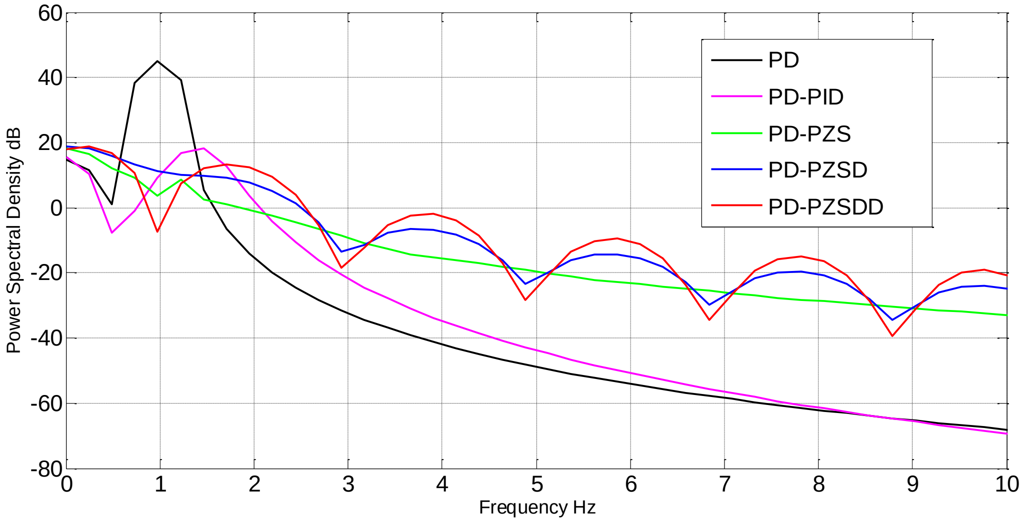

Figure 4.23: Comparison power spectral density

The Table 4.3 below show the value of power spectral density that has been taken at 0.9766 Hz.

Table 4.3: Power spectral density with different controllers

Input shaping	**Power spectral Density (dB)**
PD-PZS	3.54
PD-PZSD	11.24
PD-PZSDD	-7.398
PD-PID	9.33

After go through all the simulation by using MATLAB, all the results were taken and been record. Then the analysis of this project were done by investigating the effect of each input shaper derivative order and PID in terms of level of sway reduction and time response specification.

Table 4.4: Response specification of hub angle with different derivative

Input Shaping	**Attenuation (dB) of sway of the pendulum**	**Specification of hub angle response.**		
		Rise time (s)	**Settling time (s)**	**Overshoot %**
PD-PID	35.54	0.864	2.072	0.00
PD-PZS	41.33	0.736	1.216	0.00
PD-PZSD	33.63	1.117	1.594	0.00
PD-PZSDD	52.27	1.381	1.976	0.00

The higher performance in the attenuation of sway of the system is achieved with the proportional derivative-positive zero sway derivative derivative (PD-PZSDD). The level of sway attenuation of the swing angle using input shaping schemes and PID controller are shown with the bar graphs in Figure 4.24. The highest level of sway attenuation is achieved with PD-PZSDD, followed by PD-PZS, PD-PID AND PD-PZSD

