

UNIVERSITI MALAYSIA PAHANG

BORANG PENGESAHAN STATUS TESIS*

JUDUL: DEVELOPMENT OF HIGH PERFORMANCE LOW-PASS
FILTER FOR ANTI-SWAY CONTROL OF A GANTRY

SESI PENGAJIAN: 2006/2010

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DEVELOPMENT OF HIGH PERFORMANCE LOW-PASS FILTER FOR ANTI-SWAY CONTROL OF A GANTRY CRANE SYSTEM

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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
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NOVEMBER, 2009

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Signature

A handwritten signature in black ink, appearing to be 'Fatin Roziana Bte Misran', written over a horizontal line.

Author

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: 23 NOVEMBER 2009

*Specially dedicated to my family
To My Beloved Mother and Dad, My sister, My Aunty & My Beloved Grandmother
And those people who have guided and inspired me throughout my journey of
education*

Thank's For Everything...

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my supervisor, Mr. Mohd Ashraf B. Ahmad, for encouragement, guidance, critics, friendship, advice, information and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

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.

My sincere appreciation also extends to all my colleagues, and others who have provided assistance at various occasions especially to Nur Izana Bt. Hafizan. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family members for their moral support, advice and understanding me.

Thank you

Fatin Roziana Bte Misran

ABSTRACT

This project proposes the applications and performance of Low – pass filter for anti – sway control of a gantry crane system. The control objective is to control and reduce residual sway angle of the pendulum by using feed forward approach. An unshaped bang – bang torque input is used to determine the characteristic parameters of the system for the design and evaluation of the Low – pass filter techniques. Experiment results of the response of gantry crane to the input are presented in time and frequency domains. The effects of the order of the filtered Low – pass filter on the performance of the system are investigated. Finally, a comparative assessment of the amplitude polarities of the system performance is presented and discussed.

ABSTRAK

Projek ini mencadangkan aplikasi dan prestasi penapis laluan rendah yang bertindak menentang kawalan ayunan terhadap sistem gantri kren. Objektif kawalan adalah untuk mengawal dan mengurangkan baki sudut bandul itu dengan menggunakan pendekatan kehadapan. Satu input yang tidak berbentuk iaitu "*bang – bang torque*" digunakan untuk menentukan ciri-ciri parameter sistem tersebut untuk mereka bentuk dan menilai teknik - teknik penapis laluan rendah. Hasil keputusan daripada eksperimen bagi tindak balas gantri kren terhadap input akan ditunjukkan dalam domain masa dan domain frekuensi. Kesan terhadap beberapa perintah yang telah ditapis oleh penapis laluan rendah terhadap sistem tersebut akan disiasat. Akhir sekali, satu pantaksiran komparatif pada amplitud kekutuban terhadap prestasi sistem tersebut akan dibentang dan dibincangkan.

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LIST OF ABBREVIATIONS

CEMTool	Computer-aided Engineering & Mathematics Tool
SIMTool	Simulation Tool
PDE	Partial Different Equation
ODE	Ordinary Differential Equation
NCTF	Nominal Characteristic Ttrajectory Following
DFS	Delay Feedback Signal
IIR	Infinite Impulse Response
LQR	Linear Quadratic
LPF	Low-pass Filter

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CHAPTER 1

INTRODUCTION

1.1 Background

Gantry cranes are very important part of many material handling systems like lift, move, position, and place machinery, equipment and other large object. It also widely used in various applications for examples in shipyard, in factories and in high building constructions. This system tends to be highly flexible in nature, generally responding to command motion with oscillation of the payload and hook. These materials are usually heavy, large, and hazardous which cannot be handling by workers. There are various type of crane that widely used in heavy industries such as boom crane, rotary (tower) crane, gantry crane and others. Figure 1.1 show example of gantry crane which related in this project study.

One of the most important aspects to handling the crane is a worker who has an experience to operate the crane in safe operating manner and procedures. The swaying phenomenon introduce not only reduce the efficiency of the crane, but also case safety problems in the complicated working environment. There are many cases

and incidents regarding on the crane's accidents. For example, the incident occurred in United States of America, which is in Hanford Site and Bryan Mound Site in April 1993. The first incident occurred in 28th April 1993, where a crane becomes unbalanced while the boom was being lowered. The second incident occurred 2 days later, on 30th April 1993, which while loading the load, the weight of the load caused the crane to tip forward [1].



Figure 1.1: Gantry Crane

Thus, most of the researchers have been actively to make the crane moving smoothly without swaying when carried the load. However, there are many applications that have been used to reduce the sway of a gantry crane such as mechanical or hydro – mechanical anti-sway systems which increase natural damping and it generally succeed but both have a high initial and maintenance cost [2]. Besides that, a vision sensor is commonly used to the weather (heavy rain, direct sunlight, and so on) which is accompanied with image processing system to detect the sway angle for reducing or eliminating the sway induced by random trolley motion. There are some strategies that will be used to control the sway for examples, fuzzy control [3], neural network [4], non-linear control [5], and so on.

In this project, a different approach will be proposed to reduce the sway of a gantry crane system by using Low-pass filter. For this purpose, gantry crane has been chosen in order to achieve the aim. Feed-forward approach will be applied in order to control and reduce the sway angle of the pendulum. Therefore, an unshaped bang-bang torque input is used to determine the characteristic parameters of the system for the design and evaluation of the Low-pass filter technique. The different orders will be implemented in the performance of Low-pass filter of the system, and experiment result of the response of a gantry crane input will be presented and discussed.

1.2 Objectives

The objectives of this project are:

- (i) To develop a Low-pass filter techniques for anti-sway control of a gantry crane system
- (ii) To study the performance of Low-pass filter with different orders.

1.3 Scope of Project

The scopes that need to be proposed for this project are:

- (i) To study dynamic modeling flexible of gantry crane.
- (ii) To design a Low-pass filter by using 3rd order, 6th order, and 9th order to perform which orders are effectively reduces the

residual sway angle of the pendulum.

- (iii) To do a simulation studies using Matlab to present preliminary result of the simulink model of a crane system.
- (iv) To do an experiment studies using CEMTool software.
- (iv) To analysis the designed control model by using the Swing-up Inverted Pendulum System hardware.

1.4 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. Sway persists even if a skilled operator is operating the crane. Because of danger to the ground staff and ground equipment, these load sways can't be accepted for such material handling applications. Furthermore, another factor that must be considered is the effect of the load swing and disturbance on the load will risk hazard in material handling application of a gantry crane system. Thus, anti-swing control of material handling cranes is becoming a necessity day by day and many researchers for anti-sway system have been progressed for a long time after the first appearance of the crane.

Regarding on this matter, this project will focus on developing a Low-pass filter for anti-sway control of a gantry crane system by using feed-forward to control and reduce the residual sway angle of the pendulum. The performance of Low-pass filter by using different orders on a gantry crane model will be implementing to find which orders can reduce more sway angle of the pendulum. The design control model can be applied on Swing-up Inverted Pendulum System hardware to get the result base on the real experiment implementation.

1.5 Thesis Overview

This thesis is a combination of 6 chapters that contains and elaborates specific topics such as the Introduction, Literature Review, Methodology, Result and Discussion, and Conclusion.

Chapter 1 basically is an introduction of the project. In this chapter, the main idea about the background and objectives of the project will be discussed. The full design and basic concept of the project will be focused in this chapter. The overview of the entire project also will be discussed in this chapter to show proper development of the project.

Chapter 2 will be discussed about the literature reviews of this project based on journals and other references.

Chapter 3 will be focused on methodologies for the development of high performance low-pass filter for anti-sway control of a gantry crane system.

Chapter 4 will be focused on the experiment result and discussion of CEMTools software before and after the controller of Low-pass filter has been developed by using 3rd order, 6th order and 9th order. This chapter also discusses a performance of each order and which orders are more efficient to reduce sway angle of pendulum base on the experiment results.

Chapter 5 discusses the conclusion and future recommendation for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 An Overview

In general, gantry crane is the part of the system which has a high demand in industrial fields because it was very useful and efficient equipment to do all the heavy works such as transporting heavy load and hazardous materials in building constructions. Most of the problems that always occur are the trolley on the crane swaying caused by disturbance on the load or improper operator's control. Considering the effect of the problems, the ideas to reduce the sway by the researchers were progressed actively and then they came out with various approaches. Thus, a nonlinear coupling control laws for a three degree of freedom overhead crane system has been chosen using simple PID controller technique [6]. There are two aims in designing the controller, which are designing separately the two types of controller for this purposes. The first approach is designing anti-swing controller, which control the swing damping by a proper methods and second approach is designing a tracking controller in order to make the cart follows the specified trajectory [7].

CHAPTER 2

LITERATURE REVIEW

2.1 An Overview

In general, gantry crane is the part of the system which has a high demand in industrial fields because it was very useful and efficient equipment to do all the heavy works such as transporting heavy load and hazardous materials in building constructions. Most of the problems that always occur are the trolley on the crane swaying caused by disturbance on the load or improper operator's control. Considering the effect of the problems, the ideas to reduce the sway by the researchers were progressed actively and then they came out with various approaches. Thus, a nonlinear coupling control laws for a three degree of freedom overhead crane system has been chosen using simple PID controller technique [6]. There are two aims in designing the controller, which are designing separately the two types of controller for this purposes. The first approach is designing anti-swing controller, which control the swing damping by a proper methods and second approach is designing a tracking controller in order to make the cart follows the specified trajectory [7].

Singhose and members [8] have proposed an input shaping control to limit residual vibration by generating command profile which the vibration can be cancelled. Besides that, the command shaping control mechanism also used to reduce the oscillation of the payload and it not include the feedback mechanism of close-loop controllers because the sensor of the signal will not occurred if using the vibration reduction which ably with a reference signal that will expected the error before it occurs [9]. Therefore, input shaping command can improves the transient and steady state response of mechanical system.

Matlab and Simulink have been used to investigate the sway of industrial crane in order to develop anti-sway control strategies [10]. The model of pendulum will be accurate with respect to the aspect of the relation of different shapes of load which limit the angle of the angle at the same acceleration, and the changes of cable length during simulation or other influences like disturbances of wind. By reviewing those aspects, it will offers the potential for extensive benchmark test with a different anti-sway controller and also regarded to be appropriate in order to investigate anti-sway methods which sufficient for a purpose of simulation.

Another method was discovered by Yong and members [11] to reduce the sway of a crane which is using a new vision-sensorless anti-sway control scheme where the sway angle of the load has been estimated with the speed of the trolley. The speed of the trolley can be calculated with the rotational speed of the trolley motor. But, the calculated speed of the trolley is not exactly equal to the real speed of the trolley motor because there is nonlinearity an uncertainty in the mechanical structure. According to Chang and members, the simulations have been carried with Simulink to verify performance of the method and it consist two parts, one is the estimation of the sway angle and the other is the anti-sway control with the estimation of sway angle. The flexibility of cable crane is one of the parts that has been considered to suppress the transverse vibration of the load via a domain control based a control law, Lyapunov's second method [12]. A vibration is reduced the system with the sway dynamics that has been modeled as a hybrid partial different

equation (PDE) and ordinary differential equation (ODE) system of a laterally moving cable. The actuator is given in an ODE, while the flexible cable that moved in horizontal direction of the crane is given in a PDE. Therefore, the velocity of the point of attachment of the cable was measured to control the device and enables the implementation of the control law.

Besides that, there are some researchers have a different ways to identify the potential of the methods that will be used for example anti-sway control and position control of a crane system were separately controlled and applied independently [13]. The system is adjusted to make the position of the trolley are in desired position and at the same time the velocity response of the load with respect to changes in the velocity of the trolley is not oscillatory to prevent swaying. A practical and intelligent control method for automatic gantry crane has been developed by using nominal characteristic trajectory following (NCTF) controller and fuzzy logic controller. NCTF can control the position of the trolley while the fuzzy logic controller is used to suppress the swing vibration when the payload reaches the desired position [14].

Yang, H.C [15] stated that feed-forward techniques for sway attenuation involve developing the control input through consideration of the physical and swaying properties of the system, so that system swaying at dominant response modes is reduced. This method does not require additional sensors or actuators and does not account for changes in the system once the input is developed. Filtering technique approach is also used with proposing forward path command shaper which functions as notch filter on command manoeuvre. The pendulation of hoisting line of the boom crane during and after movement will be reduced by developing shape input on the basis of extracting the input energy around the natural frequency of the system.

The implementation of Delay Feedback Signal (DFS) and PD-type Fuzzy Logic Controller has been developed in sway reduction of a gantry crane system which both of the controller provides better performances in level of swaying angle reduction [16]. The controllers also can handle the disturbances effect for anti-sway of the gantry crane system. The filtering technique for anti-swaying control by using infinite impulse response (IIR) filter [17] was implemented with the Low-pass filter and Band-stop filter with different orders on the rotary crane system in hybrid control schemes. A Linear Quadratic (LQR) control is used to investigate the effectiveness in developing horizontal angle position control of rotary crane. The investigation was show that LQR controls with Band-stop filter provide higher level of sway reduction as compared to the Low-pass filter. The attenuation of sway in filtering techniques was increased with the increment of number of filter's order.

CHAPTER 3

METHODOLOGY

3.1 Work Methodology

Methodology is a chronology of work progress that is usually construct in flow chart. It also can be a fast review of works which takes a period of time to finish it. For this project, there are several steps to complete 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.

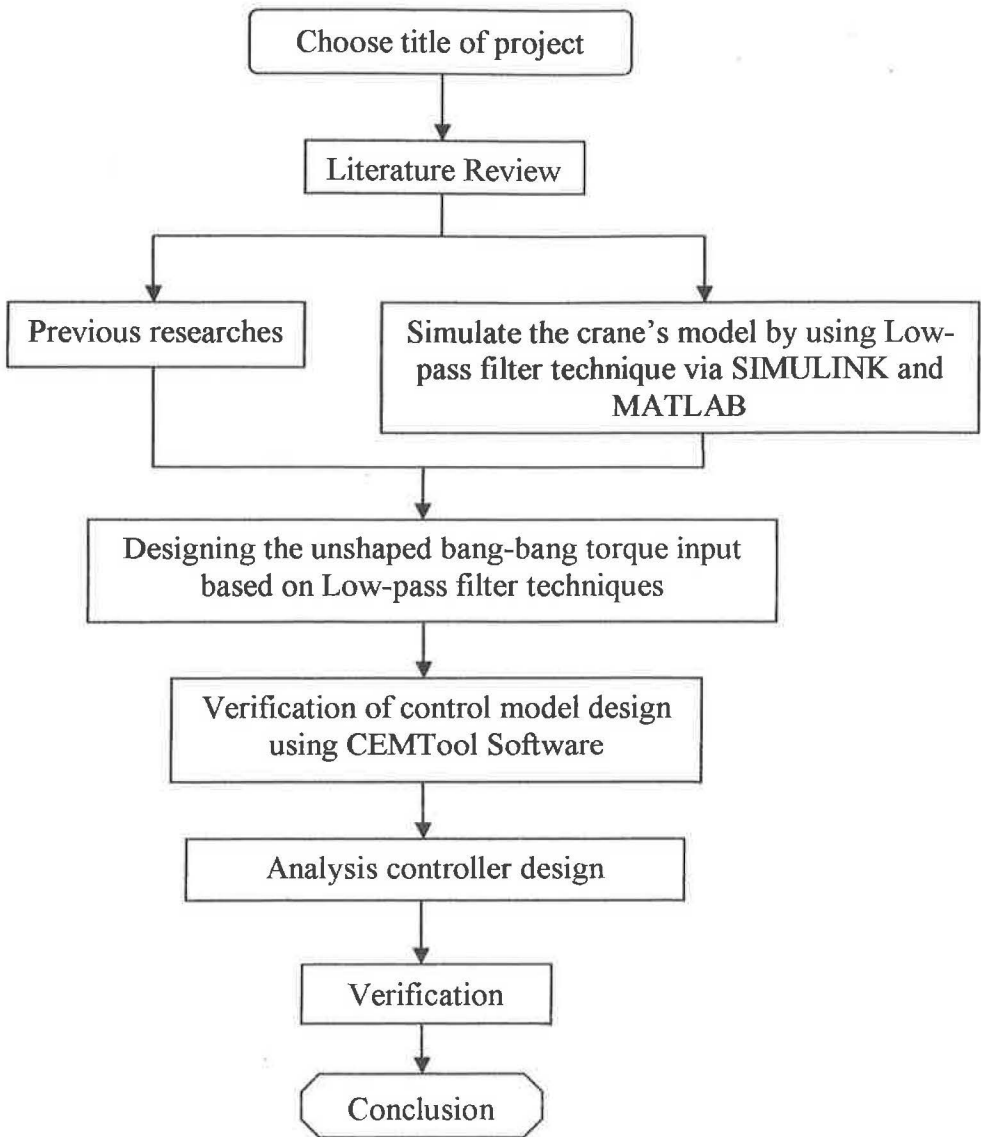


Figure 3.1: Work Methodology

3.2 Simulation of A Gantry Crane Model in MATLAB

Figure 3.2 shows a block diagram of sway control of a gantry crane system. The systems are built in the MATLAB/Simulink environment. The system is simulated to show an output before and after filtered by using 3rd order, 6th order and 9th order. The responses of the proposed input filter are respectively presented in Figure 3.3, Figure 3.4 and Figure 3.5 below. The simulated responses are presented in Power Spectral Density (PSD), amplitudes of sway angle of the pendulum and horizontal position of the cart.

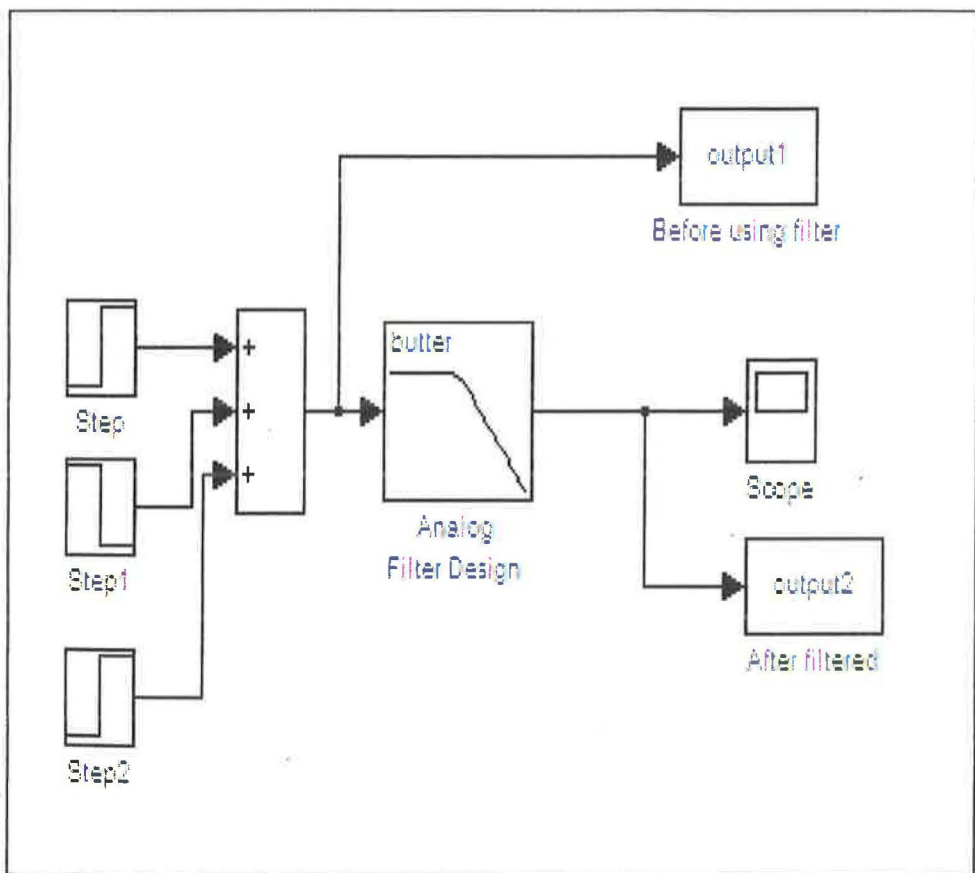


Figure 3.2: A Gantry Crane Model

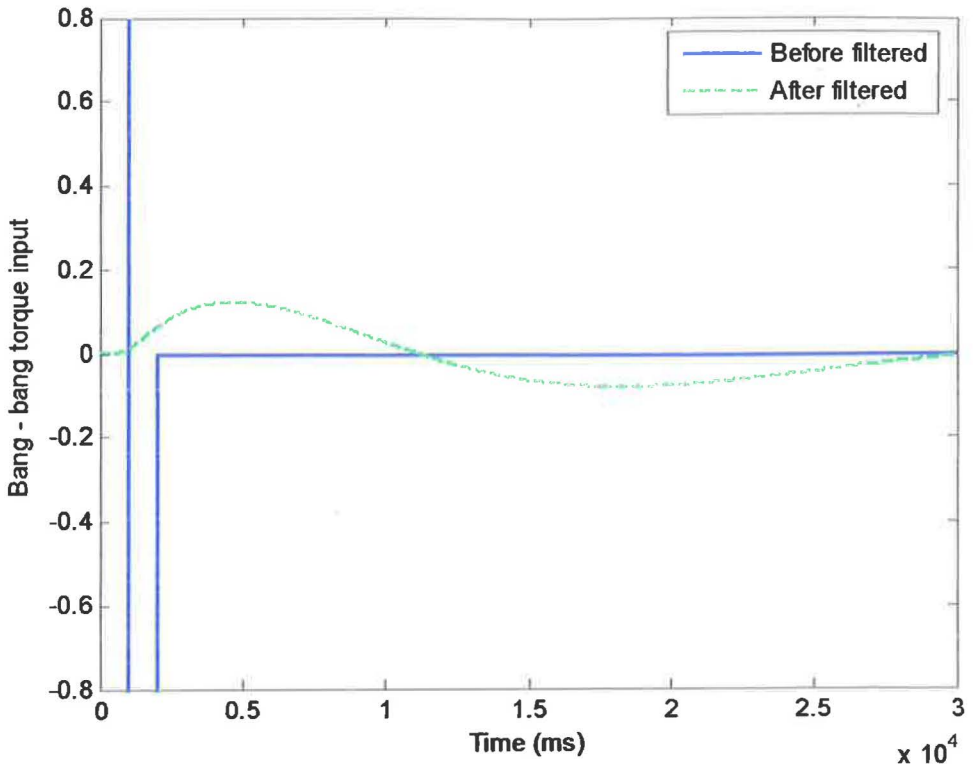


Figure 3.3: Bang-bang torque input using 3rd Order LPF

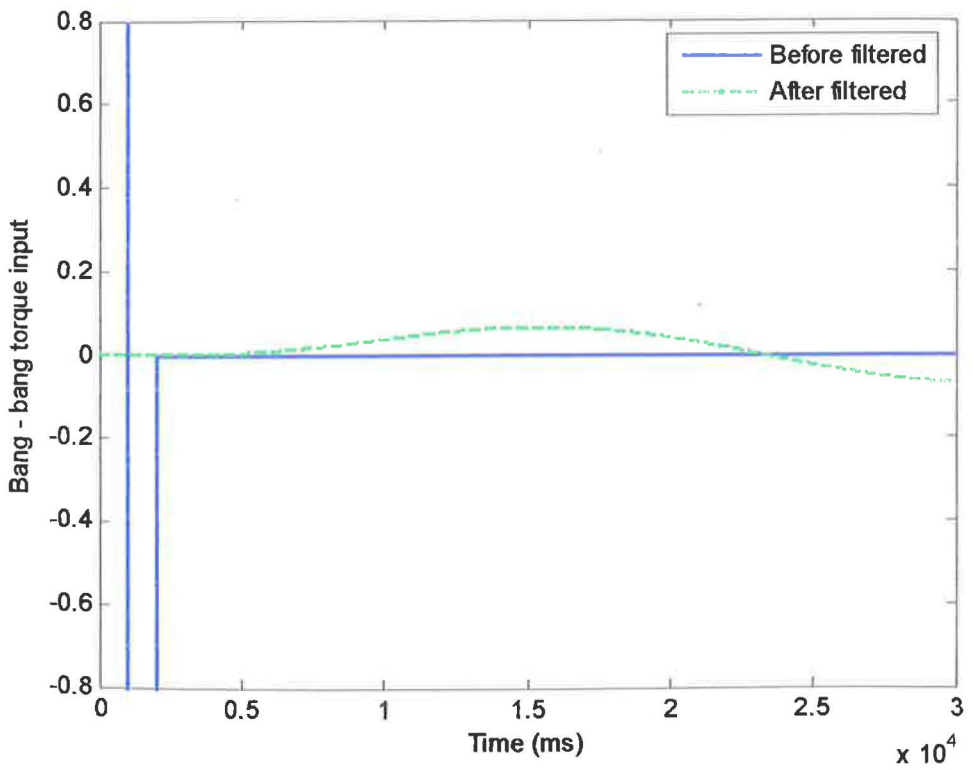


Figure 3.4: Bang-bang torque input using 6th Order LPF

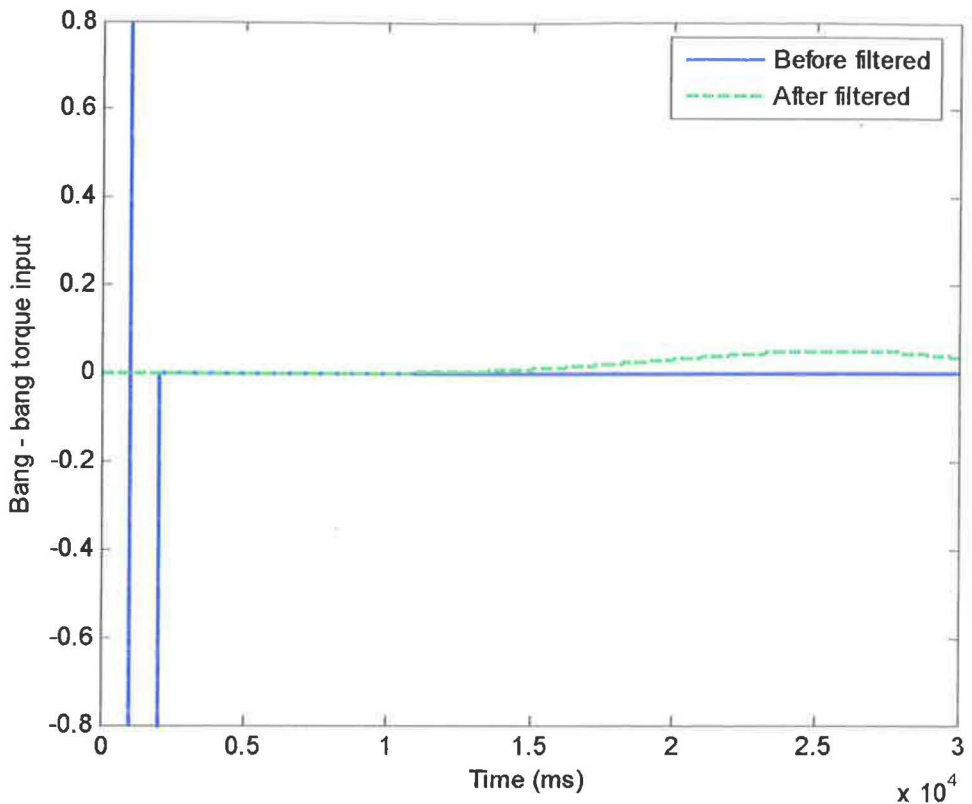


Figure 3.5: Bang-bang torque input using 9th Order LPF

3.3 The Unshaped Bang – Bang Torque Input Design in SIMTool

The unshaped bang-bang torque input is designed in SIMTool to determine characteristic parameters of the system for the SIMTool block design and evaluation of the Low-pass filter technique. After that, the experiment is continued to find the cutoff frequency without using a filter. A suitable unshaped bang-bang torque will be designed by using a small value of parameter to reduce the amplitudes sway angle of the pendulum. Thus, it will make less vibration of the sway angle and the settling down will become longer to obtain reduction of sway angle of the pendulum with the increment number of filter's order.

