VIBRATION CONTROL OF SINGLE LINK FLEXIBLE MANIPULATOR BY USING PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROLLER AND ACTIVE FORCE CONTROL (AFC) CONTROLLER

AHMAD SYAFIQ BIN SHIRO

This thesis is submitted as a partial fulfilment of the requirements for the award of the Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2013

EXAMINER'S APPROVAL DOCUMENT

UNIVERSITI MALAYSIA PAHANG
FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "*Vibration Control of Single Link Flexible Manipulator By Using Proportional-Integral-Derivative (PID) Controller And Active Force Control (AFC) Controller*" is written by *Ahmad Syafiq Bin Shiro*. "I have examined the final copy of this report and in my opinion, it is fully adequate in terms of language standard, and report formatting requirement for the award of the degree of Bachelor of Engineering. I here with recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering.

Signature :
Name of Examiner : Prof Dr Abdul Ghaffar Bin Abdul Rahman
Date : 26 June 2013

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion this project is satisfactory in terms of scope and quality for the award of Degree in Mechanical Engineering

Signature :
Name of Supervisor : Mr Rosmazi Bin Rosli
Position : Lecturer
Date : 21 June 2012

STUDENT'S DECLARATION

I hereby declare that the work in this report is my own except for quotations and summaries which have been duly acknowledged. The report has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature :
Name : Ahmad Syafiq Bin Shiro
ID Number : MA10102
Date : 21 June 2012

ACKNOWLEDGEMENTS

I would like to express my gratitude and appreciation to all those who gave me the possibility to complete this report. Special thanks is due to my supervisor Mr. Rosmazi bin Rosli whose help, stimulating suggestions and encouragement helped me in all time of simulation process and in writing this report.

I would also like to acknowledge with much appreciation the crucial role to other staff in Mechanical Department, who shared with me an expertise to build the model of simulation system from the mathematical equation and knowledge sharing..

Many thanks go to the all lecturer and supervisors who have given their full effort in guiding the team in achieving the goal as well as their encouragement to maintain the progress in track. My profound thanks go to all classmates, especially to Muhammad Zulhilmi bin Zakaria for spending his time in helping and giving support for the project.

ABSTRACT

Robots are important technology that greatly increases the productivity. In robotics a manipulator is a device used to manipulate materials without direct contact for dealing with radioactive or bio-hazardous materials, or they were used in inaccessible places. In this project, a single link flexible manipulator is used. It will be attached to the DC motor. When DC motor is rotated to certain angle, the single link also will rotate on x-axis. The vibration amplitude is produce directly from the speed of the rotation of the dc motor when it stops. A study to counter this problem had been made to control and maintains the accurate position of the single flexible manipulator. Matlab is software that will be use to conduct the study. The objective of this project to control vibration on the single link flexible manipulator using Proportional Integral Derivative (PID) Controller. Active Force Control (AFC) controller also will be used with PID Controller to compensate the vibration. The system without controller will be compare with the system with controller by the graph. The combination of AFC and PID give the best result in rise time, settling time and steady state error. The proposed controller schemes manage to produce output that able to follow the desired trajectory from 68.2 percent overshoot to zero percent overshoot.

ABSTRAK

Robot teknologi penting yang akan meningkatkan produktiviti. Robotik manipulator adalah alat yang digunakan untuk memanipulasi bahan-bahan tanpa hubungan secara langsung untuk berurusan dengan bahan-bahan radioaktif atau bio-berbahaya, atau mereka telah digunakan di tempat-tempat tidak boleh diakses. Dalam projek ini, satu link manipulator fleksibel digunakan. Ia akan dihubungkan dengan DC motor. Apabila DC motor diputar untuk sudut tertentu, link manipulator juga akan berputar pada paksi-x. Amplitud getaran menghasilkan langsung dari kelajuan putaran motor AT apabila ia berhenti. Satu kajian untuk menangani masalah ini telah dibuat untuk mengawal dan mengekalkan kedudukan tepat link manipulator fleksibel. Matlab adalah perisian yang akan digunakan untuk menjalankan kajian ini. Objektif projek ini untuk mengawal getaran pada pautan tunggal manipulator fleksibel menggunakan pengawal *Proportional Integral Derivative (PID)*. *Pengawal Active Force Control (AFC)* juga akan digunakan dengan pengawal PID untuk mengimbangi getaran. Sistem tanpa pengawal akan bandingkan dengan sistem dengan pengawal melalui graf. Gabungan AFC dan PID memberikan hasil yang terbaik dalam masa naik, menetap masa dan ralat keadaan mantap. Dengan pengawal ini, output sebenar sistem ini adalah sama seperti output yang dikehendaki.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFC	Active Force Control
PID	Proportional-Integral-Derivative
DC Motor	Direct Current Motor
KCL	Kirchhoff's Current Law

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Technological development offers new possibilities to make people's daily lives more healthy, safe, understandable, independent, fun and comfortable. New technologies provide us, for instance, with energy-friendly and sustainable solutions to improve the environment in which we live as well as tools for elderly people to live longer on their own. To make continuous production of new technology, factories opened their doors to modern industrial robots.

Robot factory workers are not without their limitations. In their simplest forms, industrial robots are mere automatons. Humans program them to perform a simple task, and they repeat that task over and over again. Tasks that require decision-making, creativity, adaptation and on-the-job learning tend to go to the humans. For instance, Australia's Drake Trailers installed a single welding robot on its production line and benefited from a reported 60 percent increase in productivity (ABB Australia, 2010).

1.2 PROJECT BACKGROUND

Robots are important technology that greatly increases the productivity. Robotic are being used in the high-value areas such as automobile manufacturing. Robotic can eliminate the problems of social security such countries competing for pool of workers and lack of workers due to old age.

Robotics is the branch of technology that deals with the design, construction, operation and application of robots and computer systems for their control, sensory feedback, and information processing. These technologies deal with automated machines that can take the place of humans, in hazardous or manufacturing processes, or simply just resemble humans.

In robotics a manipulator is a device used to manipulate materials without direct contact for dealing with radioactive or bio-hazardous materials, using robotic arms, or they were used in inaccessible places. Most of the existing robotic manipulators are designed and build in a manner to maximize stiffness in an attempt to minimize the vibration of the end-effectors to achieve good position accuracy.

There are several type of manipulator. They are single link flexible manipulators, two link flexible manipulator and multi link flexible manipulator. Single link manipulator is a link which did not have any join on it. The movement of the link is directly based on the rotation of the dc motor. Two link flexible manipulator have two joint on the link. Both join can be rotate by a controller.

In this project, a single link flexible manipulator is used. It is in a cantilever condition which first ending link will attach with a dc motor and the other end point is free condition. When dc motor is rotated to certain angle, the single link also will rotate on x-axis. The vibration amplitude is produce directly from the speed of the rotation of the dc motor when it stops. Because of being lighter and more flexible, the robot is unable to reach the precise position at high speed because of vibration (Zhang Tiemin, Liu Youwu:1996). A study to counter this problem had been made to control and maintains the accurate position of the single flexible manipulator.

Matlab (matrix laboratory) is software that will be use in the study. It is a numerical computing environment and fourth-generation programming language. Many would claim that its biggest benefit is that it is a mature program that is heavily supported and allows for quick prototyping of design ideas. For example, there is a design of a control system, using Matlab, it can quickly create a plant model and start experimenting with a controller such as a PID system. Without ever building the system, Matlab can obtain the ideal control parameters subject to some set of constraints. Later the person in charge could then see bode plots and such all within the same environment.

1.3 PROBLEM STATEMENT

A manipulator is a device used under human control to manipulate materials without direct contact. The materials are often heavy, radioactive, bio hazardous or in inaccessible places. However, in a movement there is vibration. In design and analysis of robot manipulator, it is common practice to assume that the system is structural rigid. This assumption is justified since all mechanical devices are subject to deformation under loading hence an inherent requirement of design is to stiffen the mechanical structural at the expense of performance. In order to overcome these effects controller of single link have been proposed.