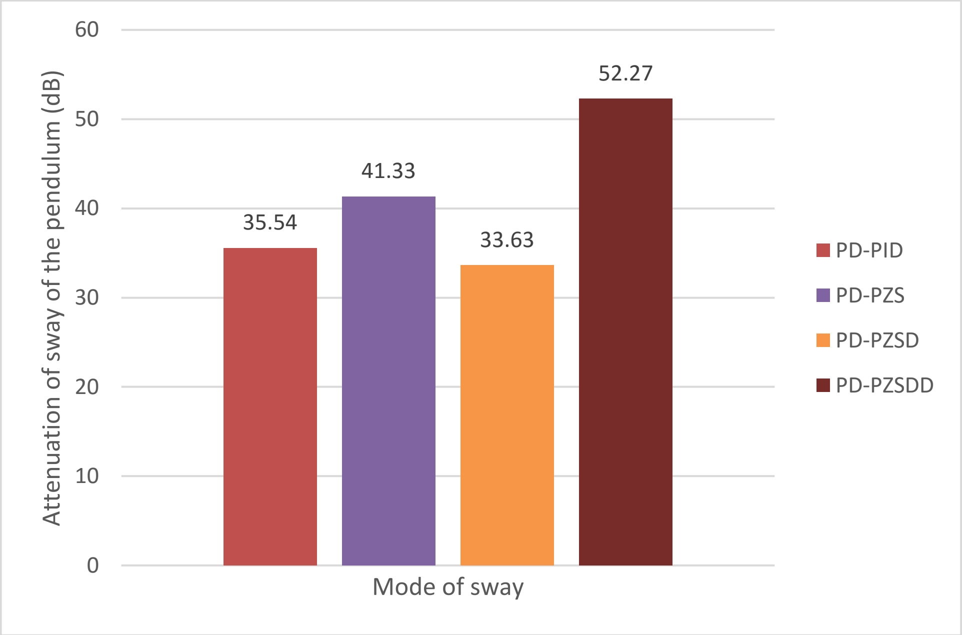

Figure 4.24: Attenuation of sway angle of the pendulum (dB)

The higher or bigger the settling time, the slow the response of the rotary crane system. Noted that the PD-PZS provide faster rise and settling times of the hub angle responses compared to others that is because it has a lowest settling time. The fastest response is achieved with PD-PZS, followed by PD-PZSD, PD-PZSDD and PD-PID. The results reveals that the system responses (speed) can be improved by using input shaping. Figures 4.25 and 4.26 shows the bar graph of rise time and settling time.

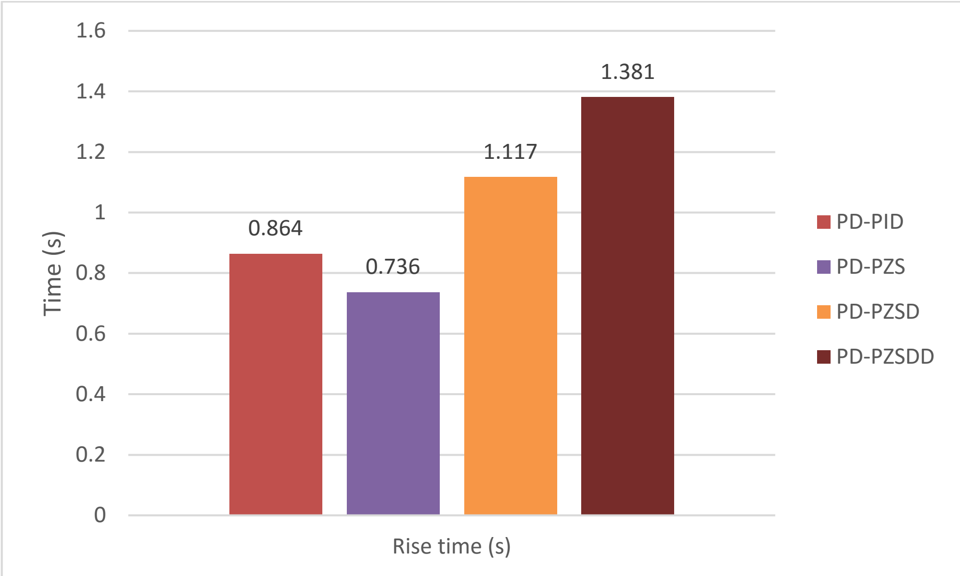

Figure 4.25: Rise time specification of hub angle response.