For parameter settings unshaped bang-bang torque input, the configuration is shown in Figure 3.6, Figure 3.7, and Figure 3.8. For Step 1, the parameter setting was set as 0.2 s, 1, and 1.5 for starting time, initial value, and final value respectively. The initial value was started with 1 because the Swing-Up Inverted Pendulum System has a problem in initializing the pendulum. Thus, the initial value will be offset of the bang-bang torque input in Step 1. For Step 2, starting time is 0.5 s while initial value is 0 and the final value is -1.5. It is followed with Step 3 which is starting time is 0.8 s, initial value is 0 and the final value is 1. The initial value and final value for each step will be as manipulation variable to show the changes of amplitude of sway angle of the pendulum. From this observation, the pendulum will move slowly with decrement value of initial value and final value of the steps.

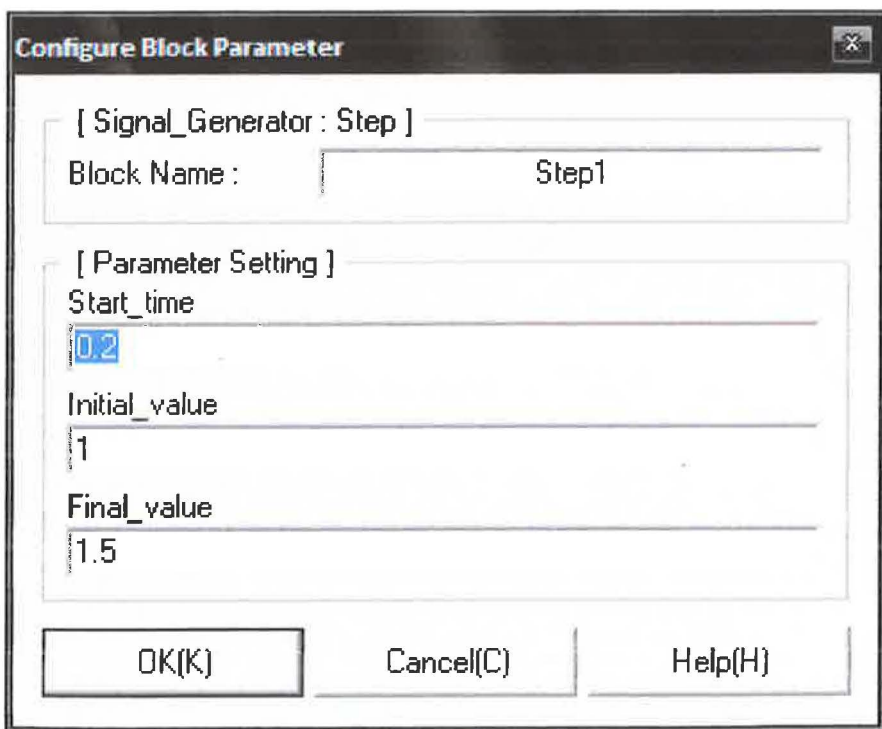


Figure 3.6: Setting of parameter for Step 1

Configure Block Parameter

[Signal_Generator : Step]

Block Name : Step2

[Parameter Setting]

Start_time
0.5

Initial_value
0.0

Final_value
-1.5

OK(K) Cancel(C) Help(H)

Figure 3.7: Setting of parameter for Step 2

Configure Block Parameter

[Signal_Generator : Step]

Block Name : Step3

[Parameter Setting]

Start_time
0.8

Initial_value
0.0

Final_value
1

OK(K) Cancel(C) Help(H)

Figure 3.8: Setting of parameter for Step 3

3.4 Determination of Cut-off Frequency

The Cut-off frequency was obtained by simulation a block design in SIMTool (Simulation Tool) with an unfiltered bang-bang torque input. The bang-bang torque command is required in order for the angle of gantry crane position. The first mode of sway of the system is considered. The responses of the gantry crane system to the unfiltered bang-bang torque input were analyzed in frequency domain (Spectral density). These results were considered as the system response to the unfiltered input and will be used to evaluate the performance of the Low-pass filter techniques.

Thus, the sway frequency of the gantry crane was obtained as 0.883 Hz for the first mode of sway. The graph of cutoff frequency is shown in Figure 4.18 below. A suitable cutoff frequency is half the sway frequency. Since the sway frequency must be higher than the bandwidth of the input signal, a cutoff frequency chosen in this way properly filters out unwanted frequency components. If the cutoff frequency is too high, those components may not be filtered out. If the cutoff frequency is too low, it might narrow the bandwidth of the input signal.

In this experiment, the value of cut-off frequency is used without having a half the sway frequency to obtain a result which is satisfied the theoretical point of view. The results has been analyzed using a cut-off frequency that half from the sway frequency and also for seventy percent from the sway frequency, but the result that using exact sway frequency is more suitable and fulfilled the theory requirements in order to reduce the sway angle of the pendulum.

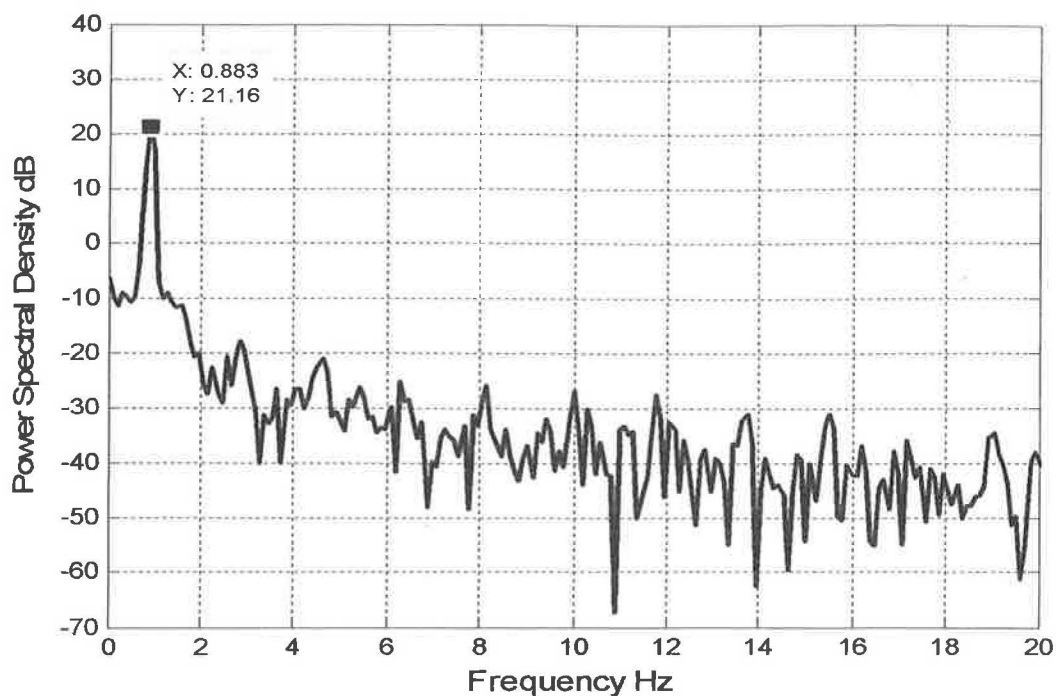


Figure 3.9: Cut-off frequency

3.5 Design Transfer Function Using MATLAB

There are three Transfer Function were designed which used as controllers for the experiment. The filter is designed by using Butterworth filter or also known as “maximally flat” in the passband and monotonic overall because the response has the maximum number of vanishing derivatives at $\omega = 0$ and $\omega = \infty$. Butter designs a Low-pass, Bandpass, Highpass, and Bandstop digital and analog Butterworth filters. Butterworth filters sacrifice roll off steepness for monotonicity in the pass- and stopbands.

A $[b,a] = \text{butter}(n,Wn,'ftype')$ designs a Highpass, Low-pass, or Bandstop filter, where the string 'ftype' is one of the following. 'high' for a highpass digital filter with normalized cutoff frequency Wn 'low' for a Low-pass digital filter with normalized cut-off frequency Wn 'stop' for an order $2*n$ bandstop digital filter if Wn is a two-element vector, $Wn = [w1 \ w2]$. The stopband is $w1 < \omega < w2$.

A $[b,a] = \text{butter}(n,Wn,'ftype','s')$ designs a highpass, low-pass, or bandstop filter. With different numbers of output arguments, `butter` directly obtains other realizations of the analog filter. The configuration using the filter in this experiment is as follows:

```
>> [b,a]=butter(3,0.88,'low') % For 3rd Order
b =
    0.6843    2.0530    2.0530    0.6843
a =
    1.0000    2.2501    1.7564    0.4683
>>
```

Figure 3.10: The numerator and denominator source code for 3rd order

```
>> [b,a]=butter(6,0.88,'low') % For 6th Order
b =
    0.4801    2.8804    7.2011    9.6014    7.2011    2.8804    0.4801
a =
    1.0000    4.5450    8.7464    9.0984    5.3862    1.7181    0.2305
>>
```

Figure 3.11: The numerator and denominator source code for 6th order

```

>> [b,a]=butter(9,0.88,'low') % For 9th Order

b =

    0.3349    3.0139   12.0557   28.1300   42.1950   42.1950   28.1300   12.0557    3.0139    0.3349

a =

    1.0000    6.8300   20.9417   37.7948   44.2111   34.7385   18.3241    6.2540    1.2527    0.1121

>>

```

Figure 3.12: The numerator and denominator source code for 9th order

3.6 Low-pass filter design in SIMTool

The experiment will use the CEMTool software with using a SIMTool to design and simulate results by modeling a system to implement the Low-pass filter techniques. In this section, state space parameters are converted into a Transfer Function by using MATLAB based on order that will be used. The numerator and denominator will be transferred in Transfer Function block in SIMTool as a controller

A filter in this form is easy to implement with the filter function. For example, a simple single-pole filter (lowpass) is

```

b = 1;          % Numerator
a = [1 -0.9];  % Denominator

```

The configuration of Transfer Function in SIMTool model is show in Figure 3.13, Figure 3.14, and Figure 3.15. The figure below shows the block of Transfer Function which the value of numerator and denominator is obtained from the design of Transfer Function by using MATLAB.

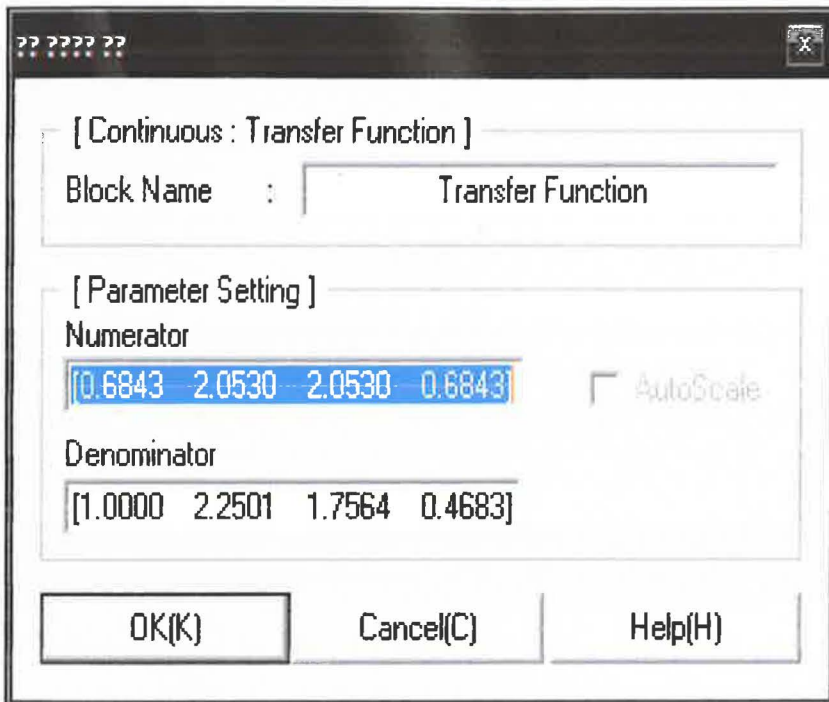


Figure 3.13: Transfer Function for 3rd Order

?? ????? ??

[Continuous : Transfer Function]

Block Name : Transfer Function2

[Parameter Setting]

Numerator

9.6014 7.2011 2.8804 0.4801 AutoScale

Denominator

1.0000 4.5450 8.7464 9.0984

OK(K) Cancel(C) Help(H)

Figure 3.14: Transfer Function for 6th Order

?? ????? ??

[Continuous : Transfer Function]

Block Name : Transfer Function3

[Parameter Setting]

Numerator

28.1300 12.0557 3.0139 0.3349 AutoScale

Denominator

1.0000 6.8300 20.9417 37.794E

OK(K) Cancel(C) Help(H)

Figure 3.15: Transfer Function for 9th Order

3.7 Block diagram structure in SIMTool

A complete design of block diagram based on the Low-pass filter technique for without filter, and with Low-pass filter of 3rd, 6th, and 9th order will be designed using SIMTool. The different orders of the filtered of Low-pass filter is used on the performance of the system, and the experiment result of the responses of gantry crane input will be analyzed to compare which order are more efficient in reduction of sway angle of the pendulum.

The specifications responses of cart position includes rise time, settling time, and overshoot for 3rd, 6th, and 9th order of Low-pass filter will be studied and investigated as a comparative assessment in this project.

Figure 3.16 show a block diagram design using SIMTool without filter. The block diagram is divided in three parts which a part one is for bang-bang torque input design. The controller will put between summation of steps and analogue output and scope. The computer will be connected with I/O board of Swing-Up Inverted Pendulum System to encode the bang-bang torque input without filter or with Low-pass filter to the Encoder 1 and Encoder 2 in part two and part three that consist of scope for angle and position. Then, the scope will show the results in CEMTool. After that, the results are transferred by using 'To File' block to the MATLAB. The responses for the attenuation of sway of the pendulum, the amplitude of sway angle of the pendulum, and the horizontal position of the cart were shown graphically in MATLAB.

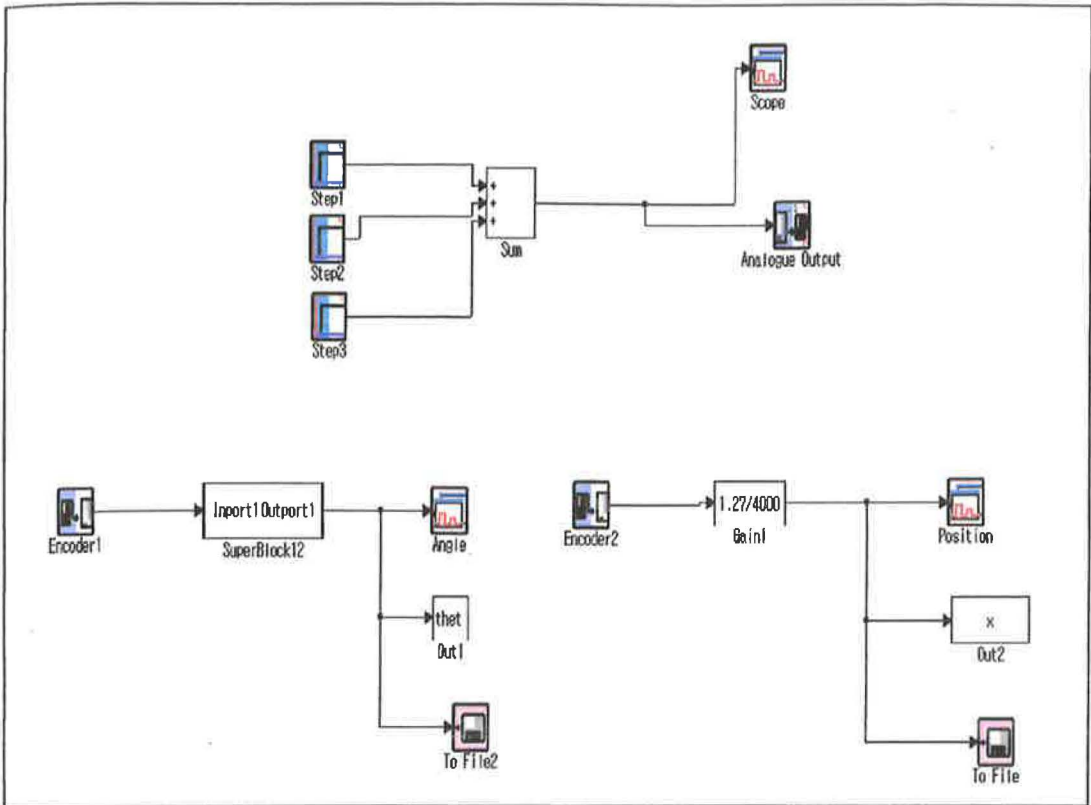


Figure 3.16: A block diagram design using SIMTool without filter

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter is discussing about the result and followed with discussions for this project which can be divided by five parts:

- Simulation results using MATLAB/Simulink
- Experiment result using CEMTool/SIMTool software
- Comparative Assessment

4.1.1 Simulation result using MATLAB/Simulink

Figure 4.1 show a block diagram of a gantry crane that has been studied to investigate the pattern of the output in Low-pass filter technique. Butterworth filter has been chosen to execute with different orders of filter and the performances of each filter are shows as below:

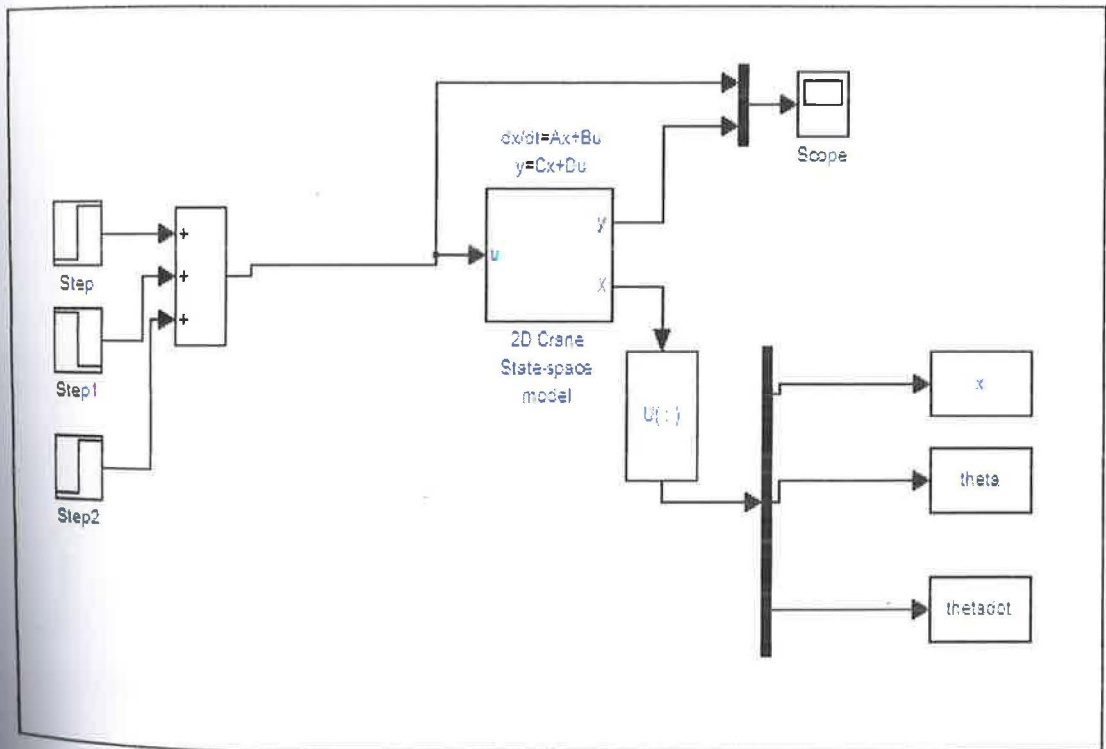


Figure 4.1: A block diagram design of a gantry crane system in MATLAB

4.1.1.1 Response without a filter

Figure 4.2 shows the responses without filter in frequency domain while Figure 4.3, and Figure 4.4 shows the responses without filter in time domain. These results were considered as the system response of the unshaped bang-bang torque input to evaluate the performance of the Low-pass filter techniques. From Figure 4.3 and Figure 4.4, the swing angle of the pendulum and the horizontal position of the cart show that a significant sway occurs during the movement of the pendulum.