1.4 OBJECTIVE

In industry, there are problems of arm vibration during high speed motion. This situation had puts a lot interest to researcher to counter the problem for industries application. The objective of this project to control vibration on the single link flexible manipulator using Proportional Integral Derivative (PID) Controller. Active Force Control Controller also will be used with PID Controller to compensate the vibration.

1.5 SCOPE

To control the study parameter, a scope is made to prevent outside course that may influence the study. The scopes are:-

1) This project chose a single link flexible manipulator as the system to control.
2) PID and AFC controller will be applied to compensate the vibration on a single link flexible manipulator.
3) Matlab is use as a medium to create the experiment with PID and AFC controller.
4) It is a first degree of freedom system since the manipulator move on one axis.
5) Angle rotation is 0-90 degree.

1.6 THESIS ARRANGEMENT

This project report consists of 5 chapters. Chapter 1 begins with an overview of effect of vibration in robotic system. Objectives and Scope of the case study are also well defined. Subsequently, some relevant literature is reviewed to justify the significance of this study.

Chapter 2 will be the literature review on a single link flexible manipulator controller. It also will focus in vibration control to reduce displacement on the single link arm. Others than vibration scope, a theory and mathematical equation will be defined. Finally, relevant research and previous journals will be summarized with emphasis on the strengths and gaps.

Chapter 3 will discuss about the methodology of the thesis, including types of data to be controlled, tools and techniques used to solve the vibration problem and improve performance trajectory launching in PID Controller.

Chapter 4 will be the result of study. The result will be obtain under simulation process and will be improve to get better trajectory. The result will be analyzed study the improvement will achieve of the proposed controller compare to passive control part.

Chapter 5 will discuss about the conclusion of the project, concluding all the process that involved. A recommendation also will be included for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In order to improve industrial productivity, it is required to reduce the weight of the arms and/or to increase their speed of operation. For these purposes it is very desirable to build flexible robotic manipulators. Compared to the conventional heavy and bulky robots, flexible link manipulators have the potential advantage of lower cost, larger work volume, higher operational speed, greater payload-to-manipulator-weight ratio, smaller actuators, lower energy consumption, better maneuverability, better transportability and safer operation due to reduced inertia.

In this chapter, a literature review of single link flexible manipulator is done to understand the modeling system. A discussion of general method of controlling manipulator and vibration problem will be issued. Then, a PID controller and AFC controller is use to counter the vibration problem on the single link flexible manipulator.

2.2 ROBOT MANIPULATOR

From Robot Institute of America, robot manipulator is a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of task. In British Robot Association, they said that robot manipulator is a reprogrammable device with minimum of four degree of freedom designed to both manipulate and transport parts, tools, or specialized manufacturing implements through variable programmed motion for performance of specific manufacturing task. From those definition, it define that robot is thing help to make the job easy and improve work performance and efficient.

Robotic has achieved its greatest success to date in the world of manufacturing industry. Robot arm or manipulator comprises a 2 billion dollar industry. The robot arm can move with a great speed and high accuracy. So it is able to locate at a specific position in assembly line of production such as welding and painting such as at Figure 2.1. Robot technology is advancing rapidly. It can replace human being as regards to physical work and decision making are categorized as robots and their study as robotic.

Figure 2.1: Spot Welding Robot of KUKA

Source: generation5.org

2.3 ROBOT MANIPULATOR AND VIBRATION

Robot manipulators or manipulators have been used in mechanical, aerospace and various other industrial applications. Most of the existing manipulators are designed to maximize stiffness and thereby minimize vibrations so that an accurate position can be achieved. The high level of stiffness makes the manipulator heavy and inefficient in terms of power consumption or operational speed. However, the use of a heavy manipulator is not affordable in some engineering fields: for instance, in an aerospace application where weight restriction is a critical constraint. In contrast to traditional manipulators, flexible manipulators have several advantages such as lower cost, higher operational speed, lower energy consumption, better maneuverability, better transportability, and safer operation due to small inertia of mass. On the down side, flexible manipulators generally have a problem with arm vibrations due to the low level of stiffness; hence, the suppression of vibrations in flexible manipulators has been a key issue in their design and development (Dwivedy and Eberhard, 2006), (Shan, *et.al*, 2005), (Tang, *et.al*, 2006), (Feliu, *et.al*, 1990).

Finding control methods that suppress vibration has been of great interest for many years. Many researchers have concentrated on developing control strategies for design and implementation in various applications. The control strategies for a flexible manipulator can be classified as feedforward control and feedback control. With regard to feedforward control, numerous studies have focused on shaped input control methods. (Bodson, 1996), (Hyde and Seering, 1991). These methods develop the control input for the electric motor in order to suppress vibration; they don't require a sensor or actuator. However, the major drawback of feedforward control methods is the limitation of parametric changes and disturbances (Khorrami, *et.al.*, 1994). With regard to feedback control, there are several control strategies, including a number of different control strategies used to overcome this drawback; these strategies can be classified in terms of the three major aspects of control theory: namely intelligent control (Lewis ,1999), robust control (for instance $H\infty$ control) (Ravichandran, *et.al*., 1993), (Lee, *et.al*, 2006) and adaptive control (Damaren, 1996).

2.4 CONTROL SCHEMES

There are several control schemes such as modal reference adaptive control, self-tuning control, feed-forward control and regular PID control used to regulate the motion of the manipulators. In all these schemes an efficient and accurate mathematical model is necessary (Beres, *et. al.*, 1993). In this section the literature on the control aspects of the flexible manipulator is reviewed only very briefly since other state-of-the-art reviews are available.

Cannon and Schmitz (Cannon and Schmitz, 1984) initiated the experiment to control the end-effector of a flexible manipulator by measuring the tip position and using that measurement as a basis for applying torque to the other end (joint) of the beam. However, they only considered a linearized model and also the arm can sweep only in the XY plane, so that it is not affected by the gravity. Since then many new control strategies are developed to control the flexible link vibration. Recently, a survey on the control of flexible manipulators presented which mostly deals with the multi-link manipulators (Benosman and Vey, 2004) and mainly works between 1990 and 2002 were cited. In this present work, many other publications are cited which ranges from 1974 to 2005 and classifications are mainly based on the number of flexible links used in the study. For continuity purpose different methods used for the control of flexible manipulator are briefly described.

The control strategies for flexible manipulator systems can be classified as feed-forward (open loop) or feedback (closed loop) control schemes. A feed-forward technique for vibration suppression involves developing the control input through consideration of the physical and vibration properties of the system, so that system vibrations at response modes are reduced. This method does not require any additional sensors and actuators and does not account for changes in the system once the input is developed. On the other hand, feedback control techniques use measurements and estimations of the system states to reduce vibration. For flexible manipulators, Benosman and Vey (2004) pointed out that the control objectives are mainly end-effector regulation problems, end-effector to rest motion in a desired fixed time, joint trajectory tracking and the end-effector trajectory tracking. The last one is the most difficult one due to the non-minimum phase nature of the system dynamics. The control schemes applied to flexible robots include proportional derivative control, computed torque control, active damping control, adaptive control, neural network based control, lead-lag control, sliding mode control, stable inversion in the frequency domain, stable inversion in the time domain, algebraic control, optimal and robust control, input shaping control and boundary control. Some works using these methods are cited in the next subsections and are grouped with respect to the number of flexible links in the manipulator.

For this project, a feed-back or close loop method is use since there is a tip deflection feedback will be attach at the end of the end of single link flexible manipulator. Through a suitable trajectory planning as choice of range of the velocity and acceleration of the single link flexible manipulator, the vibration of the single link flexible manipulator system can be significantly reduced.