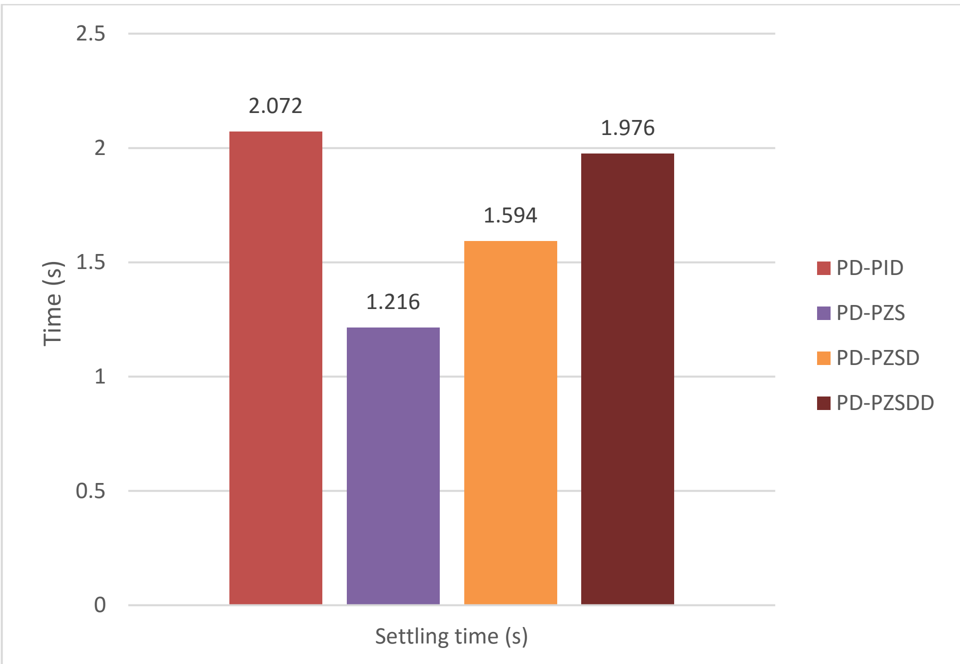

Figure 4.26: Settling time specification of hub angle response

4.5 SUMMARY

After everything were done, it shows that the hybrid input shaping and PD controller provides better sway reduction with acceptable speed of responses compare to PD-PID.

CHAPTER 5

CONCLUSION

5.1 CONCLUSION

The hybrid input shaping and PD controller has been successfully developed to control the sway of a rotary crane system for sway suppression and input tracking of rotary crane. The objectives that has been set in this project were successfully done such that a controller to control the sway of rotary crane system has been developed by using positive input shaping technique. Besides, the effectiveness of the proposed controller, in terms of input tracking capability, sway reduction and time response specifications has been investigated and analysed. A comparison of the result has been demonstrated that collocated PD control with presenting of input shaping provide higher level of sway reduction. Besides, in term of speed response, input shaping result in a higher speed of tracking response as compared to PID control. So that, hybrid controller are capable in reducing sway of the system while maintaining the input tracking performance of the rotary crane.

5.2 LIMITATION OF THE PROJECT

In this project, the investigation to the positive input shaping and PD PID control of the rotary crane were done by using MATLAB 2014 software. The result and analysis might not be the same when experiment conduct.

5.3 FUTURE WORK RECOMMANDATION

For future work, this technique maybe can be considered to be applied in the real world application at the industry. Thru this way, it can improve this technique and enhancing the industrial application.

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APPENDIX A

Program Listing

Positive Zero Sway (PZS)

```
starting_time=0;
simulation_time=5;
sampling_time=0.001;
t=starting_time:sampling_time:simulation_time;

for i=(0/sampling_time)+1:(5/sampling_time)+1
    u(i,1)=pi/2;
end

% Positive ZS shaper (2-impulse)
% mode 1

pi=22/7;
z1=0.01;
k1=exp((-z1*pi)/((1-z1^2)^0.5));
wn1=0.9766*2*pi;
wd1=wn1*(sqrt(1-z1^2));

% Determine the amplitudes and time location of the input shaper

ip=2;
tt1a(1)=0;
tt1a(2)=pi/wd1;
A1a(1)=1/(1+k1);
A1a(2)=A1a(1)*k1;

tt1a=tt1a./0.001;
tt1a=round(tt1a);
tt1a=tt1a.*0.001;

for i=1
    v1a(i,1)=A1a(1);
end

ni=1;
while ni<=ip-1
    for i=((tt1a(ni)/sampling_time)+2):((tt1a(ni+1)/sampling_time)+1)
        v1a(i,1)=0;
    end
    for i=(tt1a(ni+1)/sampling_time)+1
        v1a(i,1)=A1a(ni+1);
    end
    ni=ni+1;
end
```

```
for i=((tt1a(ni)/sampling_time)+2):((5/sampling_time)+1)
    v1a(i,1)=0;
end

imp1a=v1a;
impa=imp1a(1:(5/sampling_time)+1);

shp1a=conv(impa,u);
PZS=shp1a(1:(5/sampling_time)+1);
```