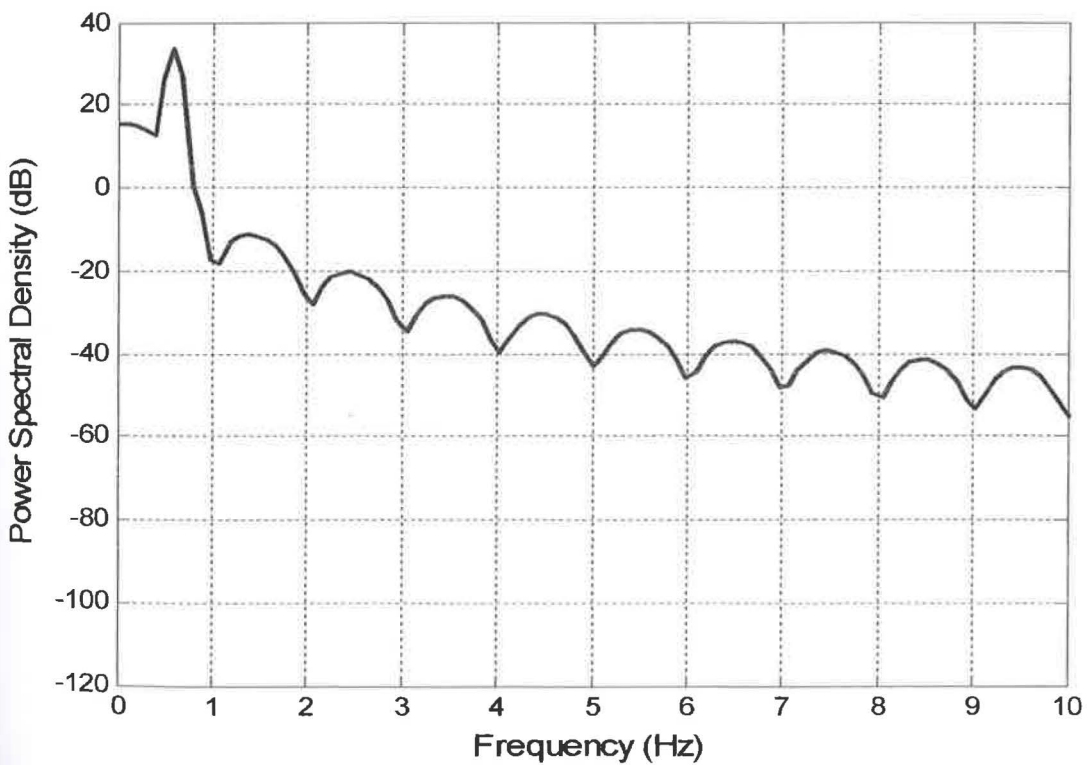


Figure 4.2: Attenuation of sway of the pendulum

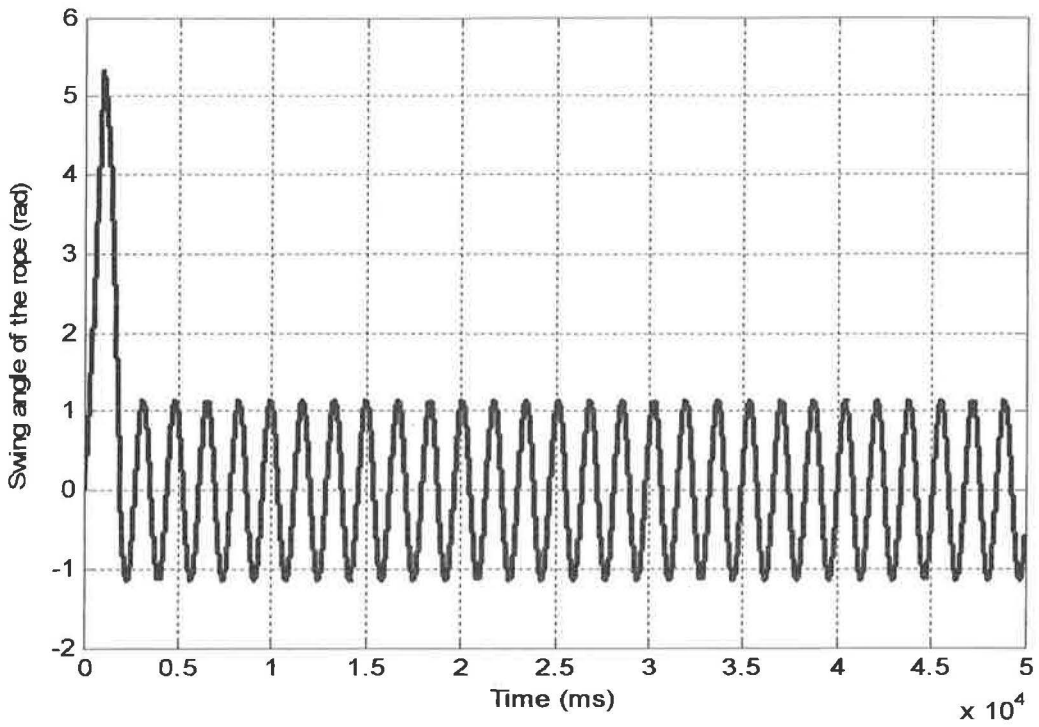


Figure 4.3: Amplitude of sway angle of the pendulum

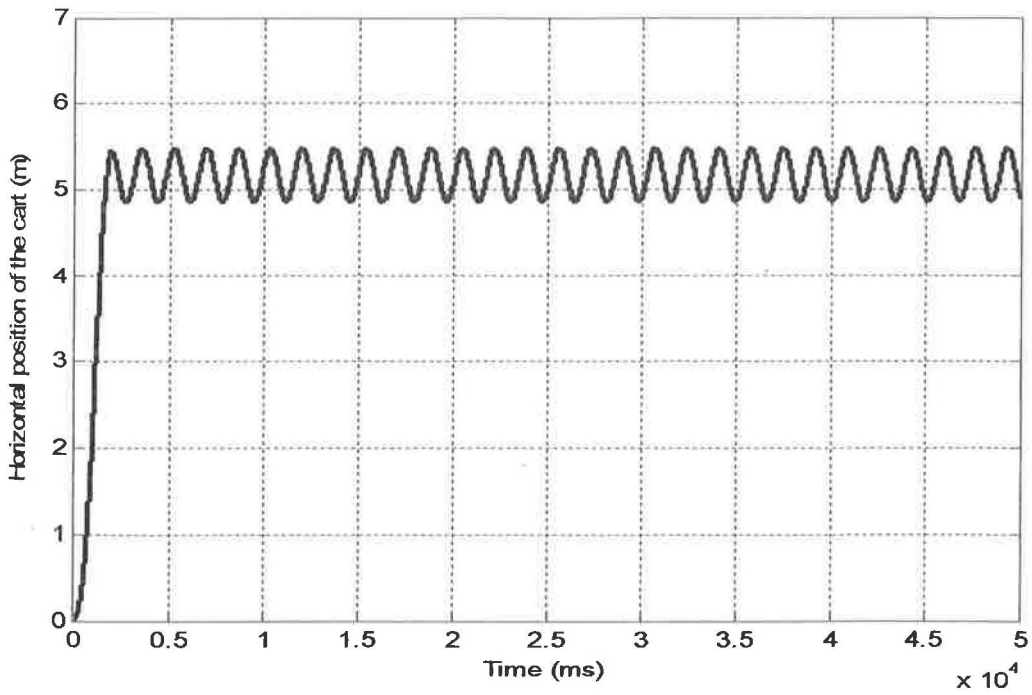


Figure 4.4: Horizontal position of the cart

4.1.1.2 Response with Low-pass filter

Figure 4.5 to 4.13 shows responses with Low-pass filter of 3rd order, 6th order and 9th order for attenuation of sway of the pendulum, the amplitude of sway angle of the pendulum, and horizontal position of the cart. These results show the performance of Low-pass filter techniques by using a different orders and it has been developed to reduce the sway angle of the pendulum.