2.5 SINGLE LINK FLEXIBLE MANIPULATOR

Flexible manipulator offer advantages in comparison to their rigid counterparts (Azad, *et.al*, 1994). The speeds of operation of lightweight elastic single-link manipulators are improving and able to handle larger payloads in comparison to rigid manipulators with the same actuator capabilities (Azad, 1994) and (Poerwanto, 1998). Therefore, researcher had put interest in flexible manipulators for industries application.

For this project, the single link flexible manipulator has an elastic behavior when it is being rotated. From this condition, the kinetic and potential energy of the system can be developed. The kinetic energy terms consist of translational and rotational energy of each link. Potential energy terms consist of elastic bending, gravity, and shearing deformation effects.

From the condition, Newton- Euler Equation of motion is used since dynamic mathematical modeling is related. This equation can prove and explained in details about derivation of kinetic and the potential energy that used in order to conduct the simulation can be described as following:

$$m\ddot{r}c = \sum F \text{ and } ICzz \propto = \sum Mc \,, \tag{2.1}$$

When we using the Cartesian component,

$$m\ddot{x}c = \sum Fx \;\; , \ddot{y}c \;= \sum Fy \text{ , and } Iczz\ddot{\theta} = \sum Mc \tag{2.2}$$

The differential equations are solved for the direct dynamic of the rigid body and the forces and moment are known.

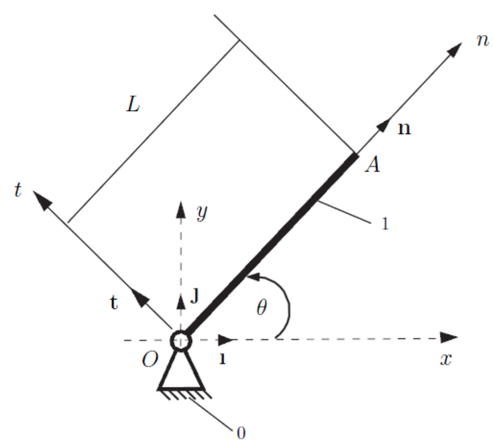

Figure 2.2: Depicts a compound pendulum of mass *m* and length *L*

Source: R. Morales, 2011

Figure 2.2 shows the compound manipulator of mass *m* and length *L*. The link is rotating at the fixed axis. The mass moment of inertia of the link about the fixed pivot point

O can be evaluated from the mass moment of inertia about the mass center C using the transfer theorem. This system has one degree of freedom.

$$I_o = I_c + m\left(\frac{L}{2}\right)^2 = \frac{mL^2}{12} + \frac{mL^2}{4} = \frac{mL^2}{3} \qquad (2.3)$$

The pin is frictionless and is capable of exerting horizontal and vertical forces on the link at O,

$$F_{O1} = F_{O1x^I} + F_{o1y^J} \qquad (2.4)$$

where F_{O1x^I} and F_{o1y^J} are the components of the pin force on the link in the fixed axis system. The force driving the motion of the link is gravity. The weight of the link is acting through its mass center will cause a moment about the pivot point. This moment will give the link a tendency to rotate about the pivot point. This moment will be given by the cross product of the vector from the pivot point, O; to the mass center, C, crossed into the weight force G = -mg.

As the pivot point, O, of the link is fixed, the appropriate moment summation point will be about that pivot point. The sum of the moments about this point will be equal to the mass moment of inertia about the pivot point multiplied by the angular acceleration of the link. The only contributor to the moment is the weight of the link. Thus we should be able to directly determine the angular acceleration from the moment equation. The sum of the forces acting on the link should be equal to the product of the link mass and the acceleration of its mass center. This should be useful in determining the forces exerted by the pin on the link.

The free body diagram shows the link at the instant of interest, Figure 2.3. The link is acted upon by its weight acting vertically downward through the mass center of the link. The link is acted upon by the pin force at its pivot point. The motion diagram shows the link at the instant of interest, Figure 2.4. The motion diagram shows the relevant acceleration information.

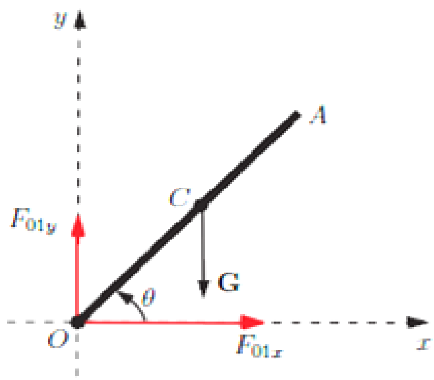

FIGURE 2.3: Free body diagram

Source: R. Morales, 2011

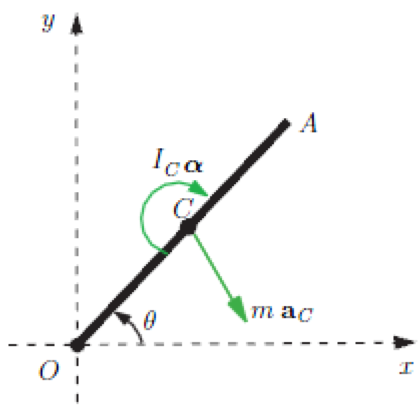

Figure 2.4: Relevant acceleration

Source: R. Morales, 2011

The Newton-Euler equations of motion for the link are:

$$ma_c = \sum F = G + F_{01}) \tag{2.5}$$

$$I_C \propto = \sum M_C = r_{co} \times F_{01} \tag{2.6}$$

Since the rigid body has a fixed point at O the equations of motion state that the moment sum about the fixed point must be equal to the product of link mass moment of inertia about that point and the link angular acceleration. Therefore,

$$I_0 \propto = \sum M_o = r_{oc} \times G \tag{2.7}$$

2.6 PROPORTIONAL INTEGRAL DERIVATIVE (PID) CONTROLLER

For this project, Proportional Integral Derivative (PID) control is used. PID control is used due to its wide-spread use in industrial control applications. It dominating more than 90% form of feedback today of all loops (Astrom and Hagglund, 1995). The PID controller attempts to correct the error between a measure process variable and desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. Figure 2.5 below show the general scheme of a PID controller in frequency domain.

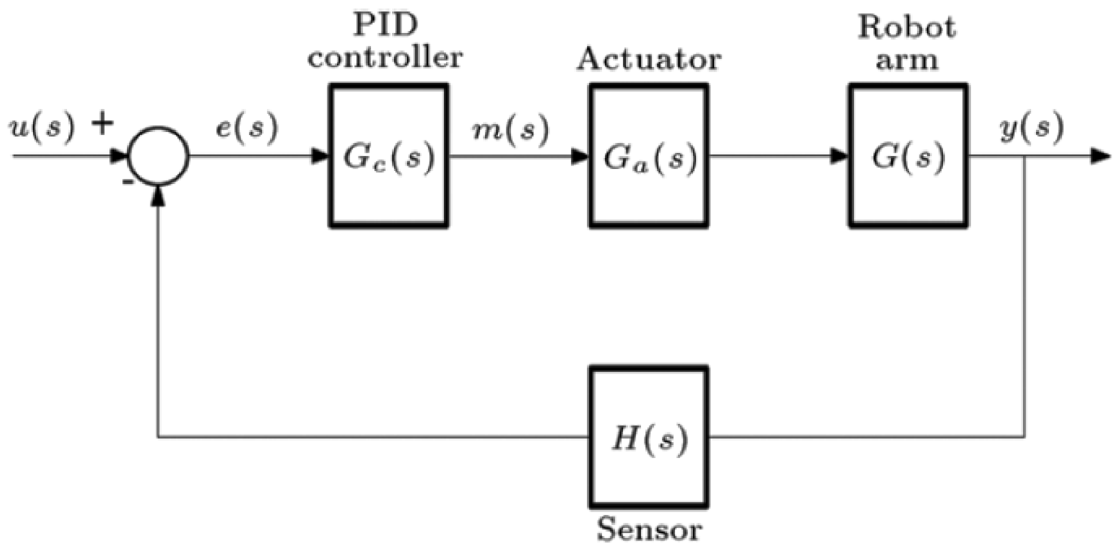

Figure 2.5: General scheme of PID controller.