Positive Zero Sway Derivative (PZSD)

```
starting_time=0;
simulation_time=5;
sampling_time=0.001;
t=starting_time:sampling_time:simulation_time;

for i=(0/sampling_time)+1:(5/sampling_time)+1
   u(i,1)=pi/2;
end
% Positive ZSD shaper (3-impulse)
% mode 1

pi=22/7;
z1=0.01;
k1=exp((-z1*pi)/((1-z1^2)^0.5));
wn1=0.9766*2*pi;
wd1=wn1*(sqrt(1-z1^2));

%Determine the amplitudes and time location of the input shaper

ip=3;

   tt1b(1)=0;
   tt1b(2)=pi/wd1;
   tt1b(3)=2.*tt1b(2);
   A1b(1)=1/(1+2.*k1+k1.^2);
   A1b(2)=A1b(1)*2*k1;
   A1b(3)=A1b(1)*k1^2;

tt1b=tt1b./0.001;
tt1b=round(tt1b);
tt1b=tt1b.*0.001;

for i=1
   v1b(i,1)=A1b(1);
end

ni=1;
while ni<=ip-1
   for i=((tt1b(ni)/sampling_time)+2):((tt1b(ni+1)/sampling_time)+1)
      v1b(i,1)=0;
   end
   for i=(tt1b(ni+1)/sampling_time)+1
      v1b(i,1)=A1b(ni+1);
   end
```

```
    ni=ni+1;
end

for i=((tt1b(ni)/sampling_time)+2):((5/sampling_time)+1)
    v1b(i,1)=0;
end


imp1b=v1b;
impb=imp1b(1:(5/sampling_time)+1);

shp1b=conv(impb,u);
PZSD=shp1b(1:(5/sampling_time)+1);
```

Positive Zero Sway Derivative Derivative (PZSDD)

```
starting_time=0;
simulation_time=5;
sampling_time=0.001;
t=starting_time:sampling_time:simulation_time;

for i=(0/sampling_time)+1:(5/sampling_time)+1
   u(i,1)=pi/2;
end
% Positive ZSDD shaper (4-impulse)
% mode 1

pi=22/7;
z1=0.01;
k1=exp((-z1*pi)/((1-z1^2)^0.5));
wn1=0.9766*2*pi;
wd1=wn1*(sqrt(1-z1^2));

%Determine the amplitudes and time location of the input shaper

ip=4;

   tt1c(1)=0;
   tt1c(2)=pi/wd1;
   tt1c(3)=2.*tt1c(2);
   tt1c(4)=3*tt1c(2);
   A1c(1)=1/(1+3.*k1+3*k1.^2+k1^3);
   A1c(2)=A1c(1)*3*k1;
   A1c(3)=A1c(2)*k1;
   A1c(4)=A1c(1)*k1^3;

tt1c=tt1c./0.001;
tt1c=round(tt1c);
tt1c=tt1c.*0.001;

for i=1
   v1c(i,1)=A1c(1);
end

ni=1;
while ni<=ip-1
   for i=((tt1c(ni)/sampling_time)+2):((tt1c(ni+1)/sampling_time)+1)
      v1c(i,1)=0;
   end
   for i=(tt1c(ni+1)/sampling_time)+1
```

```
        v1c(i,1)=A1c(ni+1);
    end
    ni=ni+1;
end

for i=((tt1c(ni)/sampling_time)+2):((5/sampling_time)+1)
    v1c(i,1)=0;
end


imp1c=v1c;
impc=imp1c(1:(5/sampling_time)+1);

shp1c=conv(impc,u);
PZSDD=shp1c(1:(5/sampling_time)+1);
```