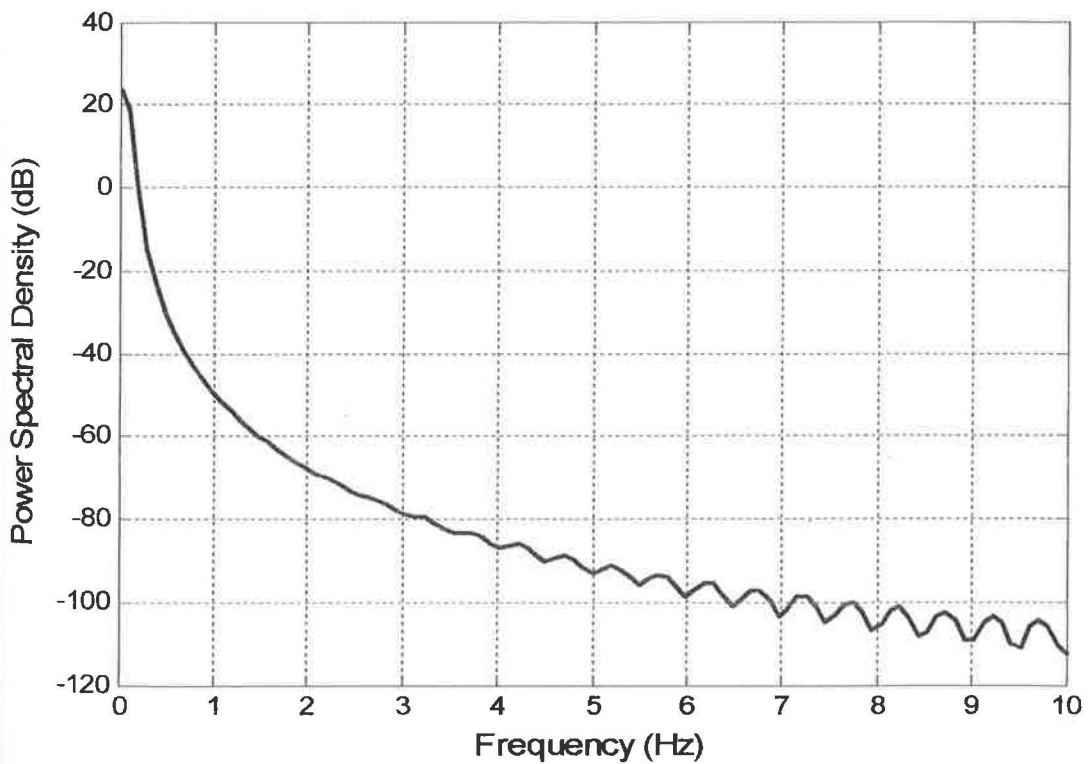


Figure 4.5: Attenuation of sway of the pendulum for 3rd Order

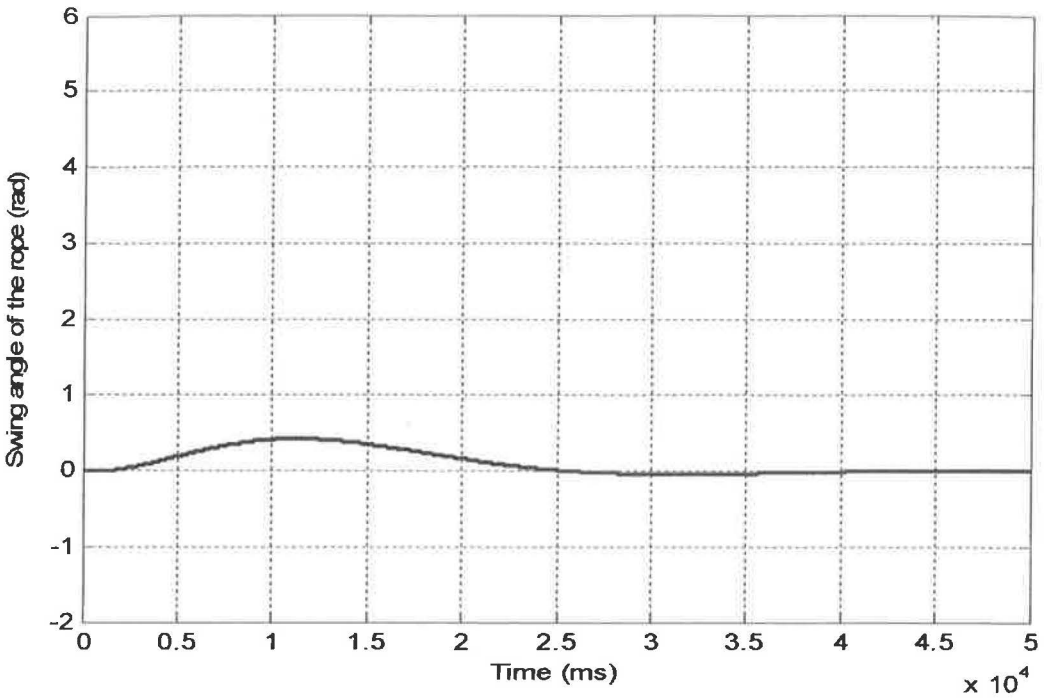


Figure 4.6: Amplitude of sway angle of the pendulum for 3rd Order

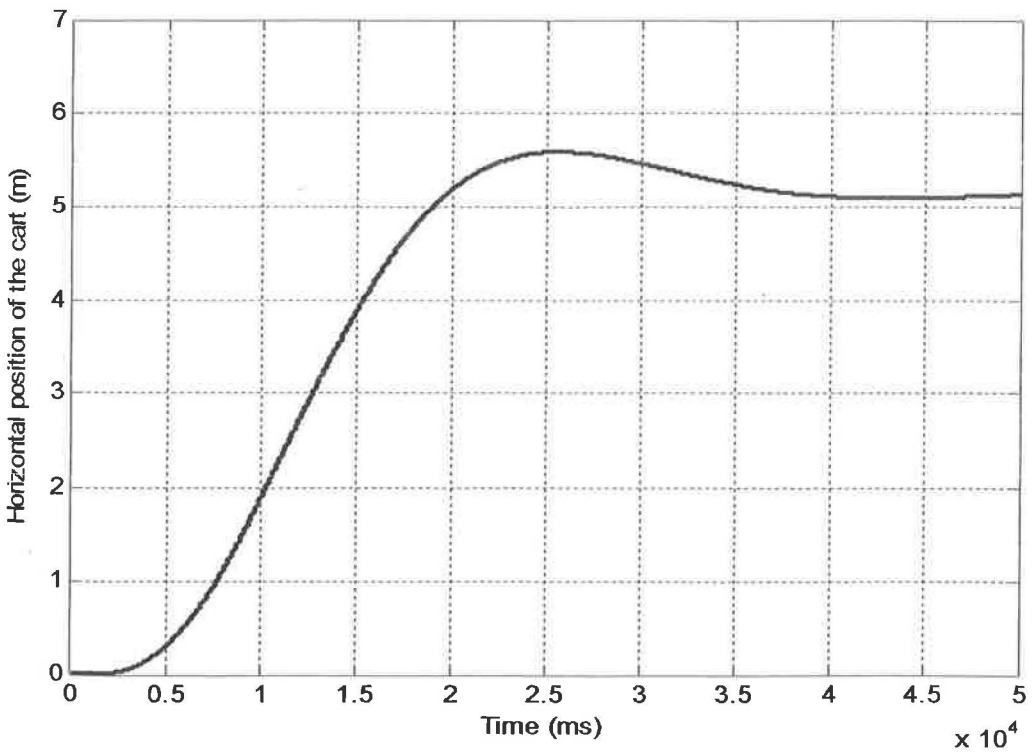


Figure 4.7: Horizontal position of the cart for 3rd Order

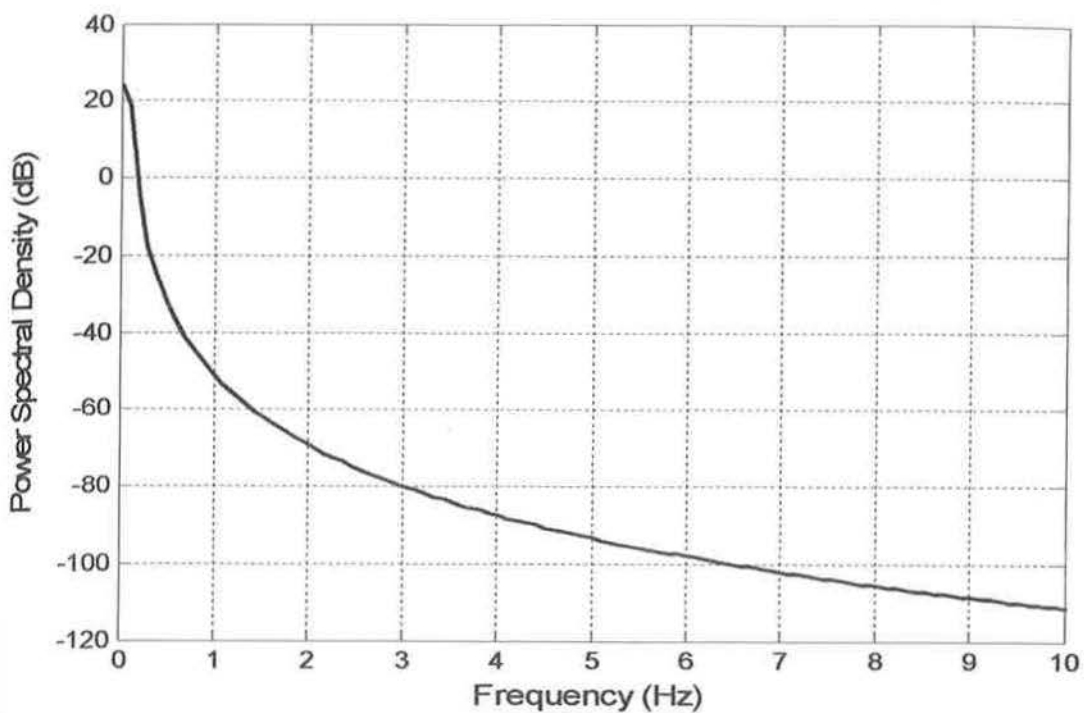


Figure 4.8: Attenuation of sway of the pendulum for 6th Order

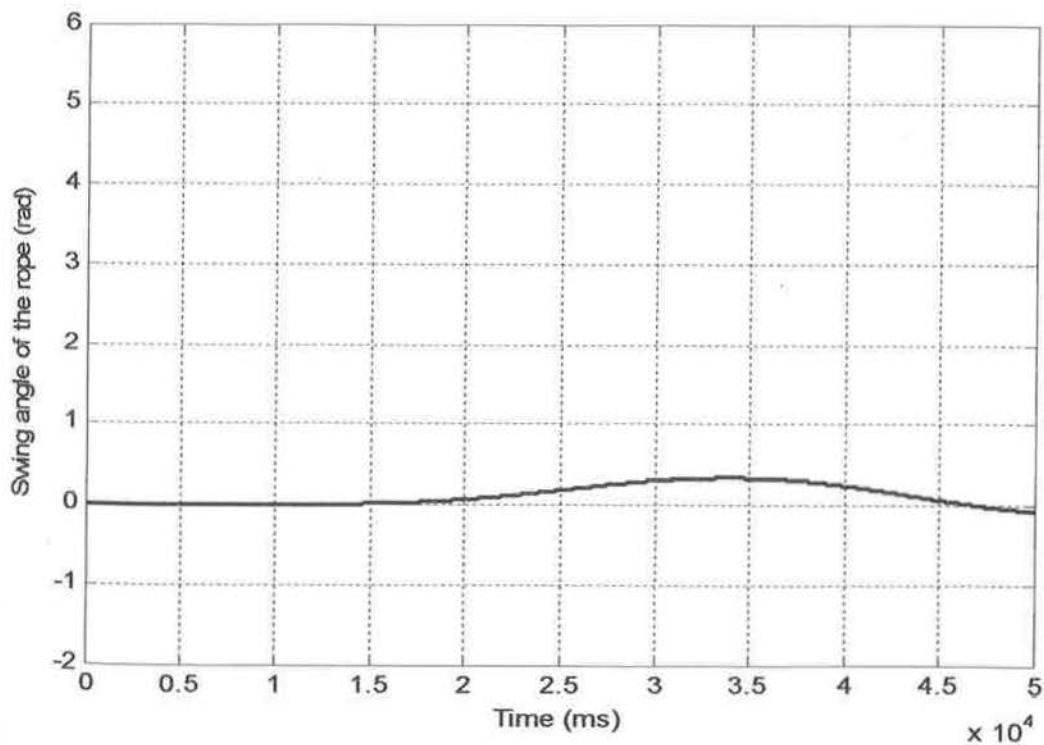


Figure 4.9: Amplitude of sway angle of the pendulum for 6th Order

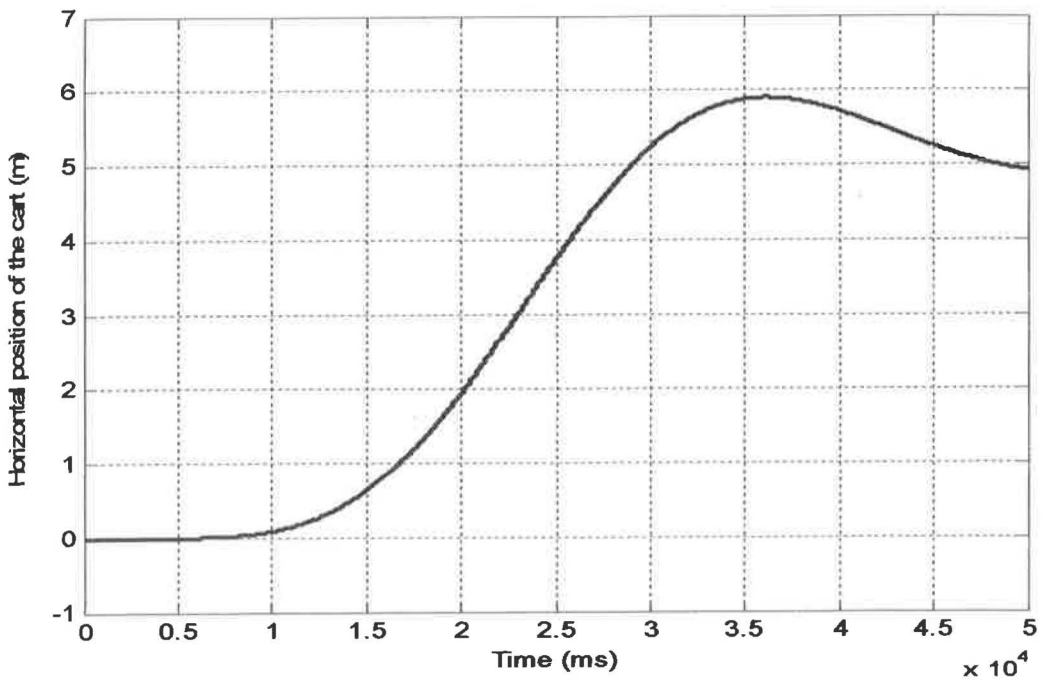


Figure 4.10: Horizontal position of the cart for 6th Order

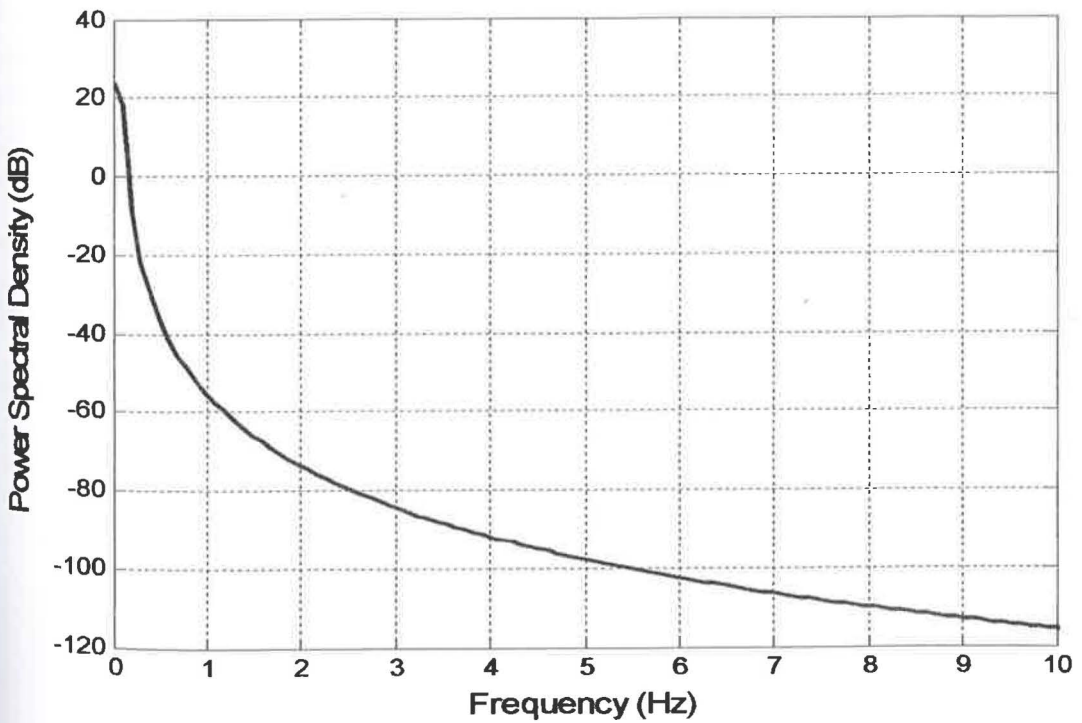


Figure 4.11: Attenuation of sway of the pendulum for 9th Order

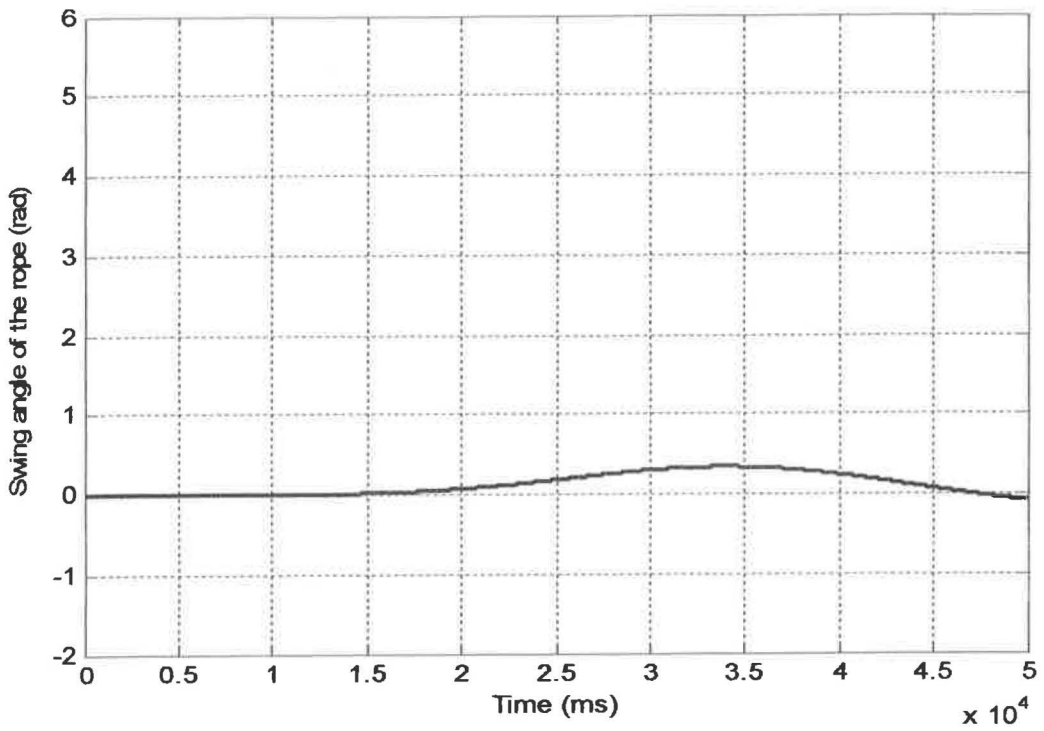


Figure 4.12: Amplitude of sway angle of the pendulum for 9th Order

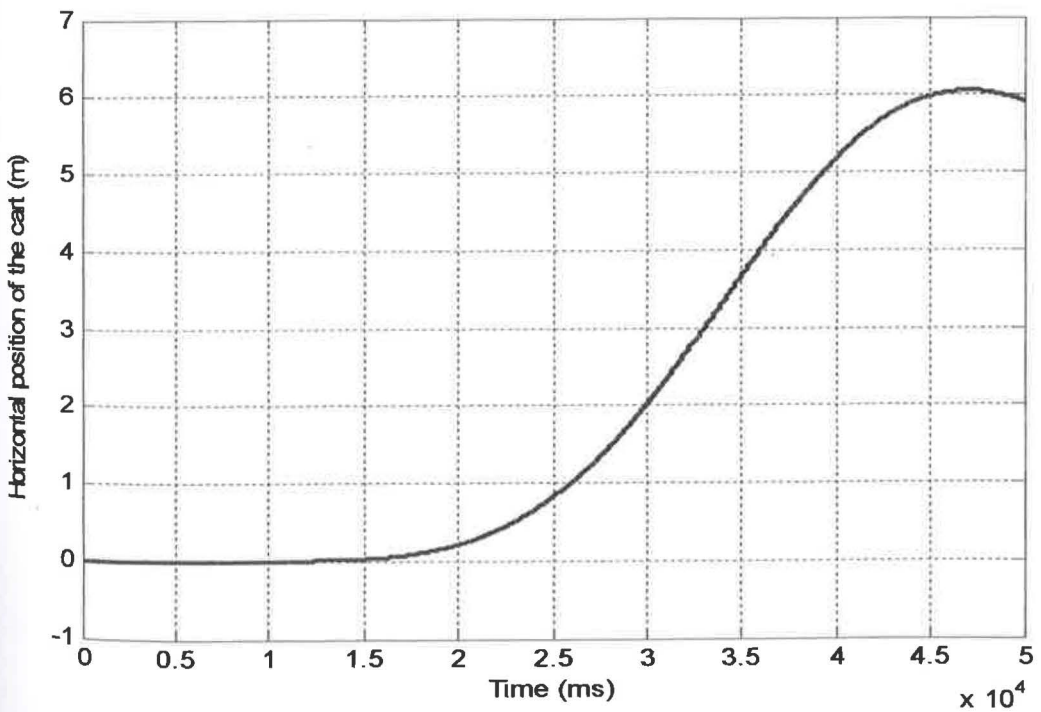


Figure 4.13: Horizontal position of the cart for 9th Order

Figure 4.14, Figure 4.15, and Figure 4.16 shows a differentiation responses without filter and with Low-pass filter of 3rd order, 6th order, and 9th order. Figure 4.15, 4.16, and 4.17 depicted that the attenuation of sway of pendulum, the amplitude of sway angle of the pendulum and the horizontal of the pendulum was decreased with the increment of filter orders. These results has been picked as references study of the performance Low-pass filter for anti-sway control of a gantry crane systems for the experiment by using CEMTool/SIMTool software.

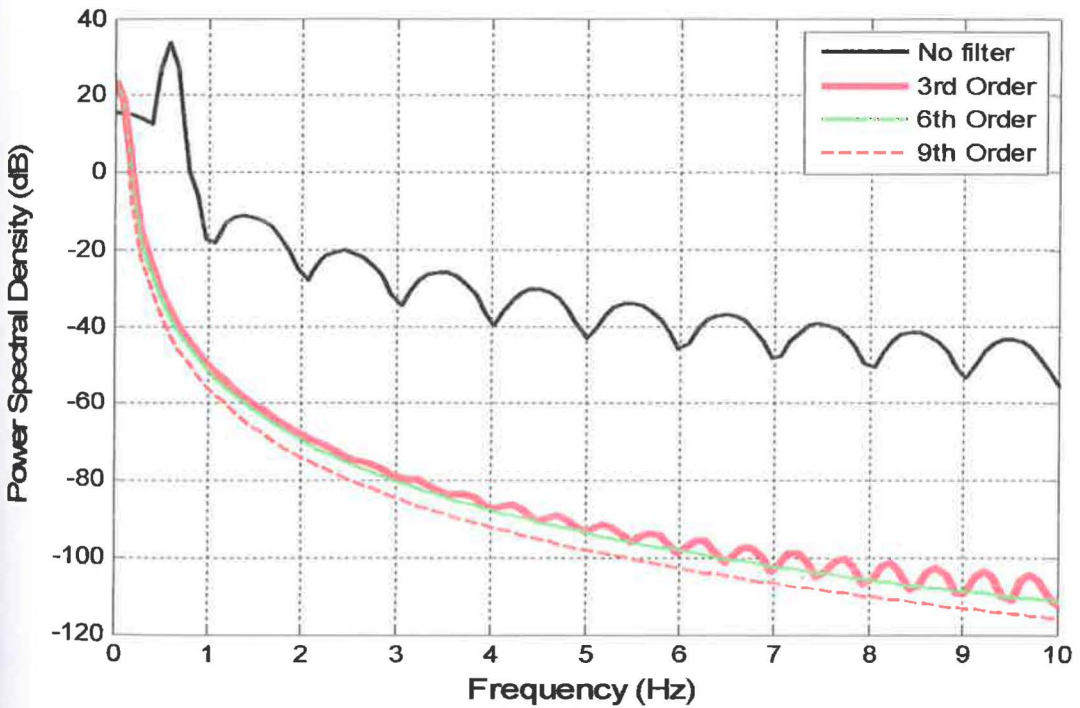


Figure 4.14: Attenuation of sway of the pendulum

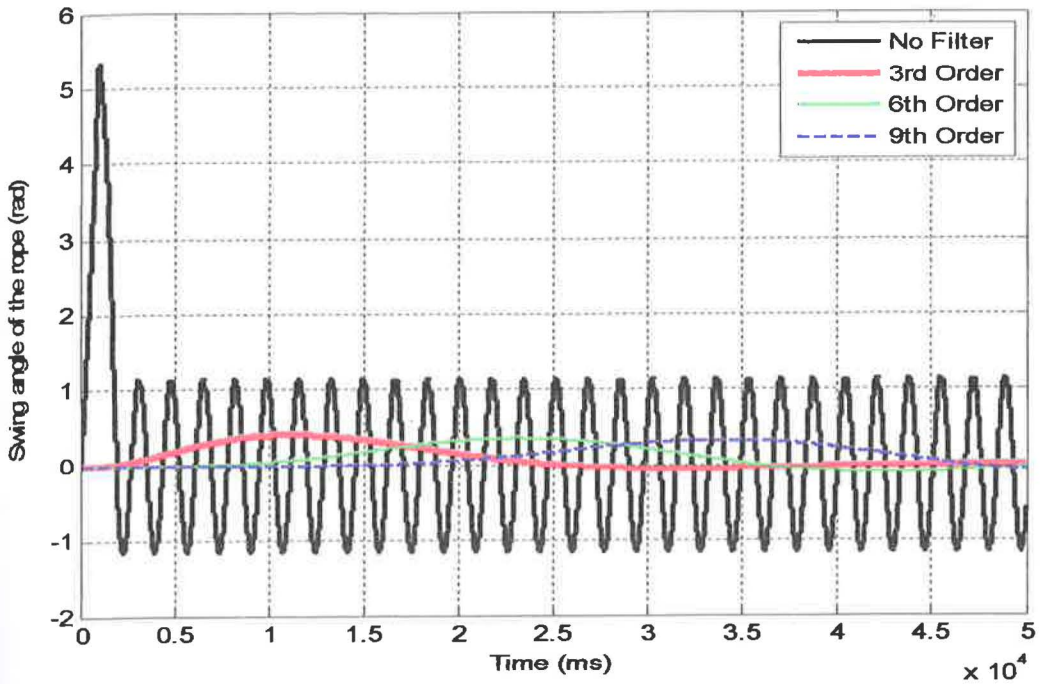


Figure 4.15: Amplitude of sway angle of the pendulum

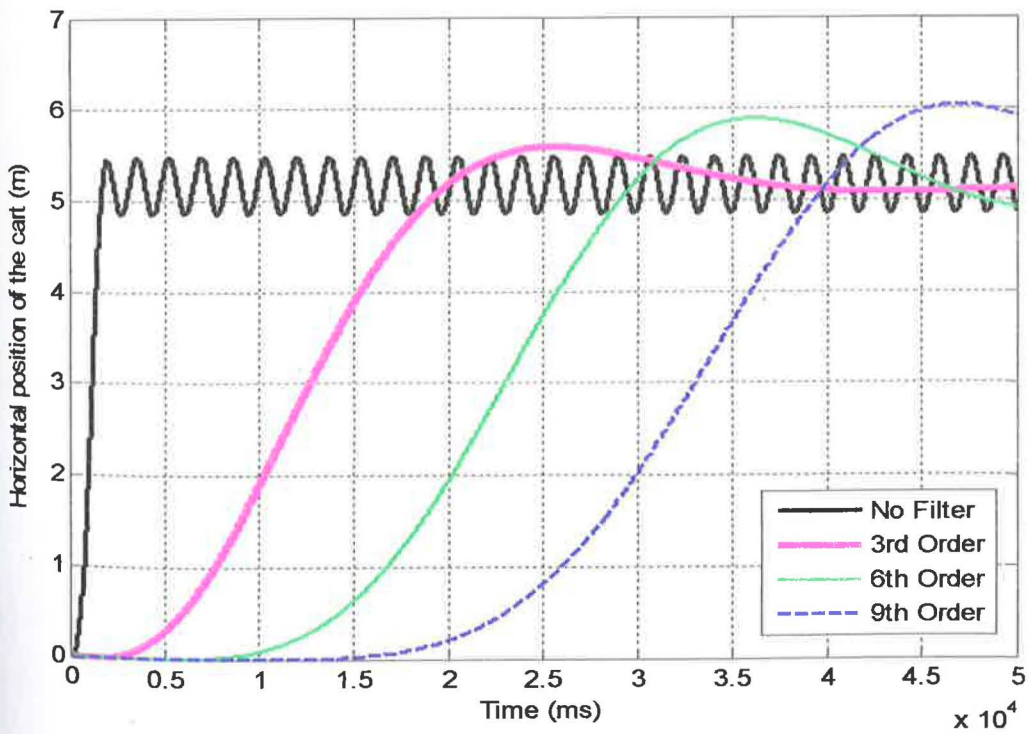


Figure 4.16: Horizontal position of the cart

4.1.2 Experiment Result Using CEMTool/SIMTool Software

The experiment results are divided by two parts:

- Without a filter
- With a Low-pass filter

4.1.2.1 Response without a filter

Figure 4.17, Figure 4.18, and figure 4.9 shows the responses of the system without a filter. These results show that a sway occurs during the movement of the pendulum. The amplitude of sway angle obtained 21.16 dB with the sway frequency 0.883Hz, while the amplitude of sway angle of the pendulum and horizontal of the cart are ± 0.342 rad and 73.24 cm respectively.

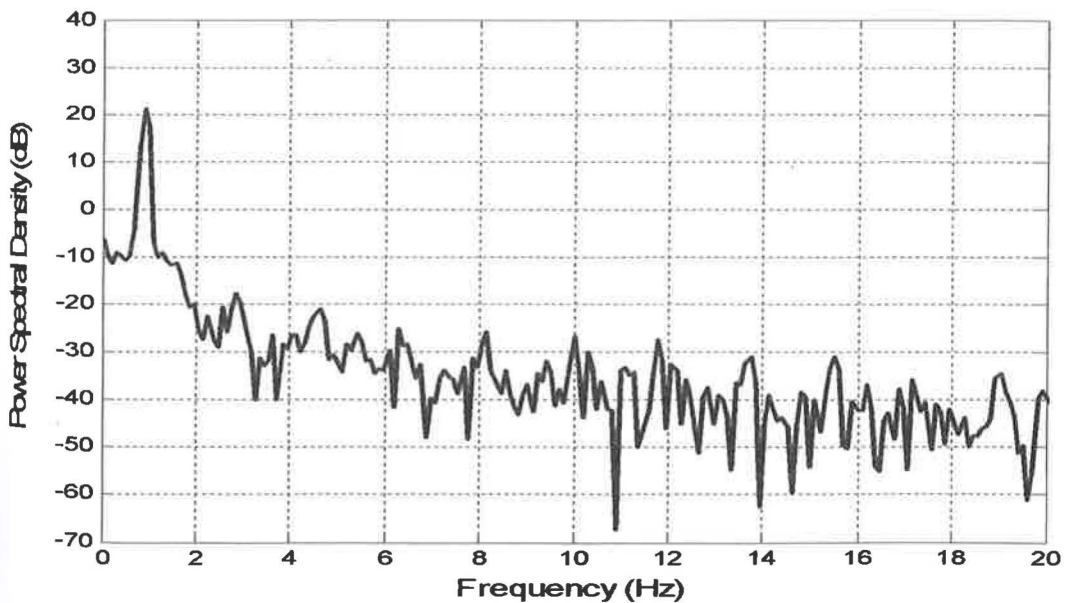


Figure 4.17: Attenuation of sway of the pendulum

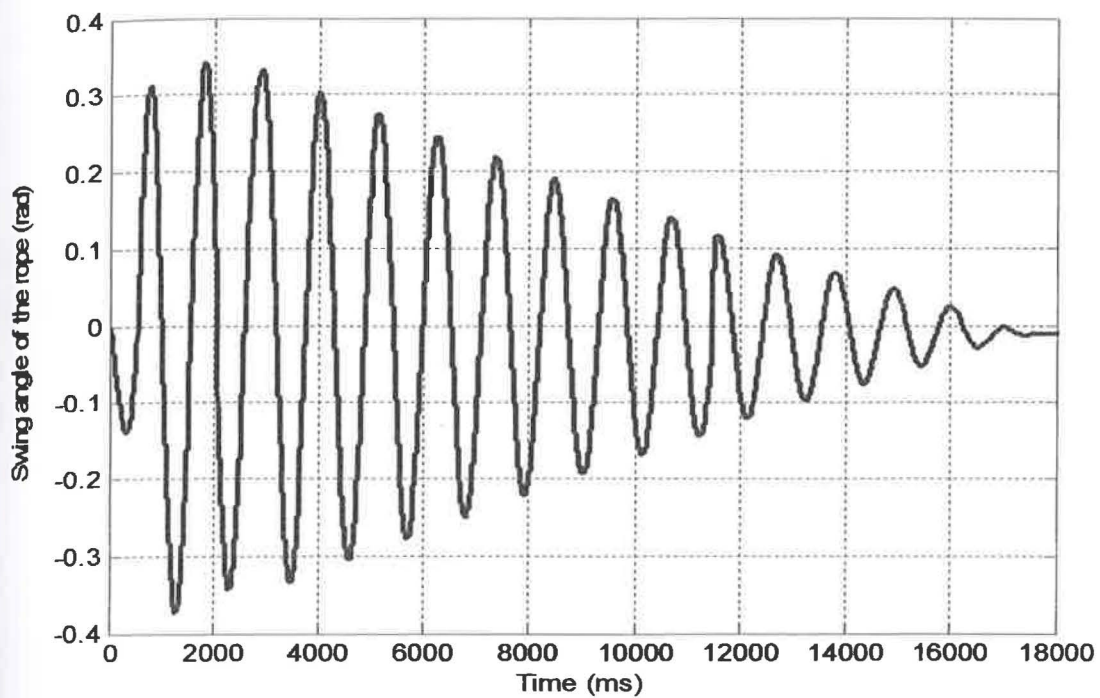


Figure 4.18: Amplitude of sway angle of the pendulum

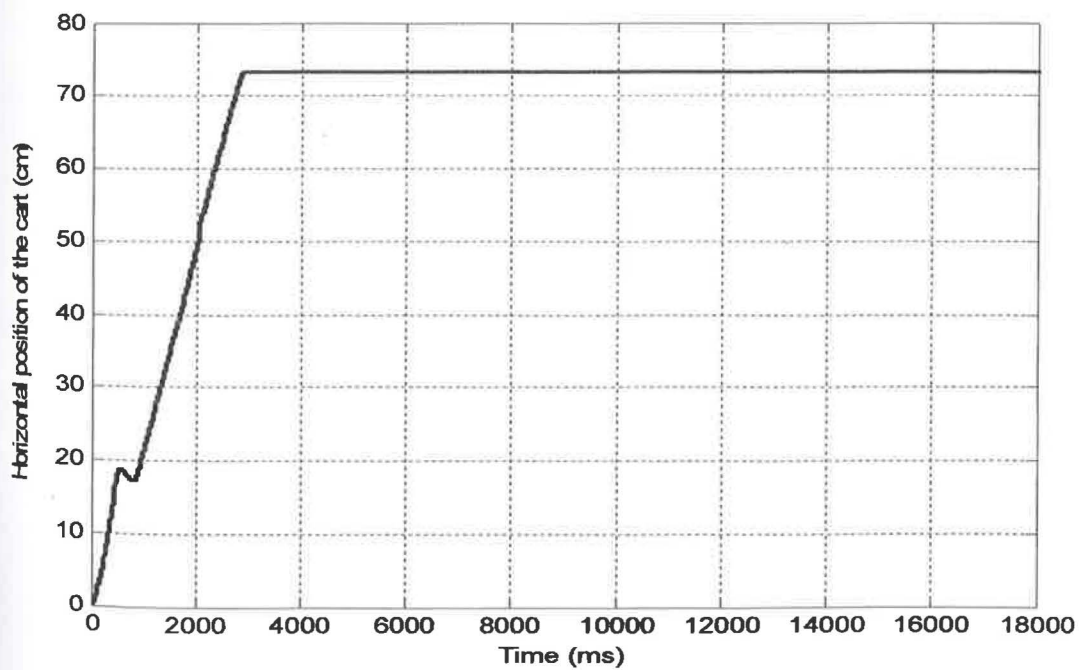


Figure 4.19: Horizontal position of the cart

4.1.2.2 Response with Low-pass filter

In these experiment, the level sway reduction of the pendulum in Figure 4.20 show a slight changed for 3rd order by achieved as much as 4.13 dB. Figure 4.21 show a reduction on amplitude of sway angle of the pendulum is ± 0.281 rad compared to Figure 4.18 which produce a higher amplitude without using a filter. The response of the cart position show the time for the pendulum to settling down is 2.46 s with zeros overshoot while the rise time is 1.94 s.

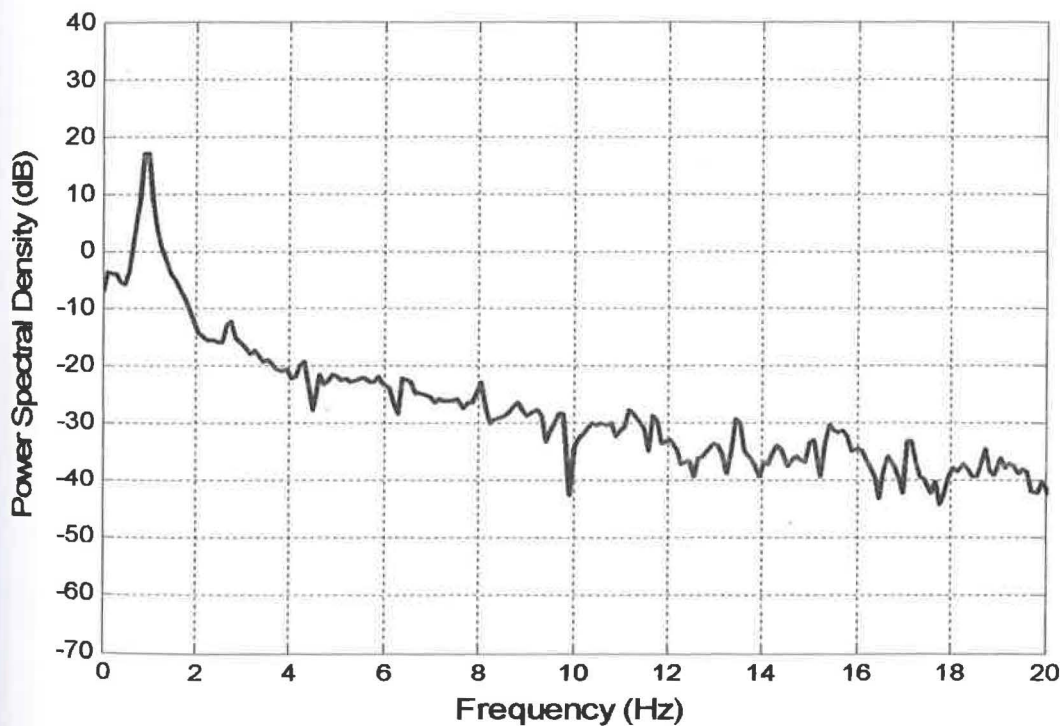


Figure 4.20: Attenuation of Sway of the pendulum for 3rd Order

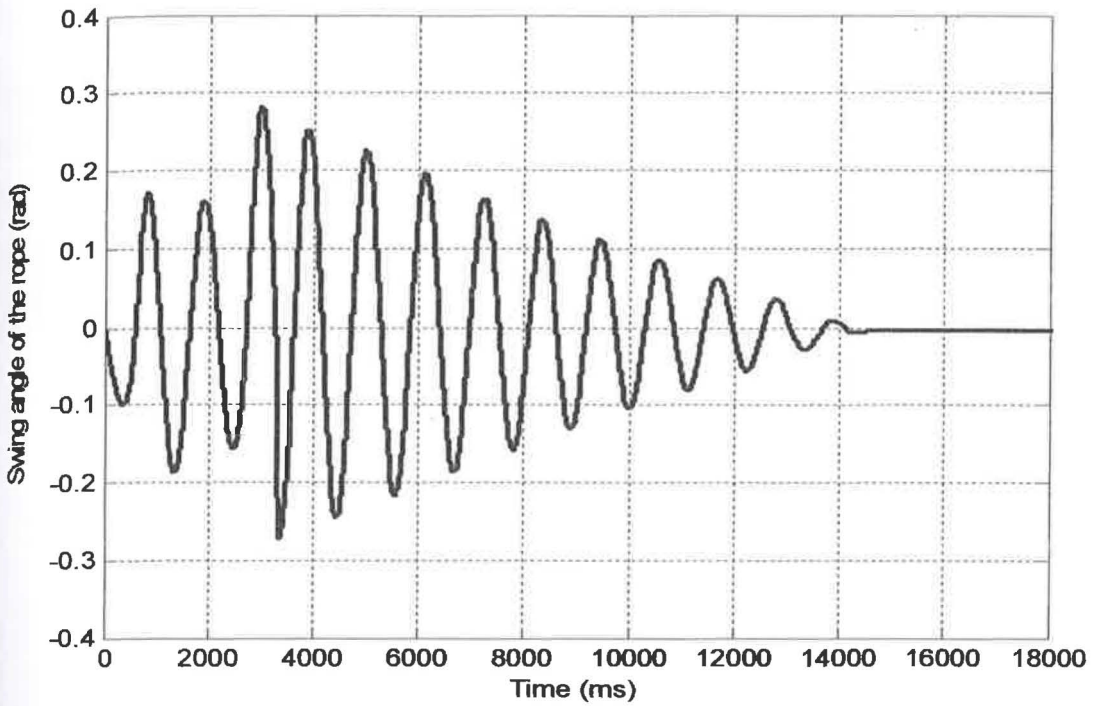


Figure 4.21: Amplitude of sway angle of the pendulum for 3rd Order

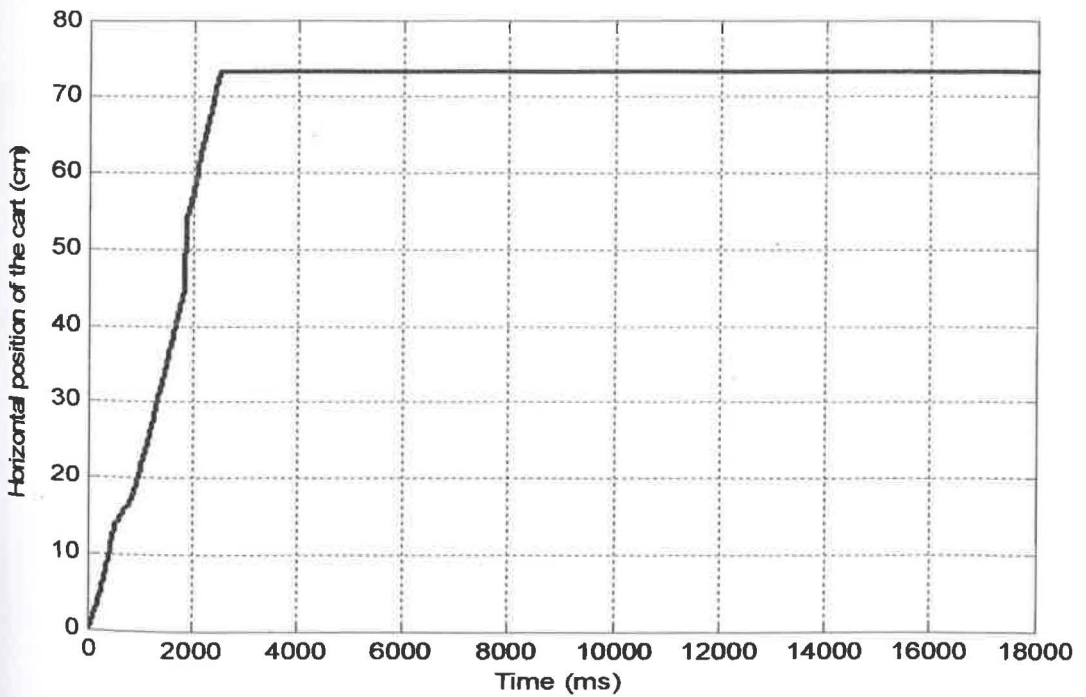


Figure 4.22: Horizontal position of the cart for 3rd Order

When increasing the filter's order with 6, the results in Figure 4.23 give an improvement which the levels sway reduction become increased to 5.49 dB. The amplitude of sway angle of the pendulum also decreased to ± 0.239 rad in Figure 4.24 while the reading position of the cart in Figure 4.25 increased to 73.65 cm and achieved time to settling down the movement of the pendulum in 2.58 s with zeros overshoot, but the rise time was increased to 2.03 s from the result of 3rd order.