In a typical feedback control system, the controller takes the error signal (difference between the desired and measured signals) and processes it. The output of the controller is passed as an input to the process. One type of controller which is widely used in industrial applications is the proportional integral derivative (PID) controller. The proportional part of this controller multiplies the error by a constant. The integral part of the PID controller integrates the error. Finally the derivative part mathematically differentiates the error. The output of the controller is the sum of the above three signals. K_p, K_i and K_d are the controller gains related to the proportional, integral and derivative terms, respectively. Taking into account the error signal, *e*(t), the control signal can be written as

$$u(t)=K_p\, e(t) + K_i \int e(t)dt + K_d\, de/dt\, (t) \qquad (2.8)$$

where, K_p = proportional gain

K_i = integral gain

K_d = derivative gain

This signal (u) will be sent to the plant, and the new output (Y) will be obtained. This new output (Y) will be sent back to the sensor again to find the new error signal (e). The controller takes this new error signal and computes its derivative and its integral again. This process goes on and on.

A proportional controller (K_p) will have the effect of reducing the rise time and will reduce but never eliminate the steady-state error. An integral control (K_i) will have the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative control (K_d) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. Effects of each of controllers Kp, Kd, and Ki on a closed-loop system are summarized in the Table 2.1.

Table 2.1: Summarize of PID controller

Closed Loop Response	Rise Time	Overshoot	Settling Time	Steady State Error
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Small Change	Decrease	Decrease	Small Change

Source: Richard C. Dorf and Robert H. Bishop, 2005

Note that these correlations may not be exactly accurate, because Kp, Ki, and Kd are dependent on each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only be used as a reference when you are determining the values for Ki, Kp and Kd.

If the PID controller gains are chosen incorrectly, the controlled process input can be unstable. Tuning a control loop is the adjustment of its control gains to the optimum values for the desired control response. There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, and then choosing P, I, and D based on the dynamic model parameters. Sometime, manual tune by feel methods can be inefficient.

The overwhelming dominance of PID controller over other forms of feedback, is due to its simple structure and reliability in a wide range of operating conditions. Some estimates state that more than 95% of the controllers used in process control applications are of PID type (Astrom and Hagglund, 1995). Due to the wide acceptance of PID controllers within industry many tuning rules have been proposed for this type of controller, since the original work of Ziegler and Nichols (Ziegler, and Nichols, 1942). However, despite the huge amount of existing tuning rules for PI/PID controllers, the test of a large set of industrial plants (Ender, 1993), indicated that 30% of the controllers were operated manually and 65% were poorly tuned. Indeed, plant operators tend to tune PID controllers by trial and error or using very simple tuning rules. A plausible explanation is the lack of appropriate educational background from most of the process control operators (Pomerleau, and Poulin, 2002) concerning the proper use of tuning methodologies. In some cases, the control operator can be responsible for hundreds of process control loops (Astrom and Haigglund, 2000), with a wide range of system dynamics, having to design and tune PID controllers to meet performance and robustness specifications. Considering the huge number of tuning rules proposed for different process models and the limited amount of effort that the plant operator can devote to each loop, the existence of an universal tuning method would simplify their role significantly. Because there is not an universal tuning method, the use of an optimization algorithm, particularly using modem heuristics, constitutes a global tool to the design and tuning of PID controllers for a wide range of control engineering applications. For the project, heuristic method will be use for the PID controller input.

2.7 ACTIVE FORCE CONTROL

The proportional integral derivative (PID) control is the fundamental common controller for all control schemes while main controller is based on the active force control

(AFC) method in simulation study. AFC had been introduced by Hewit in the late 70s for controlling a dynamic system (Hewit, 1998). This method gives good stability, robustness and effectiveness to the system even in the presence of known/unknown disturbances, uncertainties and varied operating condition. It had been verified after several experimental studies.

From Newton's second law of motion for rotational bodies, the sum of all torques applied to the system is equal to the product of the mass moment of Inertia (I) and the angular acceleration (α) of the system:

$$\Sigma\tau = I\alpha. \tag{2.4}$$

When the disturbance, τd, is considered and the mass is rotating with a joint angle, θ, Eq. (8) becomes:

$$\tau + \tau_d = I\ddot{\theta}v \tag{2.4}$$

where: τ is the applied torque to the actuated joints

τ_d is the total of applied disturbance torques to the actuated joints

$\ddot{\theta}$ is the actuated joint angles and angular acceleration, respectively.

The basic schematic of the AFC scheme applied to a dynamic system is illustrated in Figure 2.6. As mentioned previously, one physical quantity which is required to be measured by the sensing elements is acceleration of the system while the system operates. Then the estimated inertia (it is the inertial parameter) of the system with the presence of the disturbances that contributes to the acceleration should be acquired appropriately by using suitable techniques such as crude approximation method or other intelligent methods (like fuzzy logic and neural network).

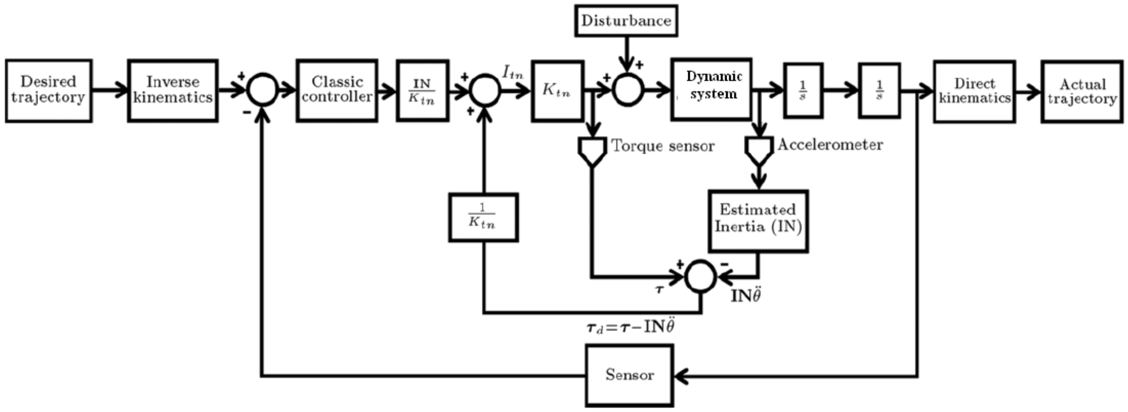

Figure 2.6: Basic schematic of an Active Force Control (AFC) scheme

Source: Kwek, *et al.*, 2003

2.8 CONCLUSION

As a conclusion, the single link manipulator arm, the controller used to reduce the vibration is described in this chapter. There are two types of controller that involve in the project which there are Proportional Integration Derivation (PID) controller and Active Force Control (AFC) controller. The study of the vibration in the single link will do in a simulation after the parameter of it being specified. The result of simulation process will be compared.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

The methodology had been done right after the problems, objectives and scopes of the project were identified. Methodology is a step to another step in order to complete the project. The completed structure of methodology had been illustrated and planned as guideline through a flowchart to achieve the objectives of the project. Through this methodology, the advanced steps in progress of control the vibration error in single link flexible manipulator being elaborated.

3.2 FLOWCHART OF METHODOLOGY

The flow chart of methodology is designed to achieve the project's objectives. Figure 3.1 shows the flow chart of this project. This final year project was based on the flow chart so that it will always work in the right flow.

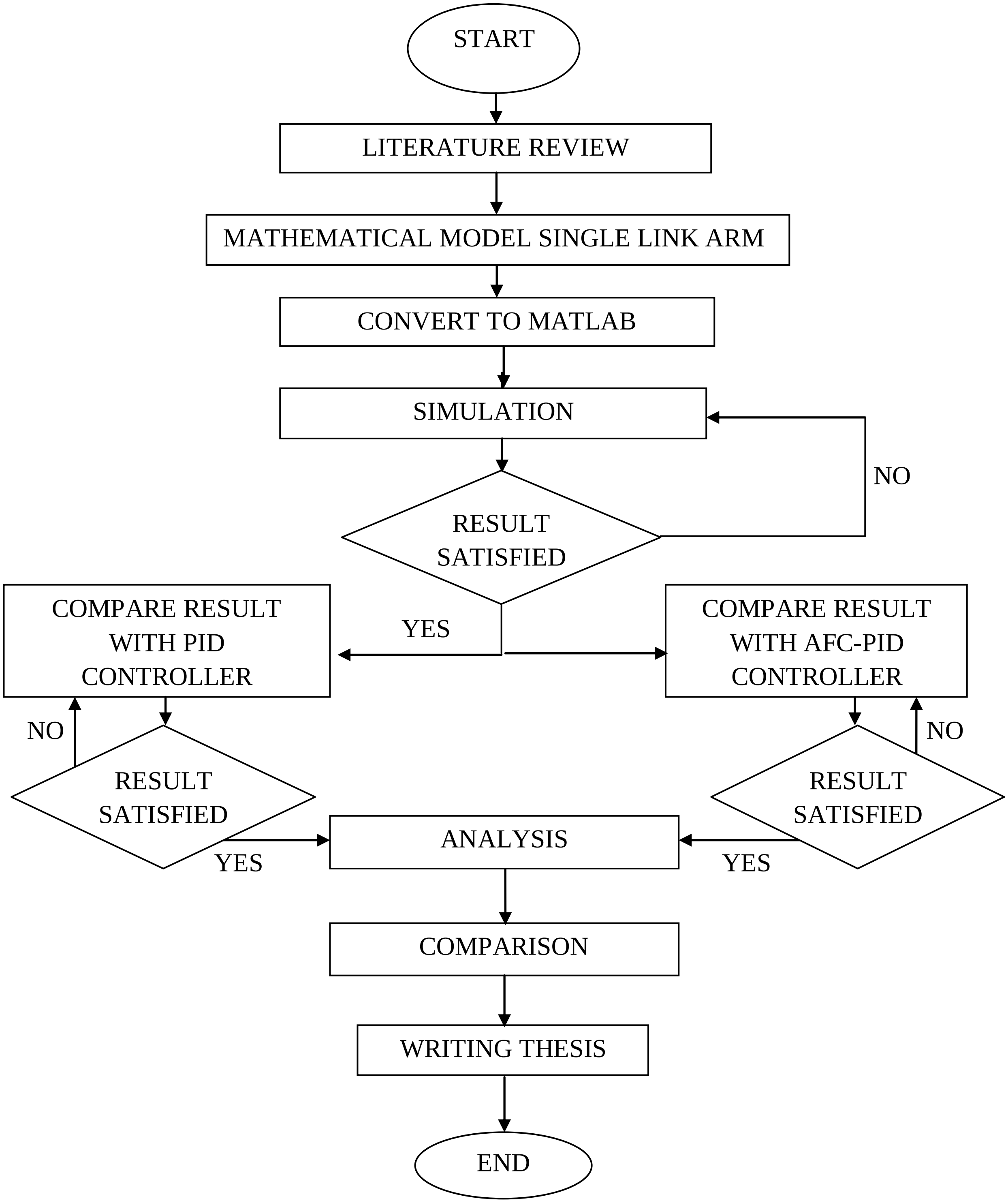

Figure 3.1: Flowchart

From the flowchart, the methodology of this project is start with collecting the journals that related to title given. The introduction, including the project background, objective and scope need to be understands. Due to these step, indirectly the literature review had been study for more understanding how these project goes on. Several journals have been identified related and valid to use as the references. For more understanding, all the journals are read for several times. The literature review will be in chapter 2 of this project report.

After that, the mathematical equation and mathematical modeling must be identified and recognized in order to implement it to the flexible link manipulator. Basically, there are a few of mathematical modeling that have been used in order to generate the single link flexible manipulator. For this project, Lagrange's equation of motion is use as a single link flexible manipulator equation.

DC motor is use as actuator to rotate the single link flexible manipulator. The mathematical equation for DC motor is get from a journal then will be converting to the simulation block diagram.

Matlab is use as a medium to create an example like real experiment with PID controller and AFC controller. The parameter of the single link is needed to decide. By implementing the control scheme, the single link flexible manipulators will be set up to run in simulation by using Matlab simulation.

There are three model system need to be do for analysis. First is system without controller. Second is system with PID controller and lastly is system with AFC-PID controller. These three systems have different result.

For the basic system, there is an input (current), actuator (DC motor), process (rotating of single link flexible manipulator). The single link flexible manipulator is attached to the DC motor. To run the system, current is supply to the DC motor, and then the DC motor will rotate from 0° to 90°. The single link flexible manipulator also will rotate follow the rotation of DC motor. When the DC motor complete 90° of rotation, the free end of link will keep moving for several time because of the inertia of the single link flexible manipulator. When controller is attaching to the system, it will reduce time taken to stop the movement.

Result of the simulation will be obtained after running the simulation. Then the result will be studied before proceed to the next step. If the result is not satisfied, either the mathematical equation checks or an arrangement need to the simulation block diagram need to be do. If result is satisfied, it will go to the next step which the result will through PID controller and AFC-PID controller. A new result will obtain here.

The system result without the controller is important as it is result to improve. Result system with controller will be compare and analyze either there is an improvement or not. For the system with PID controller, the result should be better than system without controller but system with AFC-PID controller should be the best. To describe the word best, the system should give an output as desire input.

The data will be collect and a comparison results between three methods will be summarize to see which method minimize the vibration error from the simulation graph pattern.

3.3 BLOCK DIAGRAM

Block diagram is a composition of different shapes and lines showing how the components of a program, process, or system are related to, and depend upon, one another. It may also show how the system operates, what are its inputs and outputs at various stages, and how the energy, information, and/or materials flow through it.

Figures below show systems which have different types of loop. Figure 3.2 is an open loop system. It has no feedback and not self-correcting. Figure 3.3 is a closed loop system. A closed loop system has a feedback and self correcting to improve the system process.