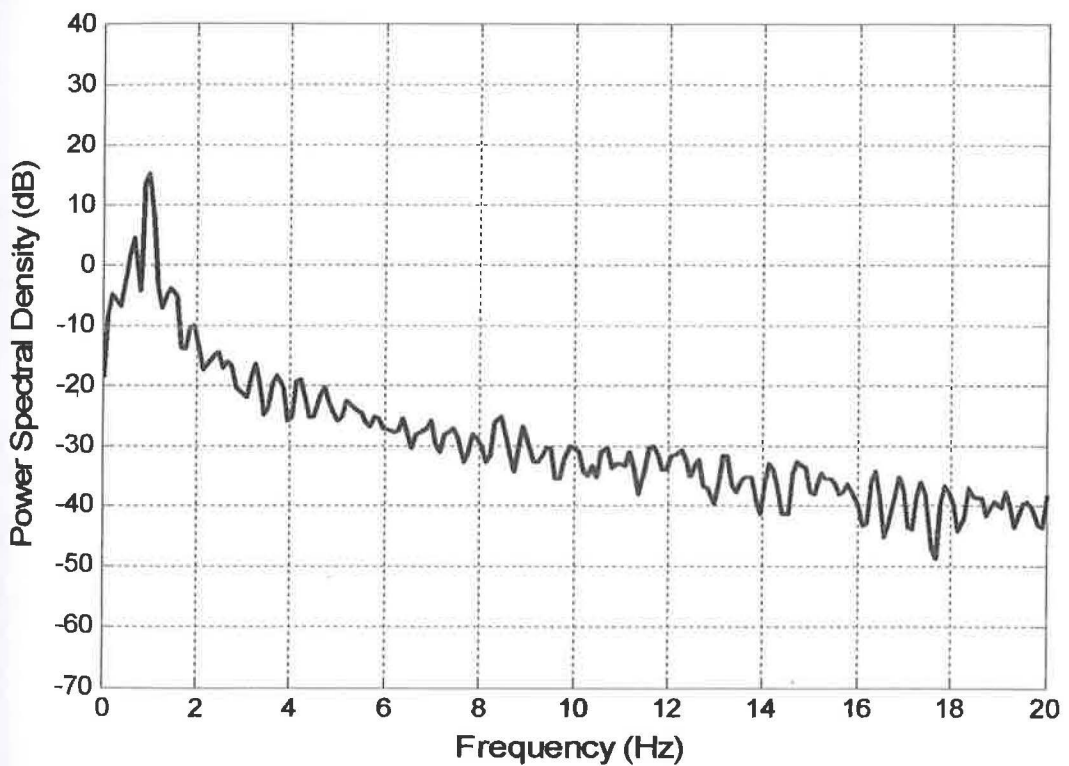


Figure 4.23: Attenuation of sway of the pendulum for 6th Order

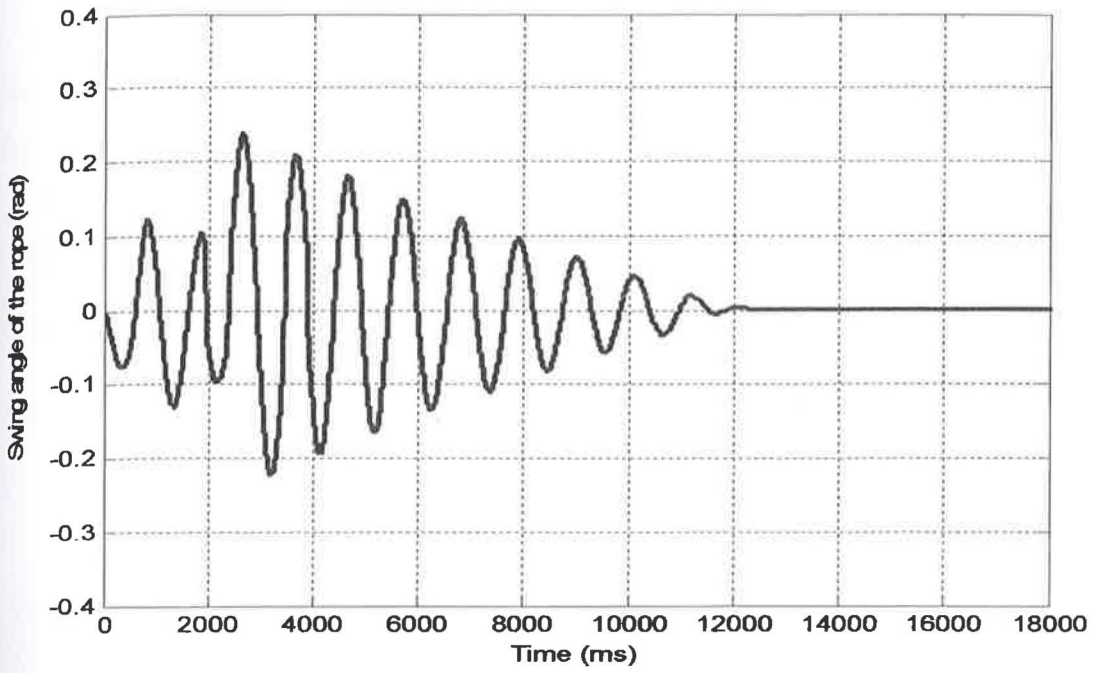


Figure 4.24: Amplitude of sway angle of the pendulum for 6th Order

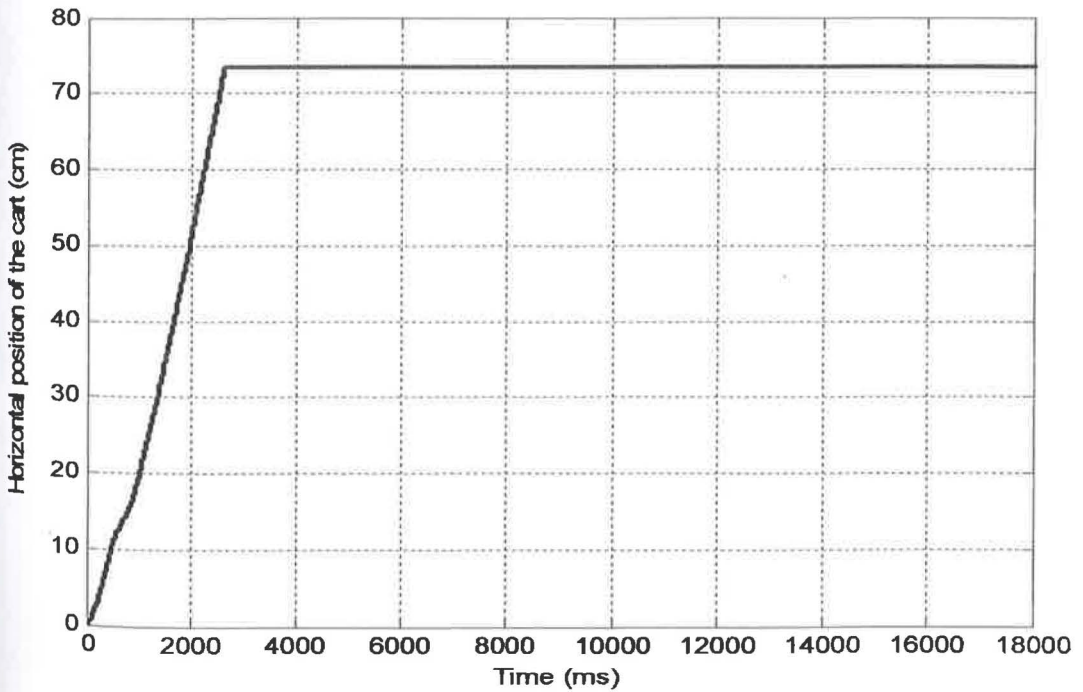


Figure 4.25: Horizontal position of the cart for 6th Order

The responses for 9th order are shown in Figure 4.26, Figure 4.27, and Figure 4.28. The level of sway reduction in Figure 4.26 shows a better improvement by giving a reading 6.90 dB. It has been proved with reducing amplitude of sway angle of the pendulum and the increasing time for the sway of the pendulum to settling down which is 2.61s with zero overshoot while the rise time become decreased to 1.99 s compared with the result from 6th order.

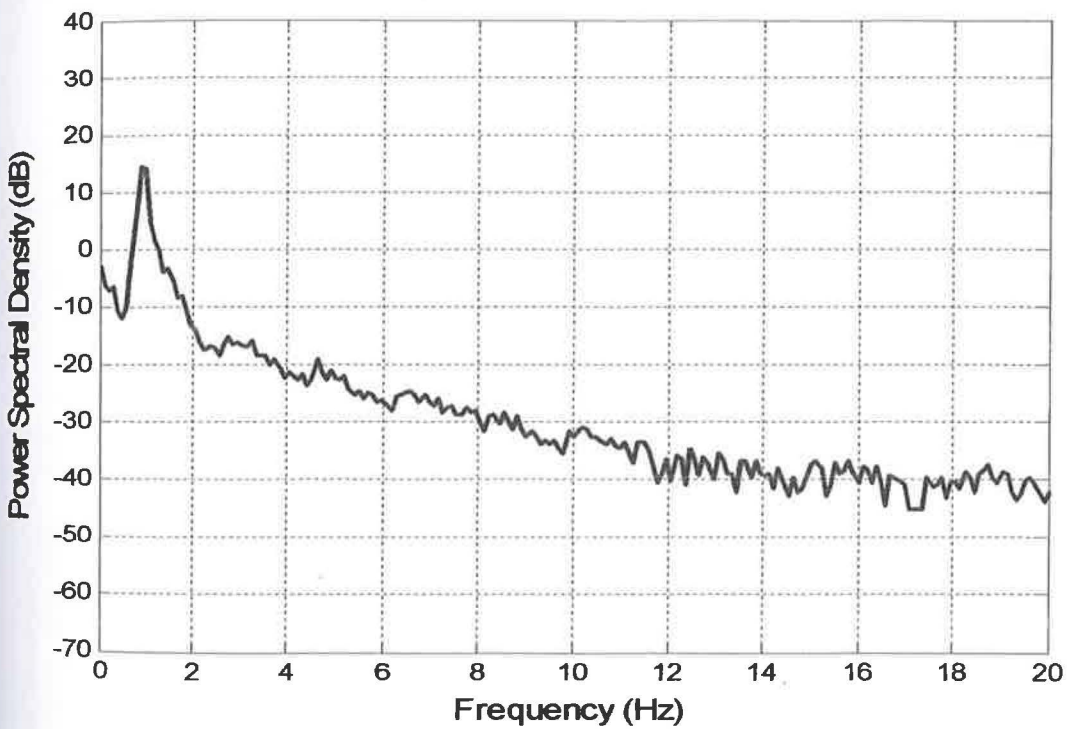


Figure 4.26: Attenuation of sway of the pendulum for 9th Order

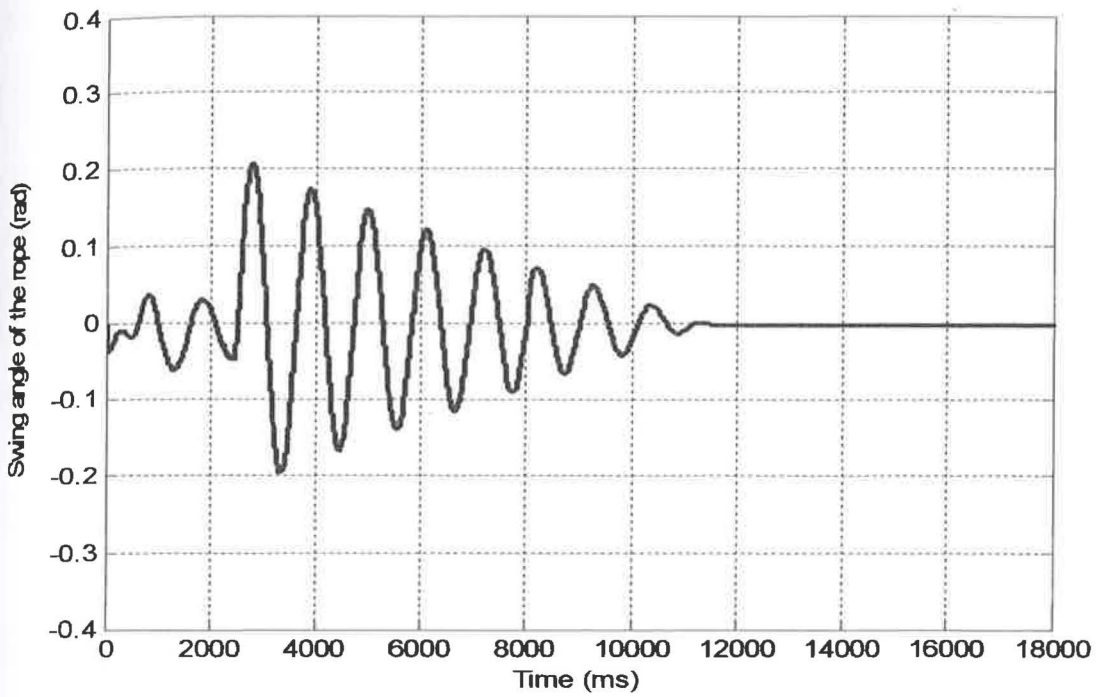


Figure 4.27: Amplitude of sway angle of the pendulum for 9th Order

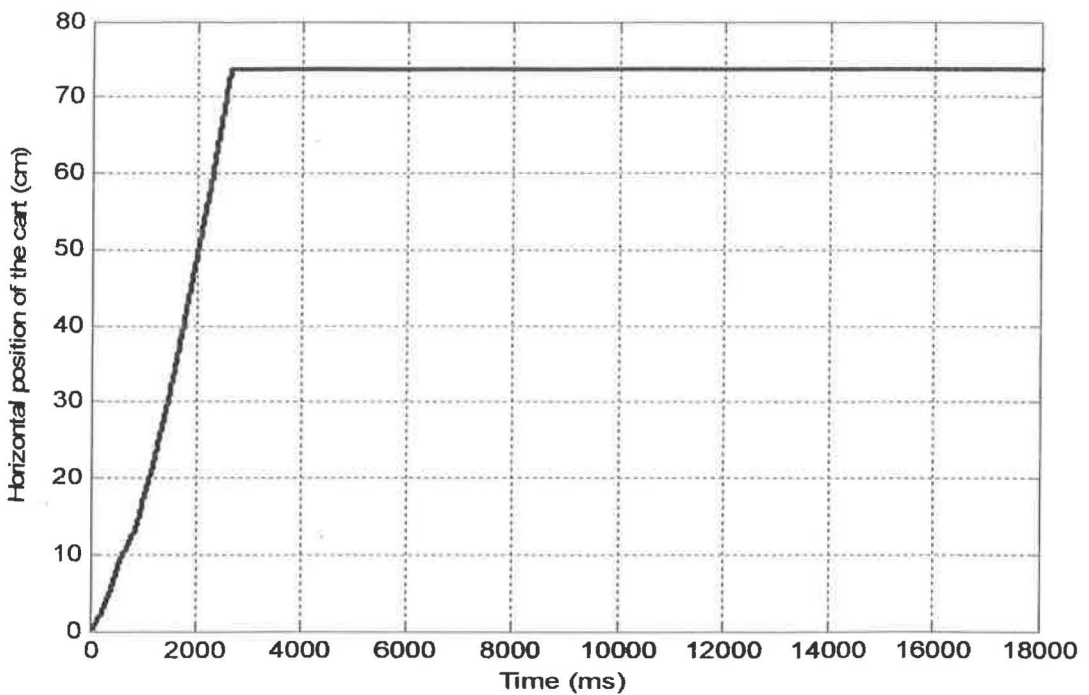


Figure 4.28: Horizontal position of the cart for 9th Order

4.1.3 Comparative Assessment

The proposed application of Low-pass filter are implemented and experimented within the simulation environment of the gantry crane system and the corresponding results are presented. The control strategies were designed from the unshaped bang-bang torque input to determine the characteristic parameter of the system for the design and evaluation of the Low-pass filter techniques. The performances of each order for attenuation (dB) of sway of the pendulum, amplitude of sway angle of the pendulum, and horizontal position of the cart are shows in Figure 4.29, 4.30, 4.31, respectively.

The overall result demonstrates that, the performances of Low-pass filter were achieved for anti-sway control of the gantry crane system. This is evidenced in sway angle of the pendulum response as shown in Figure 4.30 whereas the amplitudes of sway angle were reduced with the increment number of filter's order. The sway angle settled down higher at 2.61 s for 9th order with overshoot of zeros compared for 3rd and 6th orders. The reduction of sway angle can be clearly demonstrated in frequency domain results as the magnitudes of the PSD at the attenuation of sway of the pendulum were significantly reduced which shown in Figure 4.29.

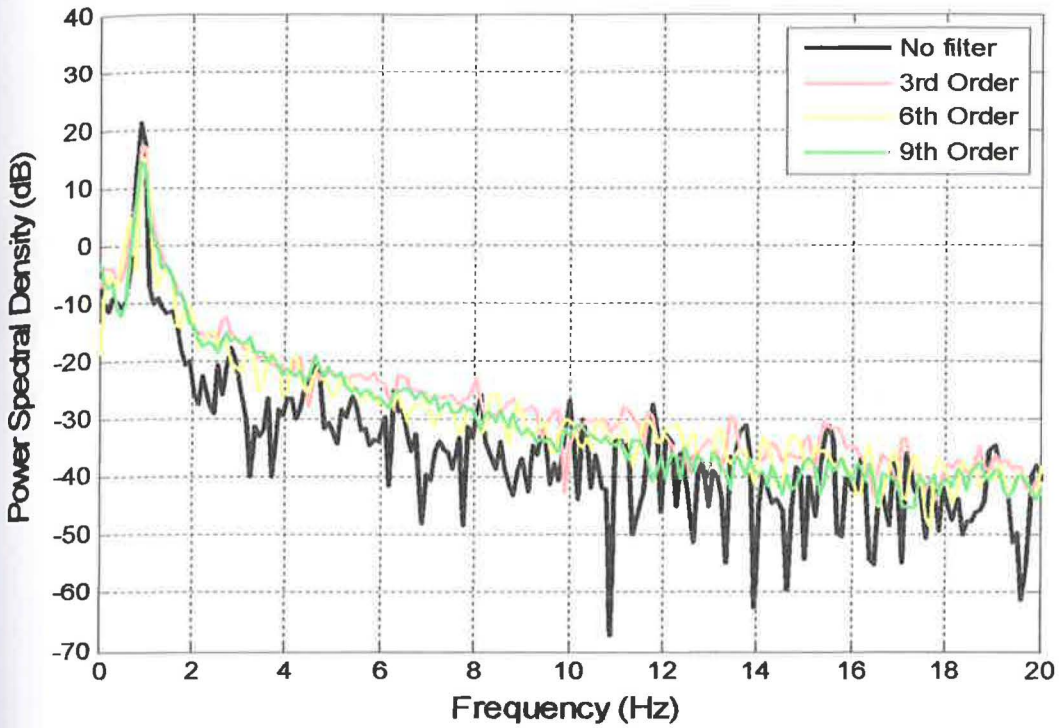


Figure 4.29: Attenuation of sway of the pendulum

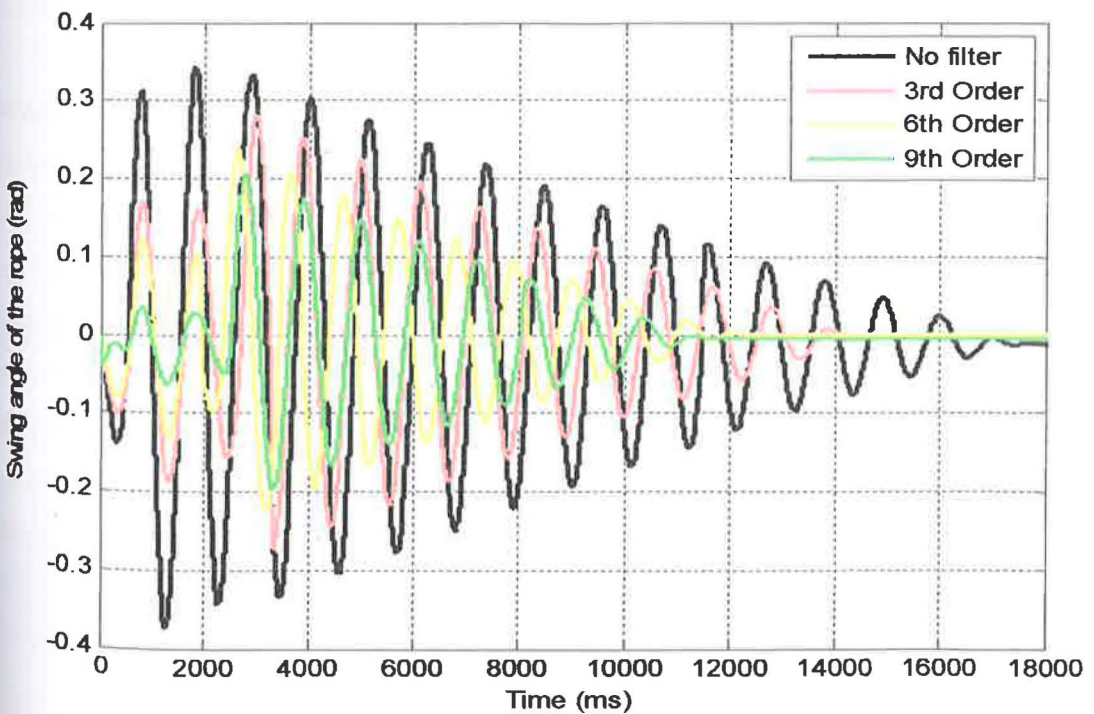


Figure 4.30: Amplitude of sway angle of the pendulum

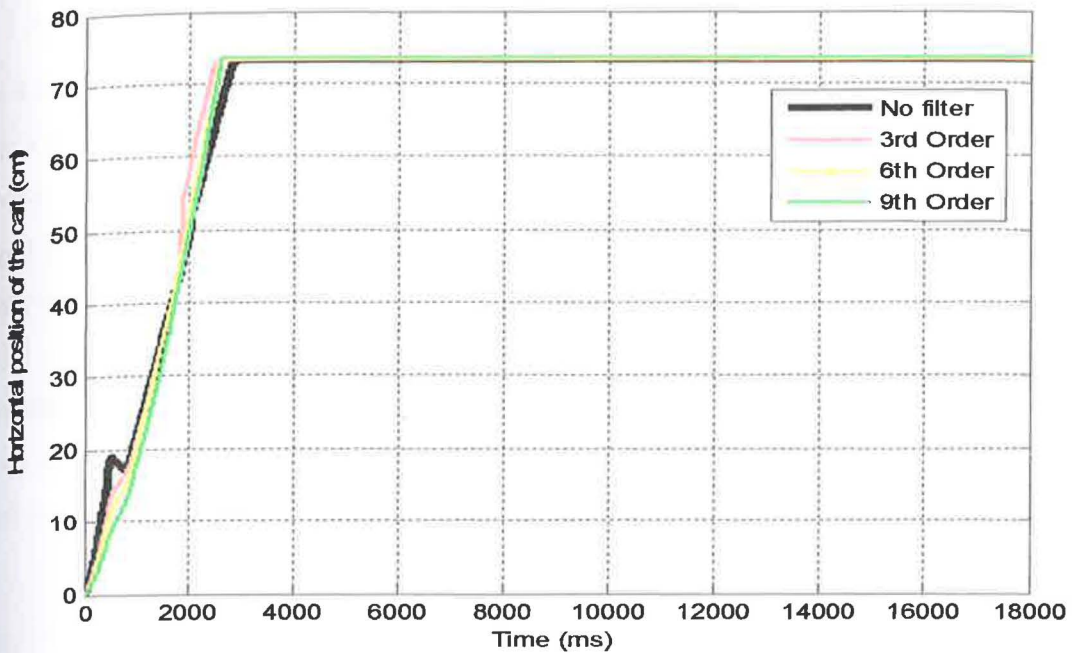


Figure 4.31: Horizontal position of the cart

The corresponding rise time, settling time and overshoot of the cart position response and level sway reduction of the pendulum are depicted in Table 4.2. The results show that the attenuation of sway in filtering techniques will be increased with the increment number of filter's order. For comparative assessments, the level of sway attenuation of the swing angle using Low-pass filter techniques are shown with the bar graphs in Figure 4.32. The result shows that the highest level of sway attenuation is achieved with the 9th order, followed by 6th order and 3rd order of Low-pass filter. Figure 4.33 show a bar graph for rise and settling time of step response with 3rd, 6th, and 9th order Low-pass filter. Bar graph for rise time does not given an increasing pattern but settling time show an increasing result and it was verified the experiment theory which is the sway angle of the pendulum reduced with the increasing of the time for the sway of the pendulum to settle down.