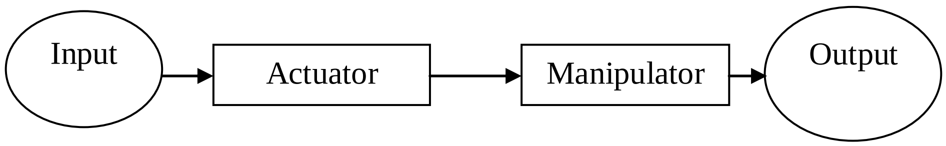

Figure 3.2: Open Loop System

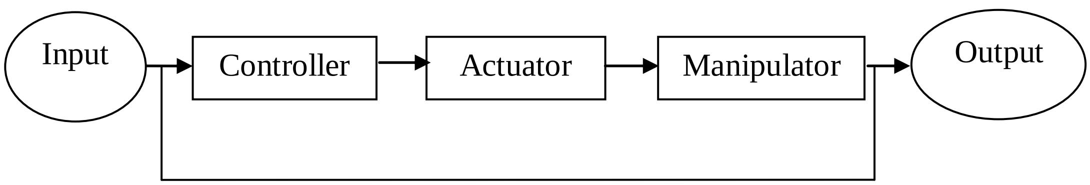

Figure 3.3: Closed Loop System

3.4 MATHEMATICAL MODELING

Mathematical equations of the motion can be defined via Lagrange equations using a total potential and kinetic energy. First, apply Lagrange's equation to derive the equations of motion of a simple pendulum in polar coordinates. This is a one degree of freedom system. It begins by describing the position of the mass point m_1 with cartesian coordinates x_1 and y_1 and then express the Lagrangian in the polar angle θ_1. Referring to Figure 3.4,

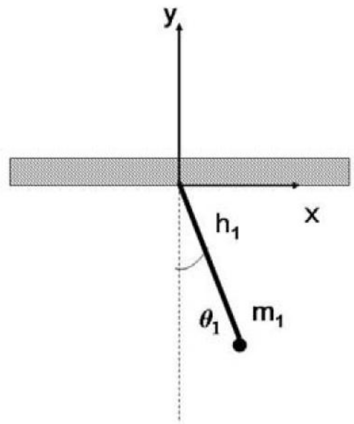

Figure 3.4: Single Pendulum

Source: S. Widnall, 2009

$$x_1 = h_1 \sin \theta_1 \tag{3.1}$$

$$y_1 = -h_1 \cos \theta_1 \tag{3.2}$$

So that the kinetic energy is

$$T = \frac{1}{2} m_1 (\dot{x}_1^2 + \dot{y}_1^2) = \frac{1}{2} m_1 h_1^2 \dot{\theta}_1^2 \tag{3.3}$$

The potential energy is

$$V = m_1 g y_1 = -m_1 g h_1 \cos \theta \tag{3.4}$$

The Lagrangian is

$$L = T - V = \frac{1}{2} m_1 h_1^2 \dot{\theta}_1^2 + m_1 g h_1 \cos \theta_1 \tag{3.5}$$

Applying with

$$\frac{d}{dt}\left(\frac{\vartheta L}{\vartheta x_1}\right) - \frac{\vartheta L}{\vartheta x_1} = 0 \quad (3.6)$$

With $q_1 = \theta_1$, the differential equation governing the motion.

$$\frac{1}{2} m_1 h_1^2 \dot{\theta}_1^2 + m_1 g h_1 \sin \theta_1 = 0 \quad (3.7)$$

The equation of the motion for the single link flexible arm,

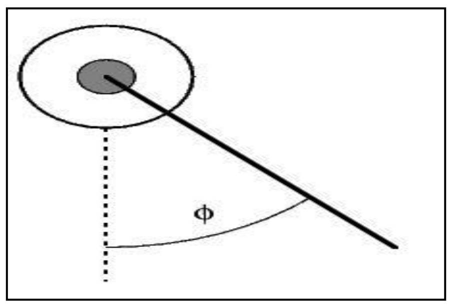

Figure 3.5: Single Link Flexible Manipulator

$$\frac{d^2\phi}{dt^2} = -10 sin\phi - 2\frac{d\phi}{dt} + u \quad (3.8)$$

Where $\phi$the angle for the arm and u is the torque supplied by the DC motor.

$$U = mgh \quad (3.9)$$

$$h = L - L\cos\alpha \quad (3.10)$$

$$U = mgL(1 - cos\alpha) \quad (3.11)$$

Defining the system Lagrangian, L as the difference between the kinetic energy and potential energy

$$L = T - U \tag{3.12}$$

A DC motor with armature control and a fixed field is assumed. The electrical model of such a DC motor is shown in figure 3.6. The armature voltage, $e_a(t)$ is the voltage supplied by an amplifier to control the motor. The motor has a resistance R_a, inductance L_a and back electromotive force constant, K_b. The back emf voltage, $v_e(t)$ is induced by the rotation of the armature windings in the fixed magnetic field. The counter emf is proportional to the speed of the motor with the field strength fixed. That is,

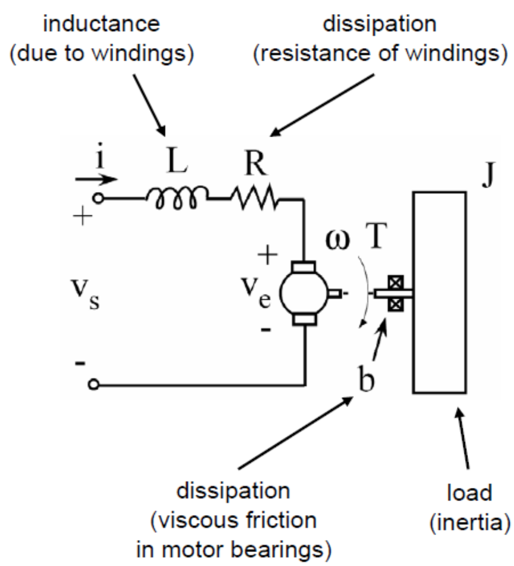

Figure 3.6: DC Motor

Source: Fall (2009)

For electrical equation of motion of DC motor, KCL:

$$v_s - v_L - v_R - v_e = 0 \Rightarrow v_s - L\frac{di}{dt} - R_i - K_v\omega = 0 \quad (3.13)$$

Where, v_s = voltage

v_L = inductance (due to windings)

v_e = dissipation (resistance of windings)

$$V_s(s) - V_L(s) - V_R(s) - V_e(s) = 0 \Rightarrow$$
$$V_s(s) - LsI(s) - RI(s) - K_v\Omega\,(s) = 0 \quad (3.14)$$

Equation of motion for mechanical of DC motor, torque balance:

$$T = T_b + T_J \Rightarrow K_m i - b\omega = J\frac{d\omega}{dt} \quad (3.15)$$

Where, T = torque

T_b = viscous friction in motor bearing

T_J = load (inertia)

$$\mathrm{T(s)} = \mathrm{T_b(s)} + \mathrm{T_J(s)} \Rightarrow K_m i(s) - b\Omega = Js\Omega(s) \quad (3.16)$$

Combine both equations of motion

$$L\frac{di}{dt} + R_i + K_v\omega = v_s \Rightarrow J\frac{d\omega}{dt} + b\omega = K_m i \quad (3.17)$$

$$LsI(s)+RI(s)+K_v\,\Omega(s)=Vs(s) \Rightarrow Js\Omega(s)+b\Omega(s)=K_m i \quad (3.18)$$

$$\left[(Ls+R)\left(\frac{Js+b}{K_m}\right)+K_v\right]\Omega(s)=Vs(s) \Rightarrow$$

$$\left[\frac{LJ}{R}s^2+\left(\frac{Lb}{R}+J\right)s+\left(b+\frac{K_mK_v}{R}\right)\right]\Omega(s)=\frac{K_m}{R}Vs(s) \quad (3.19)$$

Neglecting the impedance, $L\approx 0$

$$\left[Js + \left(b + \frac{K_m K_v}{R}\right)\right]\Omega(s) = \frac{K_m}{R} \tag{3.20}$$

This is a familiar 1st order system. If step input given, $v_s(t)=V_0u(t)$. So the step response

$$\omega(t) = \frac{K_m}{R}V_0\left(1 - e^{-\frac{t}{\tau}}\right)u(t) \tag{3.21}$$

where the time constant is

$$\tau = \frac{J}{b+\frac{K_m K_v}{R}} \tag{3.22}$$

Review: step response of 1st order systems, inertia with bearings (viscous friction), step input $T_s(t) = T_0u(t)$,

$$\omega(t) = \frac{T_0}{b}V_0\left(1 - e^{-\frac{t}{\tau}}\right), \text{where } \tau = \frac{J}{b} \tag{3.23}$$

where, J= inertia
b= bearings

RC circuit (charging of a capacitor), step input $v_i(t) = V_0u(t)$,

$$v_c(t) = V_0\left(1 - e^{-\frac{t}{\tau}}\right), \text{where } \tau = RC \tag{3.24}$$

where, R= resistance
C= capacitor

DC motor with inertia load, bearings and negligible inductance, step input $v_s(t) = V_0u(t)$,

$$\omega(t) = \frac{K_m}{R}V_0\left(1 - e^{-\frac{t}{\tau}}\right), \text{where } \tau = \frac{J}{b+\frac{K_m K_v}{R}} \tag{3.25}$$

For this section, we will check the details the control theory behind the operation of DC motor and derives an equation for the stability of the system. Theory that involves is:

1) Control theory – transfer function of a closed loop system
2) DC motor – equation that related to torque, load moment of inertia, frictional torque, circuit analysis of DC motor, and back emf.
3) Control theory – Routh's stability criterion

The closed loop transfer function for this system can be defined as:

$$\frac{open\ loop\ gain}{1 + closed\ loop\ gain} \quad (3.26)$$

$$\frac{AG(s)}{1+AG(s)} \quad (3.27)$$

Therefore, the equation of DC motor is:

$$G(s) = \frac{\theta_m(s)}{E(s)} = \frac{K_t n}{s[(Js+D)(L_a s+R_a)]+K_b K_t} \quad (3.28)$$

For the DC motor, the torque is proportional to current. Therefore,

$$T = k_t i_a \quad (3.29)$$

Moment of inertia of the load and frictional force load is member in torque of the load. The equation can be defines as:

$$T = I_L \frac{d\omega_m}{dt} + D\omega_m \quad (3.30)$$

The back emf is proportional to the speed and flux, and since flux is the value of constant

$$e_m = k_1 \emptyset \omega_m = k_b \omega_m \quad (3.31)$$

From the Kirchoff's law around the armature circuit, it will be:

$$e_a = L_a \frac{di_a}{dt} + R_a i_a + e_m \quad (3.32)$$

By combining all the equations, it will be

$$e_a = \frac{L_a I_L}{k_t} \frac{d^2\omega_m}{dt^2} + \frac{L_a D + R_a I_L}{k_t} + \left(\frac{R_a D}{k_t} + k_b\right)\omega_m \quad (3.33)$$

The angular speed ω_m is the rate of change of angle. So,

$$\omega_m = \frac{d\theta_m}{dt} \tag{3.34}$$

Therefore,

$$e_a = \left[\frac{L_a I_L}{k_t}\right]\theta_m s^3 + \left[\frac{L_a D + R_a I_L}{k_t}\right]\theta_m s^2 + \left[\frac{R_a D + k_t k_b}{k_t}\right]\theta_m s \tag{3.35}$$

In order to make it easier, the value in bracket replaced for above equation with

$$e_a = (C_0 s^3 + C_1 s^2 + C_2 s)\theta_m \tag{3.36}$$

From the previous,

$$G(s) = \frac{\theta_m}{e_a} \tag{3.37}$$

$$G(s) = \frac{1}{C_0 s^3 + C_1 s^2 + C_2 s} \tag{3.38}$$

The characteristic of the equation which determines the stability is

$$1 + AG(s) = 0 \tag{3.39}$$

$$C_0 s^3 + C_1 s^2 + C_2 s = 0 \tag{3.40}$$

It is not sufficient condition (but necessary) of the system stability that all the coefficient of this equation must have same sign. By using the Routh Array, the coefficient

Table 3.1: Routh Array

s^3	C_0	C_2
s^2	C_1	A
s	$\frac{C_1C_2 - C_0A}{C_1}$	
const	A	

The other condition of the system stability is that the entire elements in the first column are the same sign. Since the value always positive, therefore

$$\frac{C_1C_2 - C_0A}{C_1} \tag{3.41}$$

Also must be positive.

$$C_1C_2 > C_0A \tag{3.42}$$

$$0 < A < \frac{(L_aD + R_aI_L)(R_aD + k_tk_b)}{L_aI_L} \tag{3.43}$$

Since a negative gain would make the mechanism compensate for any positional error by driving the motor the wrong way, the value of A must be positive for the stability.

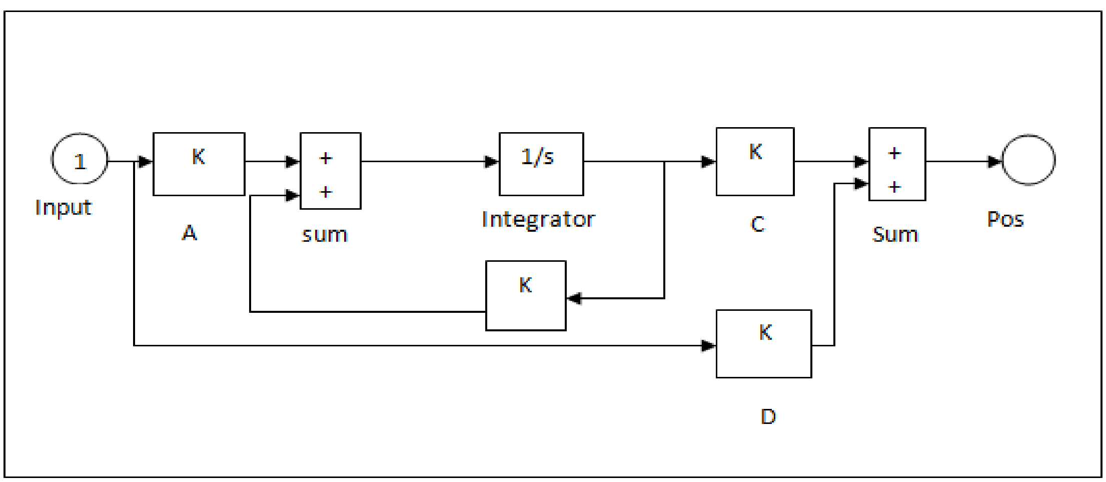

Figure 3.7: Basic Block diagram of DC motor

From the DC motor theory, the equation already discussed in previous session.
, the controlled DC motor function can be simplified as:

$$G(s) = \frac{\theta_m(s)}{E(s)} = \frac{K_t n}{s[(Js+D)(L_a s+R_a)]+K_b K_t} \quad (3.44)$$

3.5 PARAMETER

Parameter is term to identify characteristic, measurable factor that can help in defining a particular system. It is an important element to take into consideration for the evaluation for a project. Key parameters of the DC motor is show in Table 3.2 and flexible manipulator system in Table 3.3

Table 3.2: Parameter of DC Motor

Parameter	Description
La= 0.004 H	Inductance
$\boldsymbol{J_m}$= 0.0001 (kg/m^2)	Motor moment of inertia
$\boldsymbol{B_m}$= 0.0000093 (Nms/rad)	Equivalent viscous damping coefficient
$\boldsymbol{K_t}$ = 0.105 (Nm/A)	Motor torque constant
$\boldsymbol{K_m}$= 0.105 (Vs/rad)	Back-emf constant
$\boldsymbol{R_m}$= 2.7 (Ω)	Motor armature resistance
g = 9.81 (m/s^2)	Gravitational constant of earth

Table 3.3: Parameter of Flexible Manipulator

Parameter	Description
L = 0.5 m	Length of single link arm
m= 0.03 kg	Mass of single link arm
fc= 2.0µ	Friction coefficient
g = 10.0 (m/s^2)	Gravitational constant

3.6 STEP RESPONSE

These are the characteristics of the response signal. Each of the step response characteristics is described in the figure below.