Comparisons of the specification response of the cart position are summarized in Table 4.2 for the rise and settling times. It is noted that the Low-pass filter techniques shown a faster settling time with the increment of filter's order, but the patterns of rise time does not shown because of the experiment environment which made the reading changed in certain time during the experiment. The percentages of overshoots of the cart position responses are zeroes. Thus, it can be concluded that all types of filters produces a less overshoot. From Table 4.1, the differentiation levels sway reduction of the pendulum show that the increment of filter's order has affect the attenuation of sway and the cart position become increased but the result for amplitude of sway angle of the pendulum was decreased

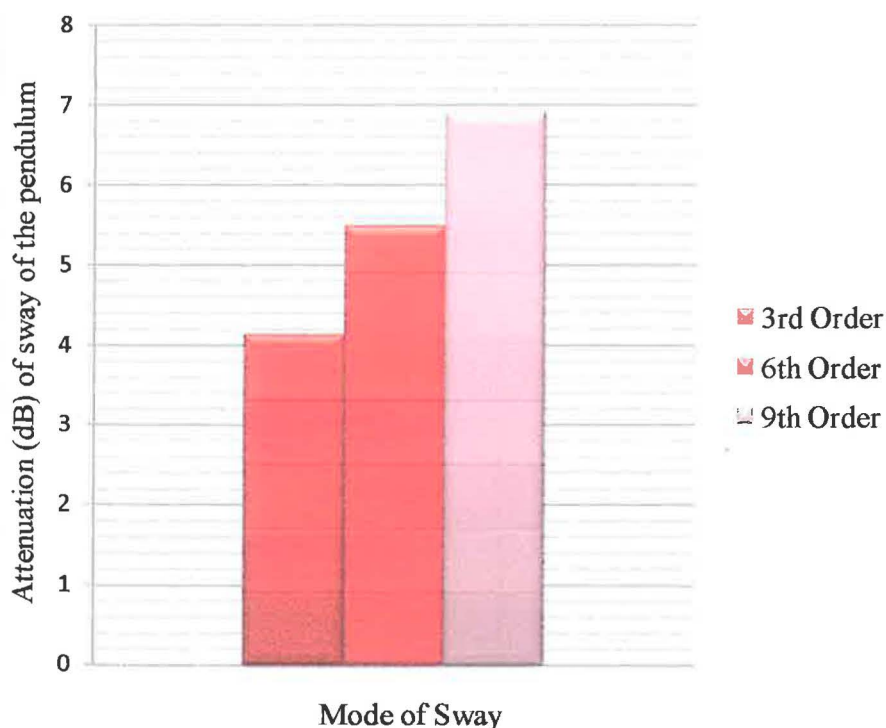


Figure 4.32: Level of sway reduction with 3rd, 6th, and 9th order of Low-pass filter

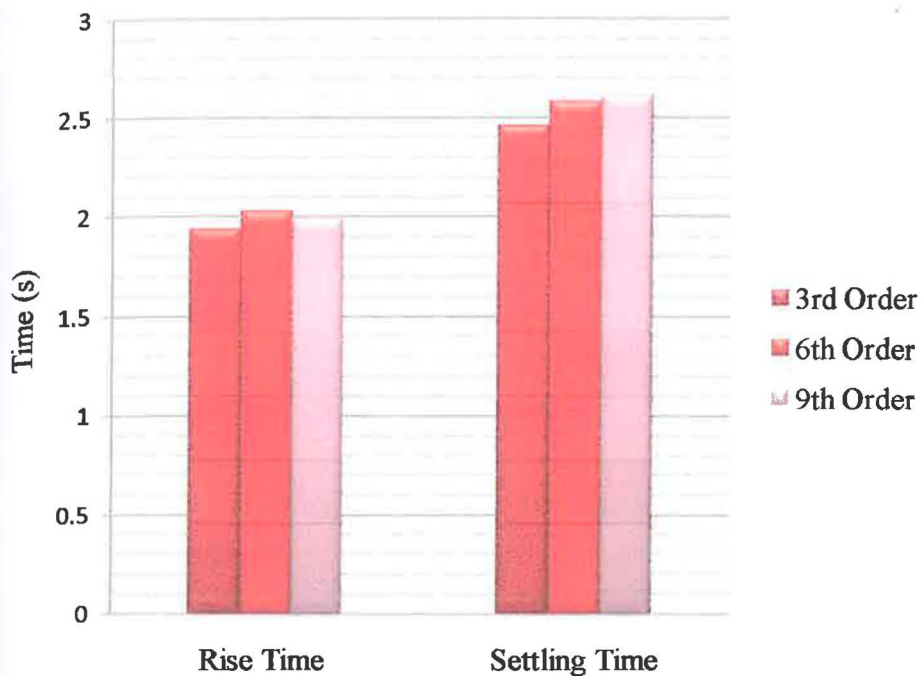


Figure 4.33: Rise and settling time of step response with 3rd, 6th, and 9th order Low-pass filter

Table 4.1: Level sway reduction of the pendulum.

Butterworth Filter	Orders	Attenuation (dB) of sway of the pendulum	Amplitude of sway angle of the pendulum (rad)	Horizontal position of the cart (cm)
LPF	No filter	21.16	± 0.342	73.24
	3 rd	4.13	± 0.281	73.43
	6 th	5.49	± 0.239	73.65
	9 th	6.90	± 0.207	73.85

Table 4.2: Level sway reduction of the pendulum and specification response of the cart position

Butterworth Filter	Orders	Attenuation (dB) of sway of the pendulum	Specification Response of Cart Position		
			Rise Time (s)	Settling Time (s)	Overshoot (%)
LPF	3 rd	4.13	1.94	2.46	0
	6 th	5.49	2.03	2.58	0
	9 th	6.9	1.99	2.61	0

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

At the end of this project, the application and high performance Low-pass filter for anti-sway control of a gantry crane system is successfully developed. The performances of the filter's order show that the attenuation of sway in filtering techniques will be increased with the increment number of filter's order. The comparison of the results of the specification response of the cart was investigated with the increasing settling time are show the reduction of sway angle to settling down was decreased at the higher order of filter. From that observation, the reduction of sway angle will be decreased. The result also depicted that the sway amplitude in the sway angle responses was reduced. The higher the filter order shows the capability to suppress the energy around the cutting edge frequency significantly. Although, there is a problems using the Swing-Up Inverted Pendulum System because the system were not robust and the crane parameter are not stabilized.

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.

REFERENCES

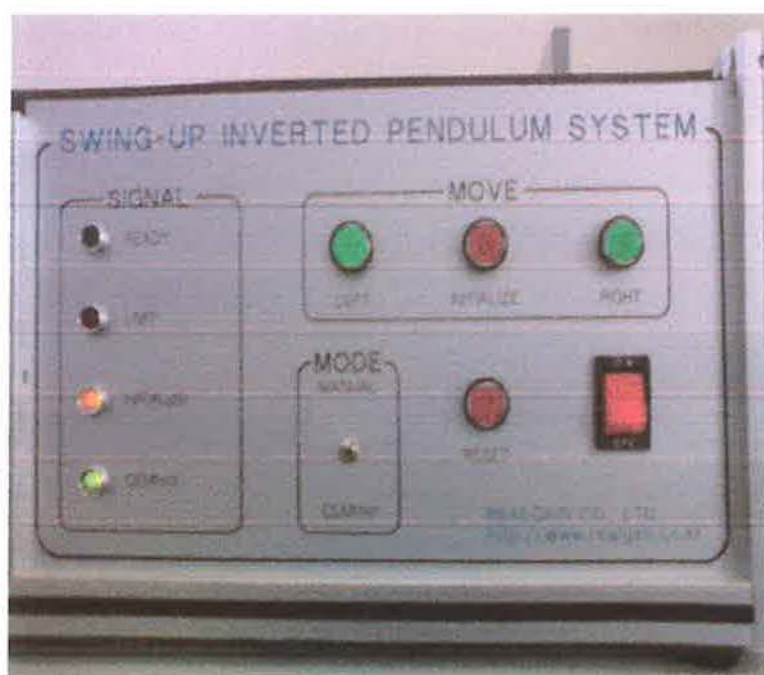
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- [15] Yang, H.C., (April 2006). *The Boom Crane Modelling And Development Of Anti-Sway Control Scheme For Boom Crane Using Command Shaping Techniques*. Universiti Teknologi Malaysia: Degree Thesis

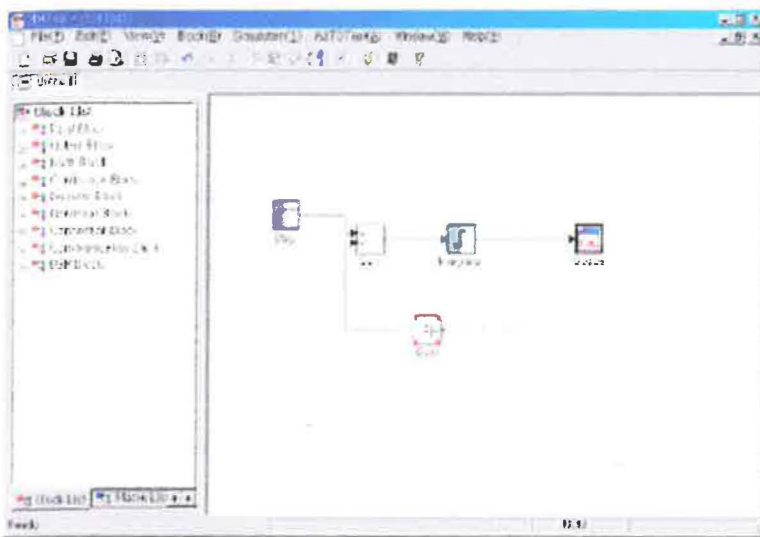
- [16] M.A. Ahmad, (2009). Sway Reduction on Gantry Crane System using Delayed Feedback Signal and PD-type Fuzzy Logic Controller: Comparative Assessment: A.Survey.*ICCA*. Universiti Malaysia Pahang
- [17] M.A. Ahmad, M.S. Ramli, R.M.T. Raja Ismail, Infinite Impulse Response Filter Technique for Sway Control of a Lab-scaled Rotary Crane System: A.Survey: *Faculty of electrical and Electronics Engineering*, Universiti Malaysia Pahang

APPENDIX A

Figure of Swing-Up Inverted Pendulum System



APPENDIX B**Manual Pendulum Designer**




[Figure 2.17] Completion of the connection from the line to the block

[3] Moving and Deleting Line

Moving Line

If you want to move the lines between blocks, spot and select the line that you want to move with the left button of the mouse. The selected line is displayed with the blue square dots. If you move while pressing the left button of the mouse on the line that you want to move the line moves along the mouse. At this time, the line can be moved upward, downward, left and right. When the line is moved, the dot mark that the line is divided from one line and the mark (→) that the lines cross remains in the original position and are marked again after the completion of the line movement.

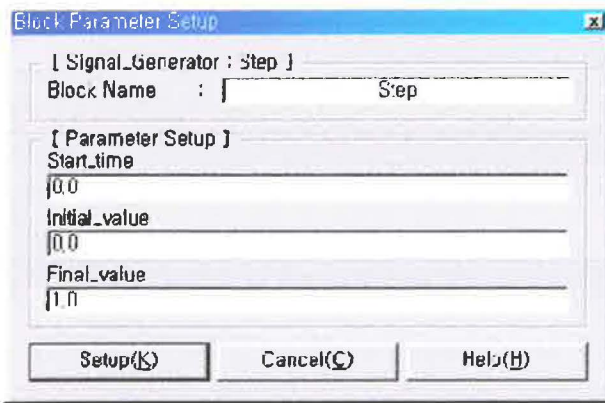
Deleting Line

How to delete the line between blocks is the same as how to delete the block. Select the line that you want to delete as pressing the left button of the mouse and press Delete key on the keyboard, press the icon  on the toolbar or press 'Edit-Delete' on the menu and the line that you want to delete is disappeared. In addition, you can delete the line as selecting 'Delete' on the menu of the right button of the mouse while the line is selected.

2.2.4 Setup of Block Parameter

For modelling, bring the blocks to the work window and connect. Next, you need to change the parameters that are set up as the default in each block to make the signal that you want. Double click each block with the mouse, and the dialogue box for the block parameter setup are displayed as shown in [Figure 2.18]. 'Block Name' is the

general item in the dialogue box. The number of parameters below are varied in accordance with the functions of each block, Enter the appropriate parameters to use the functions that you want and press 'Setup' button. Then, the setup is completed.



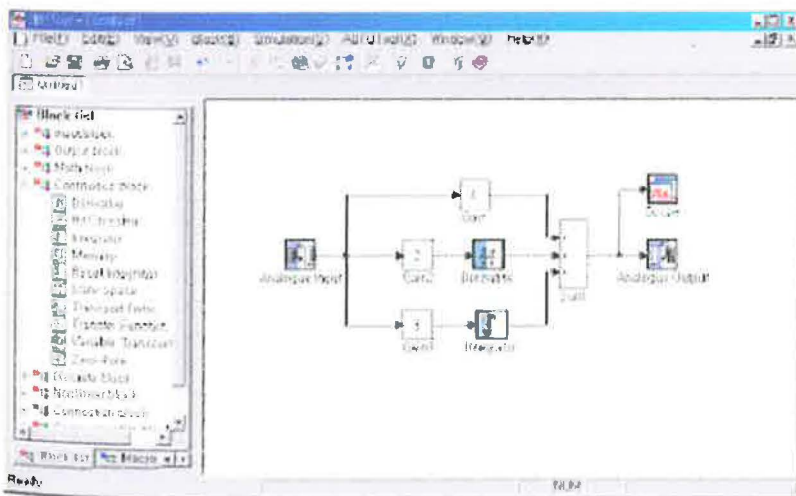
(Figure 2.18) Dialogue Box for Block Parameter Setup

[Example 2]

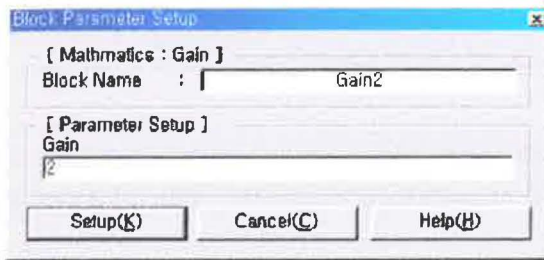
Connect each block in [Example 1] to make the configuration as same as [Figure 2.19]

(Solution)

The order to connect the lines are not defined, but connect each block as dragging and connecting as shown in [Figure 2.19]. After connecting, enter 1, 2, 3 in turn in the dialogue box that is displayed as you double click Gain block. [Figure 2.20] illustrates the completion of setup in the setup dialogue box of Gain2 block. The sum block has three inputs and all have '+' symbol. Then, set up as shown in [Figure 2.21].



(Figure 2.19) Exercise to set up the block line connection result parameters



[Figure 2.20] Setup of Gain2 Block Parameter

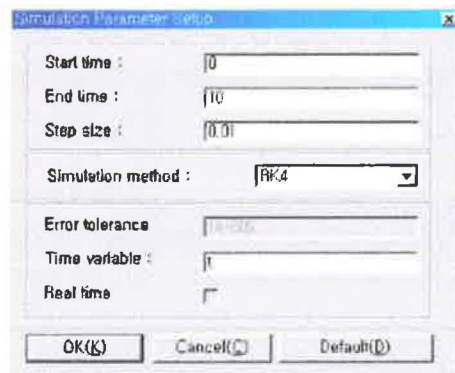


[Figure 2.21] Setup of Sum Block Parameter

2.3 Configuring and Executing Simulation

2.3.1 Simulation Configuration

After completing the parameter setup of each block, you need to set up the parameter for the execution of simulation. Select 'Execution-Setup Execution' on the menu, and you can set up the simulation parameters as shown in [Figure 2.22]. The parameters to set up for the simulation that you want are as follows.



[Figure 2.22] Dialogue Box to Set up Parameters for Simulation

[1] Starting Time/Ending Time

It means time to start and to end the simulation. The unit is 'seconds' and the initial setup times are 0 and 10 seconds respectively.

[2] Sampling Time

It means the time interval for simulation calculation. When you minimize the step size, the precision can be increased but time required for simulation is extended. The initial setup value is 0.01 sec.

[3] How to Execute Simulation

You can select the calculation algorithm for simulation. You can select one of four calculation algorithms, RK4(Runge-kutta 4次), RK3(Runge-kutta 3次), Adams and Euler. The simulation time is increased in the order of RK4 > RK3 > Adams > EULER, and the precision is increased in the same order.

[4] Error Tolerance

It is the value to adjust the error that can be included in the simulation result. The smaller the error tolerance is, the less error is included but the longer simulation time is required. The initial setup value is $1e-005$.

[5] Time Variables


After the completion of the simulation, the variables of the defined name that includes the time that the simulation calculation is executed is created in the workspace of CEMTool. These variables are used as the time axis when you plot the simulation result. The predefined name is t.

[6] Real Time Use

The time that you starts and ends the defined simulation and the time interval are not the real time but are calculated respectively during the calculation. That is to say, the time that is required for the simulation is changed in accordance with the amount of calculation. It is sometimes required to use the real time for the defined time parameters. In this case, you can select this option.

2.3.2 Execution of Simulation

If you complete the setup of parameters for the simulation that you want, you can execute the simulation. There are three methods to execute the simulation.

- ▶ Use Menu : Select 'Execute-Execute'.
- ▶ Use Toolbar : Click the execution icon 
- ▶ Use Short Cut : Press F5.

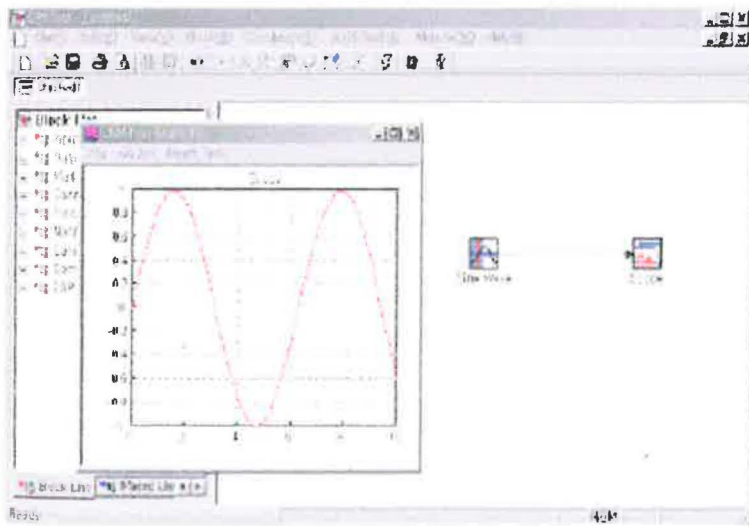
You can execute the simulation with three methods above. If you want to stop the simulation during the simulation, press ESC once and the simulation is stopped as the simulation result up to that point is displayed.

2.3.3 Checking Simulation Result

There are three methods to process the simulation results in SIMTool. First, you can see the result in the graph. Secondly, you can analyze as sending data to CEMTool. Thirdly, you can save data as the file. The method to check the result with the graph uses SCOPE block or XY Plot. The method to send data to CEMTool uses OUT block and the method to save data as the file uses To_File block. Each method is explained as follows.

[1] Seeing Result related to the time axis (Scope)

The scope block illustrates the change of input value of the block related to time with the graph.

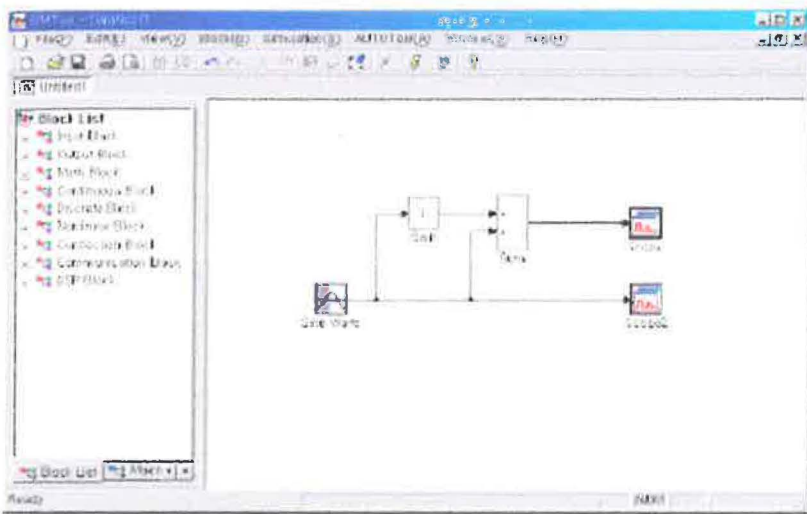


[Figure 2.23] Displaying Graph using Scope Block

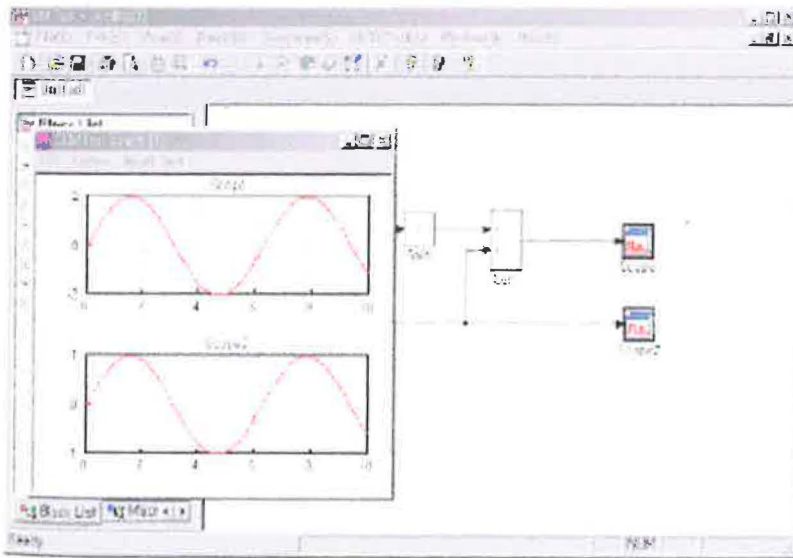
If you set up the parameter of the model that you configure and run it, the plot window is displayed as shown in [Figure 2.23] and the graph is drawn in accordance with the progress of the simulation. The graph scale is initially drawn in accordance with the condition that the maximum value and the minimum value of the y-axis are configured in the block setup dialogue box and when the simulation is completed, its scale is automatically set up and the graph is drawn again in accordance with the configured scale. If you load the scope block in the work window and do not set up anything, the minimum value and the maximum value of the y-axis are 0 and 10 respectively. Therefore, when the graph is drawn for the first time, the y-axis is set up

from 0 to 10 and the graph is drawn.

If you want to see not only one graph but also several graphs in the same block models, you need to separately connect each output block to the scope block as shown in [Figure 2.24]. Then, each graph is displayed in one plot window as shown in [Figure 2.25]. It is convenient function to make you compare the input with the output and the output values as showing several graphs at the same time.



(Figure 2.24) Connecting Two Scope Blocks



(Figure 2.25) Drawing Two Graphs in One Window

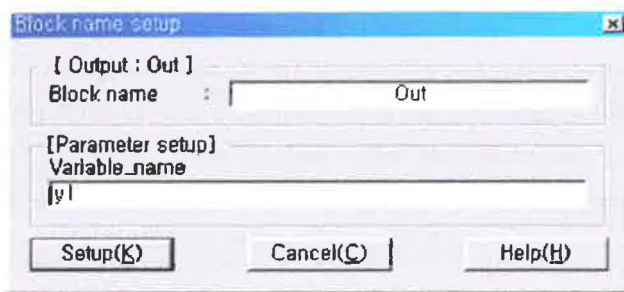
☑ Seeing Result using XY Plot Block

If you want to see not time value but the status value of the model that you want to

simulate, you can see the progress of the simulation using XY Plot block. If you connect XY Plot block to the model, the plot window is displayed as you check by connecting the scope block and you can check the progress of the simulation in the plot window.

[3] Seeing Result using OUT Block

If you want to load the simulation result that is done in SIMTool to CEMTool window and analyze it in detail, you may use the out block. [Figure 2.26] is the dialogue box to set up the block information of the out block. If you enter the variable name that you want to load from CEMTool in 'Variable name', press 'Setup' button and execute the simulation, the change of status value of the model that you configure is recorded in the designated variable name at the interval of the simulation calculation and it is registered as the variable of CEMTool.



[Figure 2.26] Setup of Output Variable of OUT Block

Execute the simulation of the model and enter the command "list" in the work window of CEMTool. This command "List" shows the variables list that are saved in the current work window of CEMTool. Then, you can see the name of variables that you set up and the variable 't' that you never enter. (See [Figure 2.27]) Those variables are created during the simulation. Time vectors that are arranged at the defined interval from the starting time to the ending time of the simulation are entered in 't' and the input value to the out block that corresponds to each moment of the time vector that is saved in 't' is entered in the variable name that you enter. You can change the names of these variables in SIMTool. You can define the name of the variable 't' that saves the time vector in Time Variable among the menus in the dialogue box where you set up the parameters for the simulation in [Figure 2.22]. You can define the name of the variable that saves the result values as opening the dialogue box to set up the blocks for the out blocks. If there is no special definition, the predefined 't' and 'y1' are created as the name of the variables.

You can analyze the variables that are created by the out block in the workspace of CEMTool in various ways. As the simple example, you can draw the graph using the command Draw in CEMTool. Enter as follows in CEMTool.

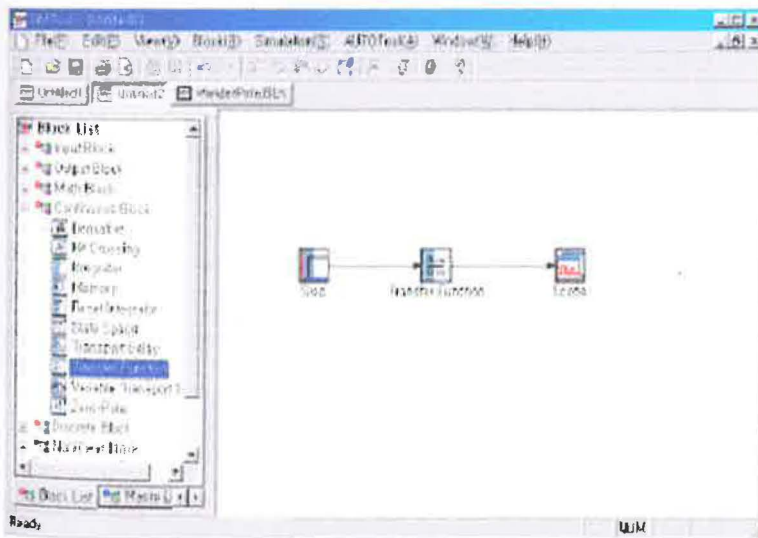
2.4 How to Configure Models (Differential Equation by SIMTool)

Let's configure the following step responses as the graphic block with SIMTool,

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

[1] Selection and Connection of Blocks

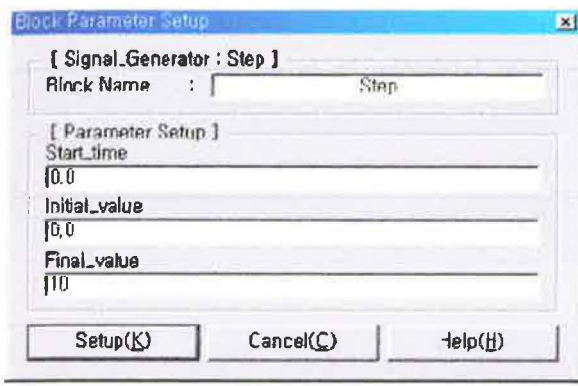
In order to configure the transfer function above with SIMTool, bring the step block into SIMTool work window from the input block window. Next enter the coefficient of Transfer Function that is modeled in the continuous time. Select the transfer function blocks that transmit the output in accordance with the input signals that are entered into the blocks in the continuous block window. After that, move the scope blocks to the work window in order to output the time graph for the calculation result. Finally, arrange and connect each block as shown in [Figure 2.29].



[Figure 2.29] Obtaining Step Response of Transfer Function of Open Loop

[2] Block Parameter Setup

After bringing the required blocks to the work window and connecting them, set up the parameter values of the step blocks and the scope blocks as shown in [Figure 2.30] and [Figure 2.31].

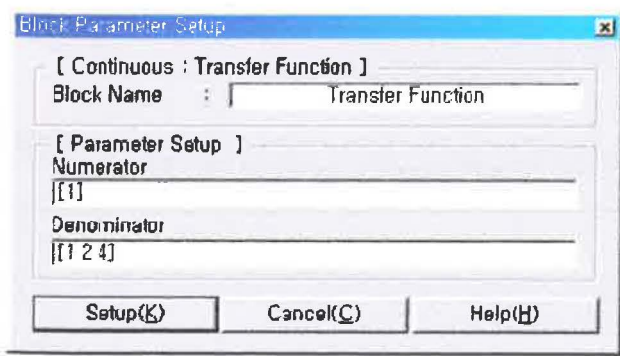


[Figure 2.30] Step Block Parameter Setup



[Figure 2.31] Scope Block Parameter Setup

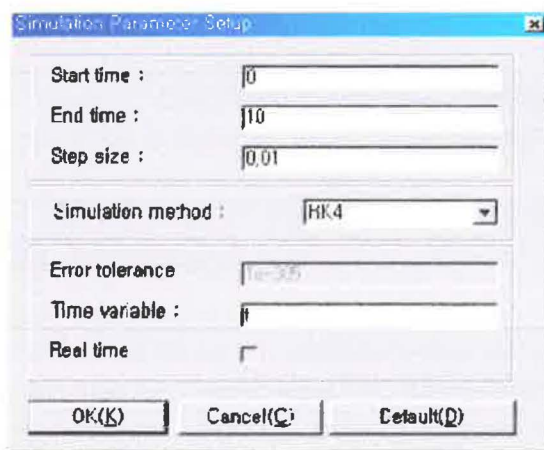
Enter and set up '[1]', numerator coefficient of the transfer function, in the numerator value and '[1,2,4]', denominator coefficient, in Denominator as shown in [Figure 2.32].



[Figure 2.32] Transfer Function Block Parameter Setup

[3] Simulation Setup

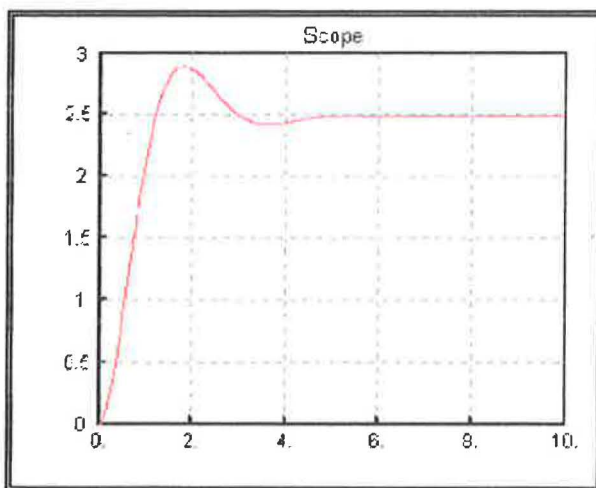
After completing the block setup, set up the simulation parameter as explained in the paragraph 2.3.1 as shown in [Figure 2.33]. Select RK4 as the numerical analysis algorithm and close the parameter setup window.



[Figure 2.33] Simulation Parameter Setup

[4] Execution

Press the simulation execution button to run the simulation. And the step response that you want to obtain is as shown in [Figure 2.34].



[Figure 2.34] Step Response of Transfer Function

3. AUTOTool

AUTOTool is the user-friendly C-Code generator for the block files that the user makes by using SIMTool. You can execute the real-time simulation as directly downloading to DSP board using C-Code in AUTOTool. In addition, you can execute the real-time control test for the real plants through input and output boards. In this simulation, we will create C-Code in the generator algorithm using AUTOTool, download it to DSP board and execute the control simulation for the pendulum system in real time.

3.1 How to Use AUTOTool

According to the following procedure, the block algorithm that the user configure by SIMTool is automatically converted to the common C-Code and can be downloaded to DSP board. After configuring the control algorithm and connecting the communication block of SIMTool in accordance with the purpose of input and output parts, use AUTOTool in accordance with the following procedure. Then, the real-time control simulation can be executed through the input and output boards.

[Step 1] Algorithm Configuration using SIMTool

Configure the block algorithm using SIMTool and set up each block in accordance with the purpose.

[Step 2] AUTOTool Configuration Setup

Select 'AUTOTool Parameters' in SIMTool menu or press SHIFT+H. Then, 'Hardware Interface' window is appeared as shown in [Figure 2.35].



[Figure 2.35] Hardware Setup Window

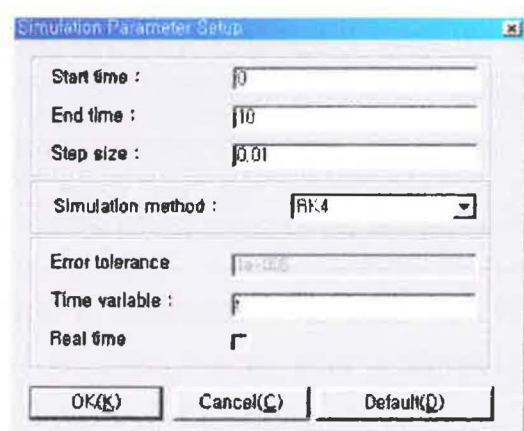
The setup in 'Hardware Setup Window' is done as follows.

- ▶ DSP/IO Board : Select the type of DSP/IO board to use
- ▶ Compile Mode : Select DSP for the calculation using DSP
- ▶ DSP Board : Select the type of DSP board to use
- ▶ IO Board : Select the type of input and output boards to use
- ▶ Parameter Setup : Set up the starting and ending time of simulation and the sampling time
- ▶ View C Code : It shows C-Code that is created using AUTOTool.
- ▶ C-Code Generation and Compile : Convert the algorithm that is configured through SIMTool using AUTOTool into C-Code and at the same time, transplant C-Code into DSP board.
- ▶ Execution : Operate the algorithm that is transplanted to DSP board and then operate the system as applying the algorithm that the user configures.

Select "RG-DSP[001]" for DSP/IO board in this simulation, but do not select DSP board and input and output boards.

[Step 3] Execution Time Setup

Press 'Parameter' menu and 'Simulation Parameter Setup' window is displayed as shown in [Figure 2.36]. You can set up the starting and ending time of the simulation, the sampling time and whether to use the time variable and the real-time.



[Figure 2.36] Simulation Parameter Setup Window

4. DSP Function of RG-DSPIO01

RG-DSPIO01 board enables the rapid operation and the real time simulation using DSP function. This simulation executes the control of the pendulum through the real time simulation that uses DSP function and input/output function of RG-DSPIO01 at the same time.

[Table 3.6] DSP Specification of RG-DSPIO01

Division		RG-DSPIO01
Processor	Main Processor	TMSC320C32
	Operating Frequency	60 MHz
Memory	ROM	128 Kbyte
	Normal SRAM	128 Kbyte (or 512 Kbyte)
	Fast SRAM	256 Kbyte
Serial Communication	Controller	Z85C30
	No. of Ports	1
Interface		PCI BUS

5. Input/Output(Communication) Block Setup

Use the input/output function of RG-DSPIO01 board using the analogue output and analogue input block, the digital input and output block and encoder block among communication blocks of SIMTool. Let's learn how to use and set up each block.

5.1 Analogue Input & Analogue Output Block Parameter

The block that receives the signal from the plant in SIMTool is the analogue input block. The block that transmits the signal to the plant is the analogue output block. The followings are the meaning of each block parameter.

(1) Analogue Input Block

- ① channel_num : Channel number(0-7) of Input/Output board
- ② low_voltage : Minimum voltage required for the input/output board(within the limits that are set up in ③)
- ③ high_voltage : Maximum voltage required for the input/output board(within the limits that are set up in ③)

④ **low_input** : Minimum mapping value of voltage that the input/output board transmits to PC

⑤ **high_input** : Maximum Minimum mapping value of voltage that the input/output board transmits to PC

⑥ **Selection of Voltage Limit**: Select the input voltage limit that is set up in the input/output board

(2) Analogue Output Block

① **channel_num** : Channel number(0-7) of Input/Output board

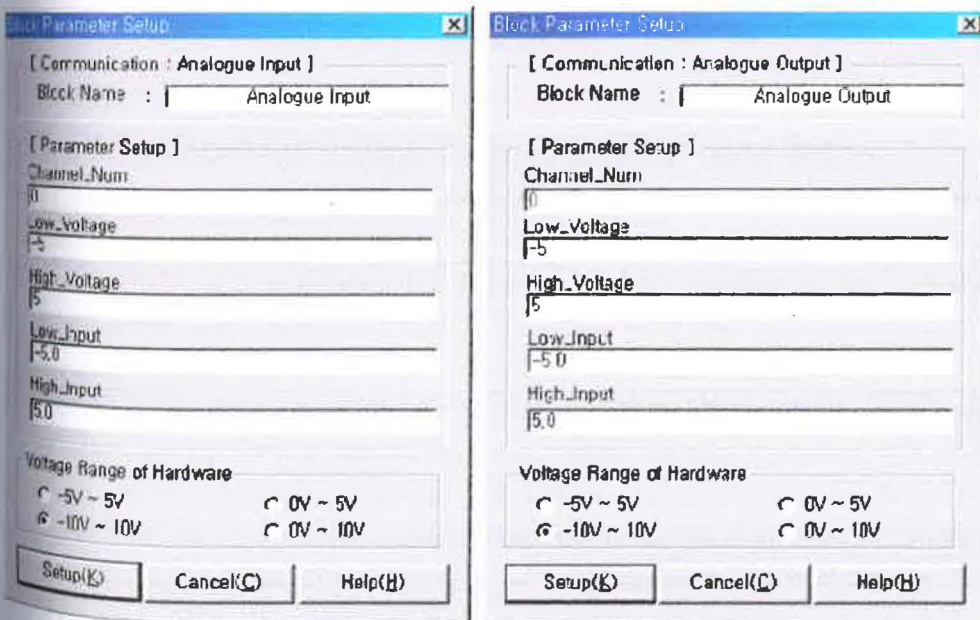
② **low_voltage** : Minimum voltage required for the input/output board(within the limits that are set up in ⑥)

③ **high_voltage** : Maximum voltage required for the input/output board(within the limits that are set up in ⑥)

④ **low_input** : Minimum mapping value of voltage that PC outputs through the input/output board

⑤ **high_input** : Maximum mapping value of voltage that PC outputs through the input/output board

⑥ **Selection of Voltage Limit**: Select the output voltage limit that is set up in the input/output board



[Figure 3.4] Analogue Input & Analogue Output Block

5.2 Scaling Principle

The value that SIMTool receives depends on the volume of the input and output

voltage that is changed in accordance with the setup value of the analogue input or output block parameter of SIMTool. Setting the volume of the input and output is called Scaling. This paragraph will explain how the volume of input and output is changed in accordance with the parameter that is set up in the analogue input or output block of SIMTool.

5.2.1 Relation between Voltage Limit and Input/Output Board

We need to know the relation between maximum and minimum input/output voltage of the actual plant (pendulum system or AC servo trainer Kit, etc.) and the input/output value on the input/output board. The input/output resolution of RG-DSPIO01 is 16bit and the value that RG-DSPIO01 can receive is 2^{16} , that is to say, 65536. The value that RG-DSPIO01 is 2^{16} , that is to say, 65536. Therefore, the input/output voltage on RG-DSPIO01 is converted into 65536 values (0 ~ 65535).

(Example) Minimum voltage of the plant is -5v and the maximum input/output voltage is +5v.

If the mapping value for 16bit input/output board is -5v, the voltage is 0x0(0) and if the mapping value is +5v, the voltage is 0xffff(65535).

5.2.2 Low voltage/High voltage & Low input/High input Setup

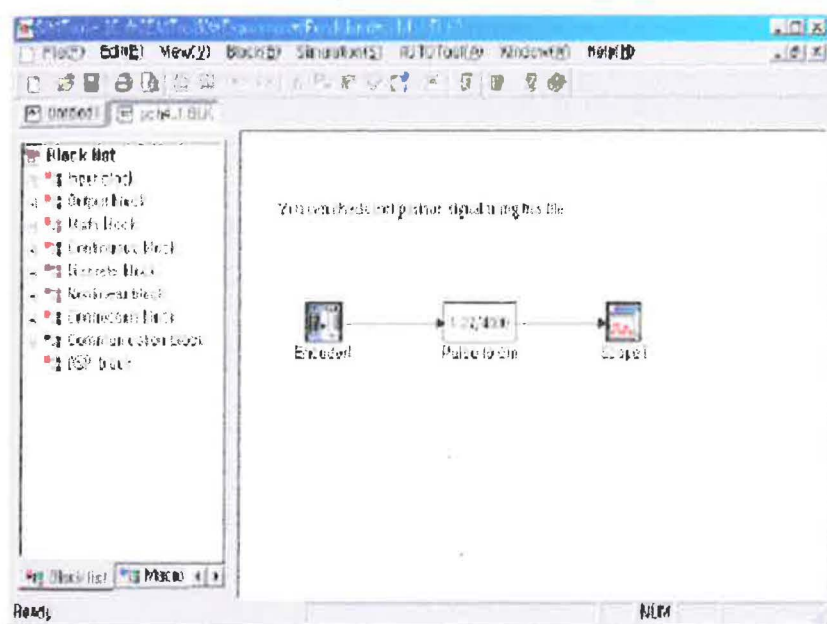
The low voltage and the high voltage are the parameters that you can set up the minimum and maximum value of the voltage within the voltage limits that are configured on the input and output board among the input variables of the analogue input and output block parameters of SIMTool. That is to say, you can adjust the input/output voltage limits of the plant within the voltage limits of input/output board and you can select the appropriate value for the adjustment. However, the value may be different from the physical quantity that you want to calculate. Therefore, you need to set up the value to be converted into the physical quantity that you consider. The parameters that are set up in the analogue input and output block of SIMTool for this purpose are Low Input and High Input. The low input means the physical quantity for the low voltage and the high input for the high voltage. In addition, this parameter value does not have any limits for setup.

3.1 Pendulum Cart Location Signal Check

Reference Files : pch4_1 blk (X:\CEMWare\Experiment\Pendulum\pch4_1.blk)

[Step 1] Block Configuration

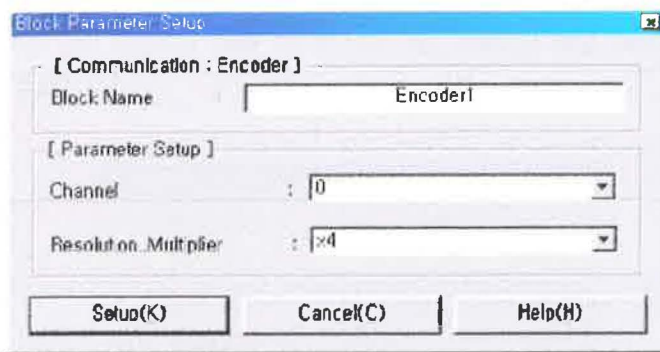
Firstly configure the blocks in SIMTool work window as shown in [Figure 4.4]. At this point, Pulse to cm block is to convert the pulse signal of the encoder into the displacement(cm) of the cart using the gain block.



[Figure 4.4] Block Configuration to See Pendulum Cart Location Signal (pch4_1 blk)

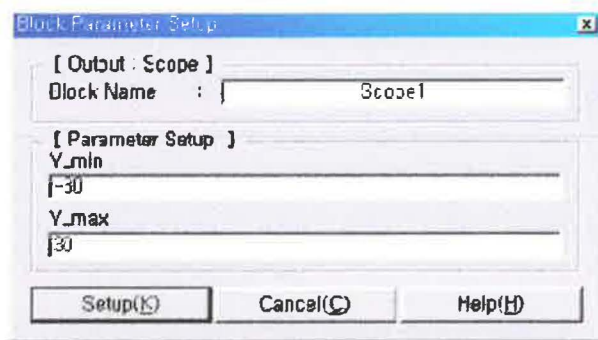
[Step 2] Block Parameter Setup

The cart location converts the pulse that is measured by the encoder into the length (cm) in the pulse to cm block. The location signal of the cart is received from the channel number 0 so that the encoder block is set up as shown in [Figure 4.5].



[Figure 4.5] Encoder Block Setup

Set up the scope block from the minimum value -30 to the maximum value 30 in accordance with the displacement of the cart as shown in [Figure 4.6]. The unit of the displacement is cm.



[Figure 4.6] Scope Block Setup

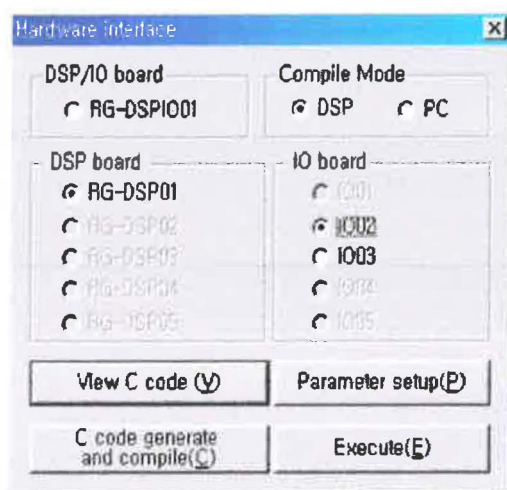
If you set up the encoder block as shown in [Figure 4.6], it is configured to receive the encoder pulse as 4 multiplies. It means that the encoder is configured to receive 4,000 pulse per rotation of the motor. In addition, the ball screw of the pendulum system moves 1.27cm per rotation so that gain block (Pulse to cm) is set up as '1.27/4000'. You can apply the formula(4.1) in accordance with the setup of the resolution multiplier (multiply) item of the encoder block. At this point, the multiplier is 1, 2 or 4 and the number of encoder pulse that is used in this experiment is 1,000 pulses.

$$\frac{1.27}{\text{Number of Encoder Pulse} \times \text{Multiplies}} \quad (4.1)$$

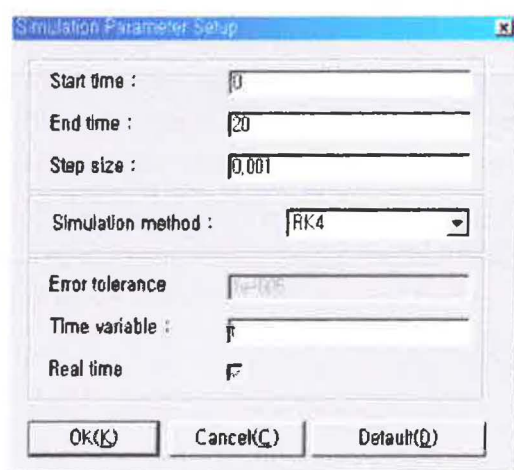
[Step 3] Hardware Setup/ C-code Generation / Transportation to DSP

Select 'AUTOTool- Parameter' in SIMTool menu for the hardware setup and set up the hardware as shown in [Figure 4.7]. Set up the execution time in the setup window

that is displayed as pressing 'Parameter Setup' button of [Figure 4.7]. As shown in [Figure 4.8], set up the starting time as 0 sec., the ending time as 20 sec, and the sampling time as 0.001 sec,



[Figure 4.7] AUTOTool Configuration Setup



[Figure 4.8] Execution Time Setup

After you set up the execution time, press 'C-Code Generation and Compile' button in [Figure 4.7] and convert the blocks that you configure with SIMTTool and transfer it to DSP board. After transferring to DSP board, DOS window as shown in [Figure 4.9] is displayed.

```

C:\CENT00150\Work\c138 -g -s -eo .o38 -af -nb d2_main.o38 d2.o38 ode_rk4.o38 Unt
it.c => d2.o38 => Untit.lys
untit.c1
clinking?

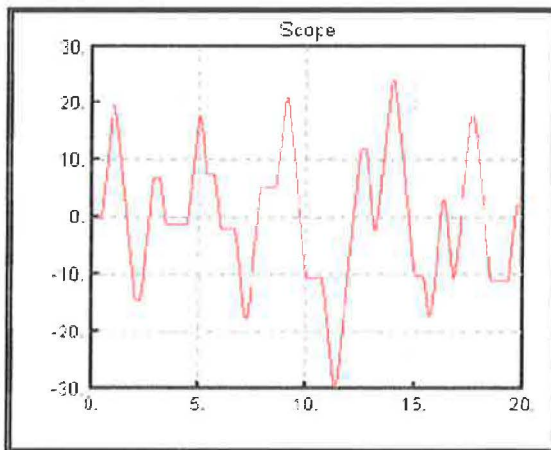
C:\CENT00150\Work\hex38 Untit.lys -o Untit.bin d2hex.cmd
TMS320C3x/4x Hex Converter Version 4.5B
Copyright (c) 1982-1992 Texas Instruments Incorporated
Translating Untit.lys to Motorola-S format...
'Untit.lys' => .text
'Untit.lys' => .const

```

[Figure 4.9] C-code Generation and Compile

[Step 4] Result Check

After completing the transfer to DSP board, close the window in [Figure 4.9] and change the mode to Manual on MODE that is in the electric part of the pendulum. Then, turn the power on and click 'Execution' button in [Figure 4.7]. Finally, the graphic window is displayed. At this time, move the cart location as pressing the left and right button of MOVE. Then, the change of the encoder pulse that is generated in accordance with the cart location as shown in [Figure 4.10] is converted as the length(cm) and is displayed as the graph. In this graph, the x-axis is time (seconds) and the y-axis is the displacement(cm) You can change this graph as moving the cart.



[Figure 4.10] Location Signal of Pendulum Cart

3.2 Pendulum Angle Signal Check

If the pendulum system is connected to the input/output board as shown in [Table

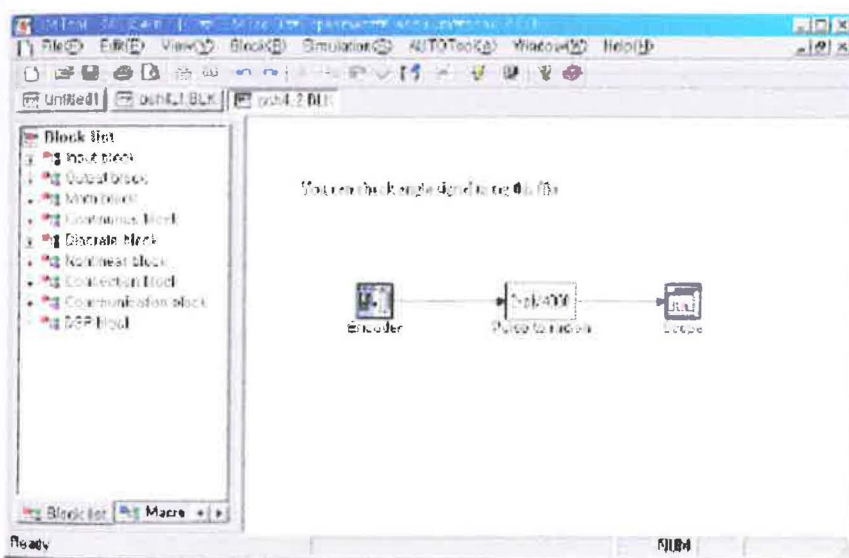
4.4). you can measure the angle signal of the pendulum in accordance with the following order.

(Note) If you execute only the location control experiment of the pendulum motor using this text, you can skip the experiment in the paragraph 3.2.

Reference Files : pch4_2.blk (X:\CEMWare\Experiment\Pendulum\pch4_2.blk)

[Step 1] Block Configuration

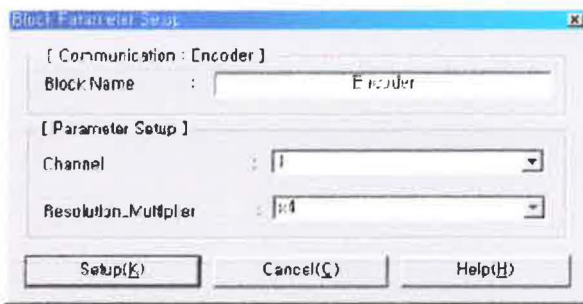
Firstly, bring the scope block from the output block in SIMTool work window, the encoder block from the communication block and the gain block from the operation block and configure the blocks as shown in [Figure 4.11].



[Figure 4.11] Block Configuration to See Angle Signal of Pendulum(pch4_2.blk)

[Step 2] Block Parameter Setup

The pendulum angle is transmitted through the channel no. 1 of RG-DSPIC01 board. Set up as shown in [Figure 4.12] to receive as four multiplies.

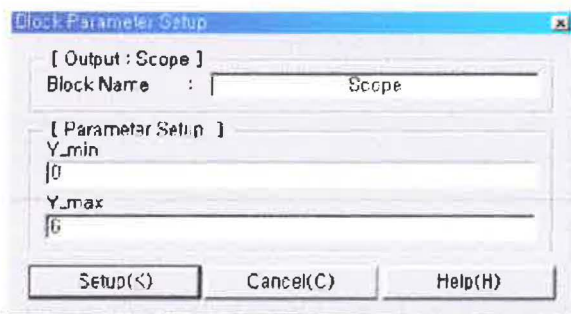


[Figure 4.12] Encoder Block Setup

In addition, set up the gain block (Pulse to radian) as shown in [Figure 4.13] to indicate the pendulum angle as radian. This is because 4,000 pulses are generated in the encoder as the pendulum rotates once and if it is converted as the radian unit, it becomes 2π . Set up the scope block as the pendulum movement is indicated up to about 2π as shown in [Figure 4.14].



[Figure 4.13] Gain Block Setup



[Figure 4.14] Scope Block Setup

[Step 3] Hardware Setup /C-code Generation/ Transferring to DSP Board

Select 'AUTOTool- Parameter' in SIMTool menu for the hardware setup and set up the hardware as shown in [Figure 4.5]. Set up the execution time in the setup window that is displayed as pressing 'Parameter Setup' button of [Figure 4.15]. As shown in

[Figure 4.16], set up the starting time as 0 sec., the ending time as 20 sec. and the sampling time as 0.001 sec.



[Figure 4.15] AUTOTool Configuration Setup



[Figure 4.16] Execution Time Setup

After you set up the execution time, press 'C-Code Generation and Compile' button in [Figure 4.15] and convert the blocks that you configure with SIMTool and transfer it to DSP board. After transferring to DSP board, DOS window as shown in [Figure 4.17] is displayed.

(note) The different window may be displayed instead of DOS window as follows in accordance with CEMWare version.

```

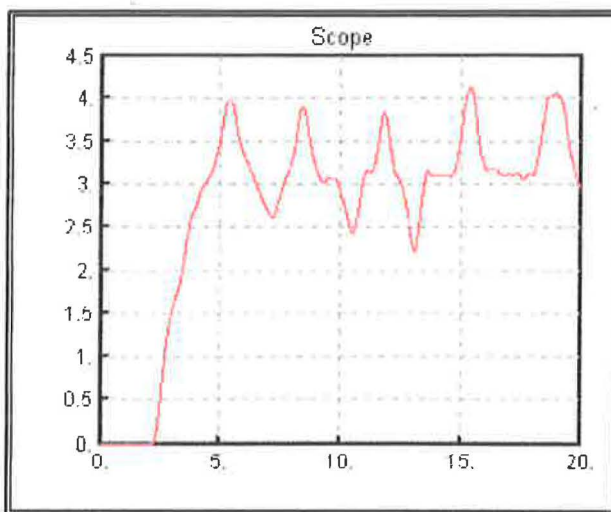
C:\MCE\Tool\EMWork\hew38\q -> res_020 -rd /nb 02_0win_020 02_020 nca_040_020 Unt
it.c -> 02.cod -> Unit1.lys
Unit1.c1
(Linking)
C:\MCE\Tool\EMWork\hew38 Unit1.lys -> Unit1.bio d2hex.cod
Int.EDK/32/32 Hex Converter Version 4.50
Copyright (c) 1987-1992 Texas Instruments Incorporated
Translating Unit1.lys to Motorola's Format...
"Unit1.lys" ==> .text
"Unit1.lys" ==> .const

```

[Figure 4.17] C-code Generation and Compile

Step 4) Result Check

After completing the transfer to DSP board, close the window in [Figure 4.17] and change the mode to Manual on MODE that is in the electric part of the pendulum. Then, turn the power on and click 'Execution' button in [Figure 4.7]. Finally, the graphic window is displayed. At this time, move the cart location as pressing the left and right button of MOVE. Then, the change of the encoder pulse that is generated in accordance with the cart location as shown in [Figure 4.18] is converted as the angle(cm) and displayed as the graph. In this graph, the x-axis is time (seconds) and the y-axis is the displacement(cm). This graph can be changed by how a person moves the cart.



[Figure 4.18] Angle Signal of Pendulum

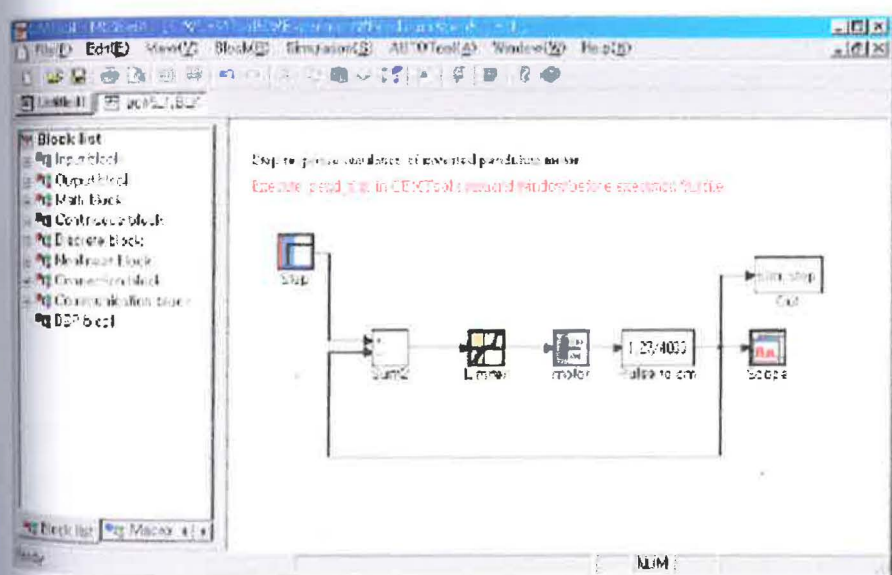
3. Simulation (Step Response)

Reference Files : pend_tf.m (X:\CEMWare\Experiment\Pendulum\pend_tf.m)
pch5_1.blk (X:\CEMWare\Experiment\Pendulum\pch5_1.blk)

(Note) You need to execute pend_tf.m file in CEMTool window to load the models of the pendulum for this simulation.

(Step 1) Connection of Step Input Block and Output Block(Scope, Out)

Configure the reference file pch5_1.blk to be the closed loop using the transfer function block(reference file pch1_3.blk) of the pendulum motor that is configured by SIMTool in the paragraph 5.2.1 of Chapter 4 as shown in [Figure 5.7]. Use the step block to insert the step input into the model of the pendulum motor and connect the out block in order to compare the simulation result to the experiment result.



[Figure 5.7] Step Response Simulation Block (pch5_1.blk)

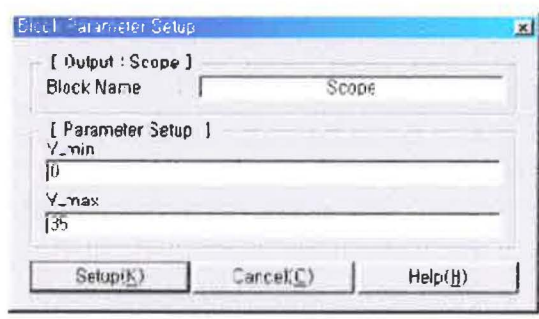
(Step 2) Block Setup

Set up the step input block in the block setup window as shown in [Figure 5.8]. In this case, the size of input can be decided as you want. However, the maximum displacement range of the cart in the pendulum system is about 35 cm to the left and right side. Therefore, it is recommendable to set up the range within 30cm. The step is set up from the initial value 0 to move the cart 30cm after one second. In

In addition, set up the minimum value of the scope block as 0 and the maximum value as 30 that is determined in the step. Set up the maximum and minimum value of the limiter block as 24 and -24 respectively. And set up the coefficient of the transfer function as executing pend_tf.m file in CEMTool command window for the transfer function block.

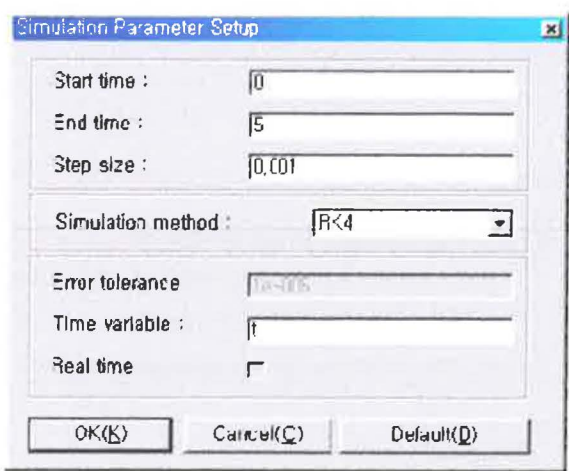


[Figure 5.8] Step Input Setup



[Figure 5.9] Scope Block Setup

[Step 3] Simulation Time Setup



[Figure 5.10] Simulation Time Setup

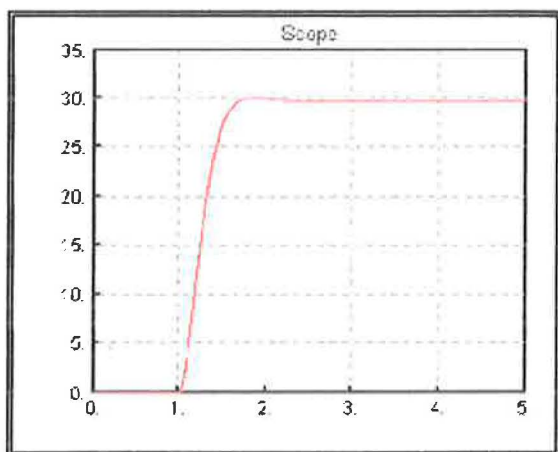
If you complete the block setup to check the step response, you need to set up the simulation time. You can set up the simulation time as you want, but set up as 5 seconds for the simulation. The simulation interval can be set up as you want, however, set up the same interval as the sampling time to use later in the experiment and it is set up as 0.001 sec, to be used in the experiment here.

Step 4) Execution and Result Check of Simulation

Press the simulation execution button, and the graph window is displayed. After the completion of the simulation, you may check the graph window as shown in (Figure 5.11). Close the graph window and execute the following commands in CEMTool.

```
plot(sim_step)
```

If you execute the command above, the simulation result is saved in the variable `sim_step` and the graph is generated as shown in (Figure 5.11).



[Figure 5.11] Step Response Simulation Result

experiment

reference Files pend_jo.m (X:\CEMWare\Experiment\Pendulum\pend_jo.m)

pch5_2.blk (X:\CEMWare\Experiment\Pendulum\pch5_1.blk)

initial.blk (X:\CEMWare\Experiment\Pendulum\initial.blk)

comp_step.m (X:\CEMWare\Experiment\Pendulum\comp_step.m)

The simulation in the paragraph 3 shall be completed before the execution of the

reference files. If the simulation in the paragraph 3 is not executed, the experiment in this paragraph cannot be executed.

Step 1] Power-off and Pendulum Removal of Pendulum System

Firstly, check if the power of the pendulum system is off and separate the pendulum of the pendulum system while the power is off.

Step 2] Experiment Block Configuration

Configure the experiment block as shown in [Figure 5.12] that is the reference file pch5_2.blk using SIMTool in order to get the step response of the actual pendulum motor. Provide the input to the pendulum through the analogue output block. Convert the pulse signal that is transmitted from the encoder block into the pulse to cm block and do the feedback. Therefore, the cart location of the pendulum is converted as the length unit. Connect the out block to the scope block to save the experiment result in the variable exp_step.

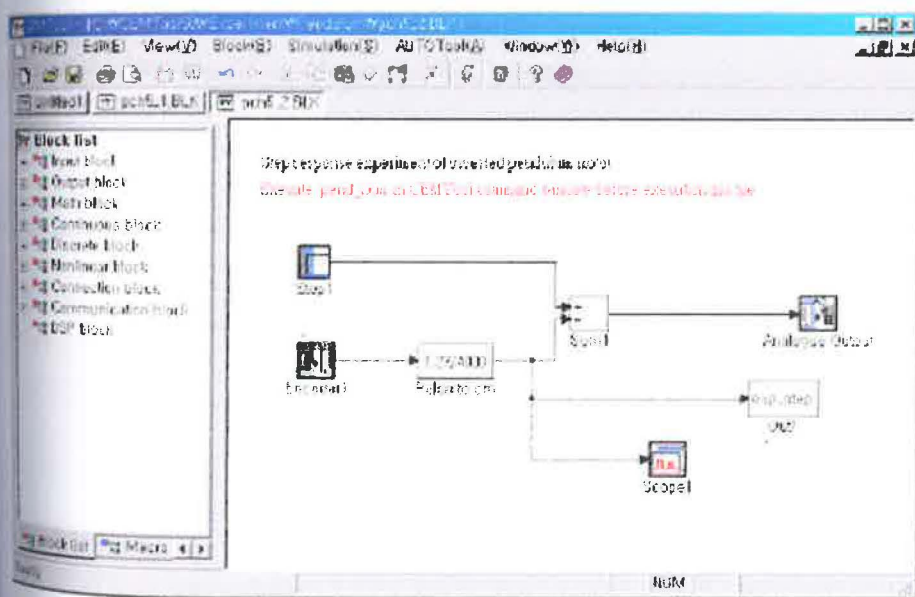


Figure 5.12] Step Response experiment Block Configuration of Pendulum Motor (pch5_2.blk)

Step 3] Block Setup

After you configure the experiment block, set up each block. Set up the step block as shown in [Figure 5.8] like the setup of the simulation. Set up the encoder block to measure as four multiplies through the channel number 0. Set up the gain block with the same Pulse to cm and set up as 1,27/4000. This aims to convert the pulse signal of the encoder into the length unit as considering that the cart moves 1,27cm when the motor rotates once. Set up the scope block as shown in [Figure 5.9]. Set up the out block to

Save the experiment result in the variable `exp_step`. Set up the analogue output block as executing `pend_io.m` file in CEMTool command window.

[Step 4] Hardware Setup and C-Code Generation

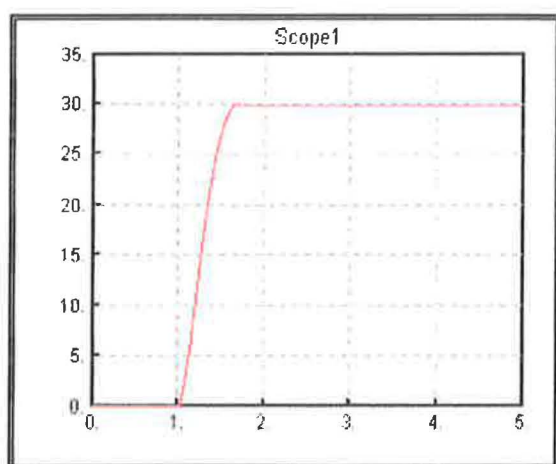
Check if the hardware is set up as RG-DSPIO01 in 'Hardware Interface' window that is displayed as selecting 'AUTOTool- Parameter' in SIMTool menu. Set up the execution time in the setup window that is displayed as pressing 'Parameter Setup' button of the window above. Set up the starting time as 0 sec., the ending time as 20 sec. and the sampling time as 0.001 sec. After completing the execution time setup, press 'C-Code Generation and Compile' in 'Hardware Interface' window, and convert the block that is configured by SIMTool to C-Code. Transfer it to DSP board. After transferring to DSP board, DOS window is displayed.

[Step 5] Power on and Initialization of Pendulum System

If DOS window is displayed, put Mode switch in the electric part of the pendulum system to Manual mode and turn the power on. Initialize the cart location as pressing INITIALIZE button on MOVE. Open the reference file `Initial.blk` and press 'Execution-Execution' button on SIMTool menu or the execution icon. Then, convert Mode switch of the pendulum system to CEMTool mode.

[Step 6] Result Check

After completing the transfer to DSP board and fixing the cart location in the center as the pendulum system is initialized, close DOS window and press 'Execution' button in 'Hardware Interface window'. Then, the scope block is connected to make you check the displacement of the cart. Therefore, the graph window as shown in [Figure 5.13] is displayed.



[Figure 5.13] Step Response experiment Result of Pendulum Motor

save the experiment result in the variable `exp_step`. Set up the analogue output block as executing `pend_io.m` file in CEMTool command window.

[Step 4] Hardware Setup and C-Code Generation

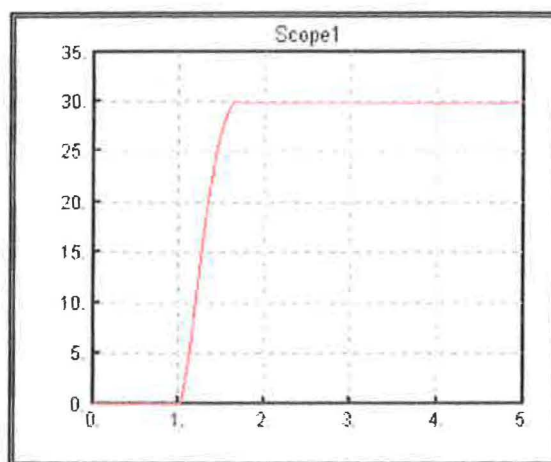
Check if the hardware is set up as RG-DSP1001 in 'Hardware Interface' window that is displayed as selecting 'AUTOTool- Parameter' in SIMTool menu. Set up the execution time in the setup window that is displayed as pressing 'Parameter Setup' button of the window above. Set up the starting time as 0 sec., the ending time as 20 sec, and the sampling time as 0.001 sec. After completing the execution time setup, press 'C-Code Generation and Compile' in 'Hardware Interface' window, and convert the block that is configured by SIMTool to C-Code. Transfer it to DSP board. After transferring to DSP board, DOS window is displayed.

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[Step 6] Result Check

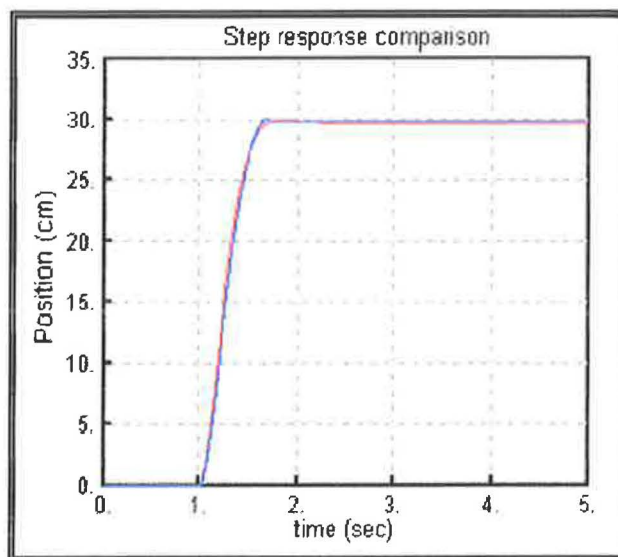
After completing the transfer to DSP board and fixing the cart location in the center as the pendulum system is initialized, close DOS window and press 'Execution' button in 'Hardware Interface window'. Then, the scope block is connected to make you check the displacement of the cart. Therefore, the graph window as shown in [Figure 5.13] is displayed.



[Figure 5.13] Step Response experiment Result of Pendulum Motor

[Step 7] Comparison to Simulation Result

Execute `comp_step.m` file in CEMTool command window to compare the simulation result to the experiment result. However, you shall run the file only in the case that you do not execute other simulation, or experiment right after completing the simulation or the experiment. The graph that the simulation result and the experiment result are drawn is as shown in [Figure 5.14]. The blue line is the experiment result and the red line is the simulation result. As a result of comparing the experiment result to the simulation result, we can recognize that two results are very similar.



[Figure 5.14] Comparison of Simulation experiment and experiment Result