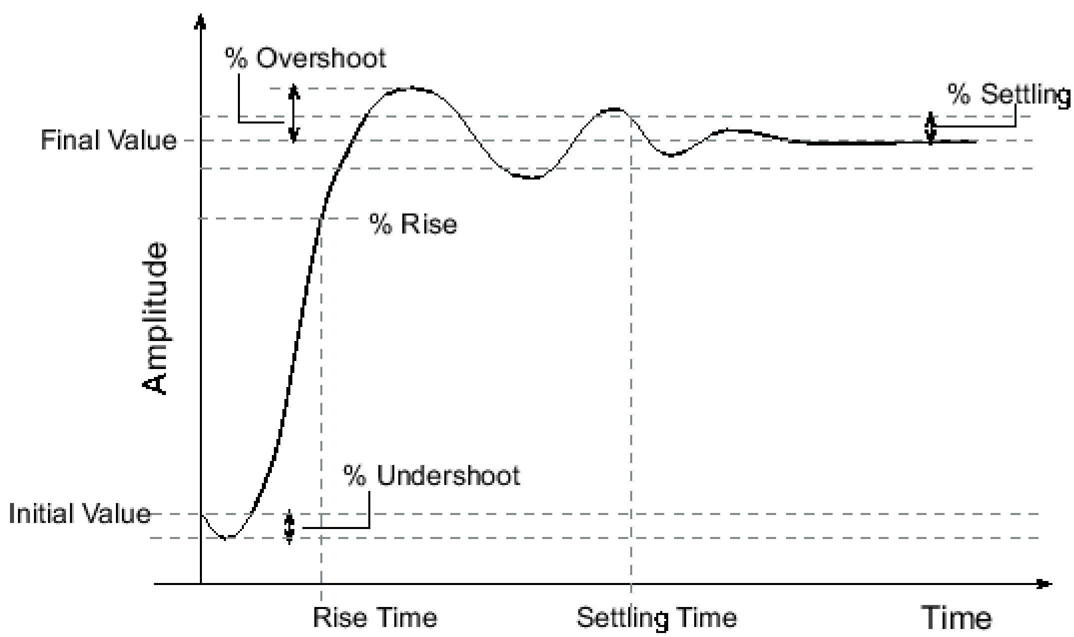

Figure 3.8: Step Response Graph

Source: mathworks.com

Rise time is the time taken for the response signal to reach a specified percentage of the step's range. The step's range is the difference between the final and initial values. Percent rise is the percentage used in the rise time.

Settling time is the time taken until the response signal settles within a specified region around the final value. This settling region is defined as the final step value plus or minus the specified percentage of the final value. Percent settling is the percentage used in the settling time.

Percent overshoot is the amount by which the response signal can exceed the final value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.

Percent undershoot is the amount by which the response signal can undershoot the initial value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

In this chapter, the result of simulation using Matlab software will be discussed. The result of various control will be analyze in term of rise time, overshoot, settling time and steady state error. The result comparison from various controls also will be show and analyze.

4.2 DC MOTOR SYSTEM

Rotation of DC motor provides motion to the single flexible manipulator. It received current input then produce torque as output. There is also disturbance input in the DC motor system.

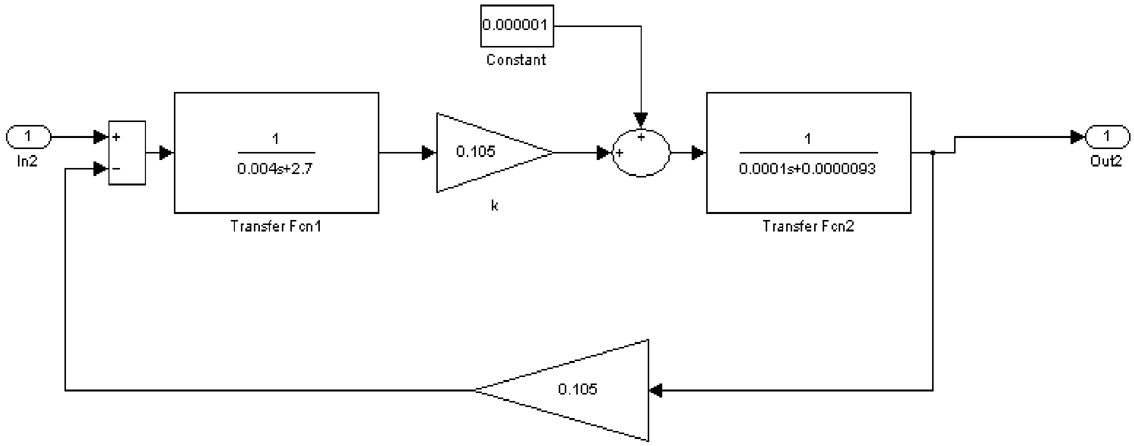

Figure 4.1: DC motor block diagram.

4.3 SINGLE LINK FLEXIBLE MANIPULATOR

Single link flexible manipulator rotated as DC motor rotate. From the block diagram, it received torque input to rotate and show position of angle in radian/second as output.

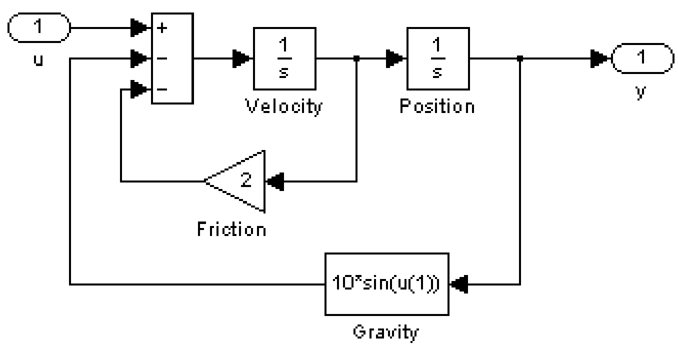

Figure 4.2: Single link flexible manipulator block diagram.

4.4 SYSTEM WITHOUT CONTROLLER

In this part, the block diagram of the system, the result of the system and the discussion of the system result will be show.

4.4.1 Block Diagram

Figure 4.3 show the block diagram of system without controller that had been setup in Matlab simulation. To get the data, the simulation is being run. There is no error feedback in the system.

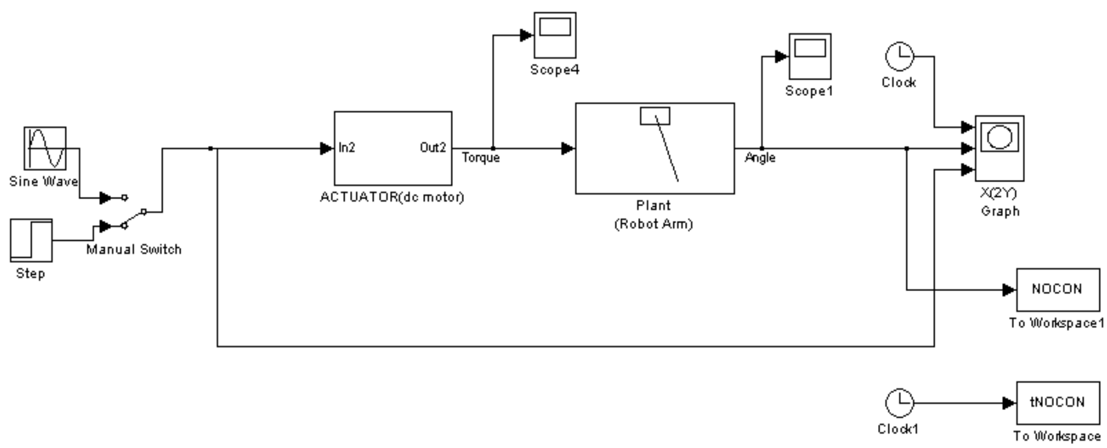

Figure 4.3: System without controller block diagram.

4.4.2 Result of Step and Sine Wave Response with System without Controller

Figure 4.4 and 4.5 show the result for the system without controller. The green line show desire output and blue line show actual output. Figure 4.4 is graph for step response and Figure 4.5 is graph for sine wave response.

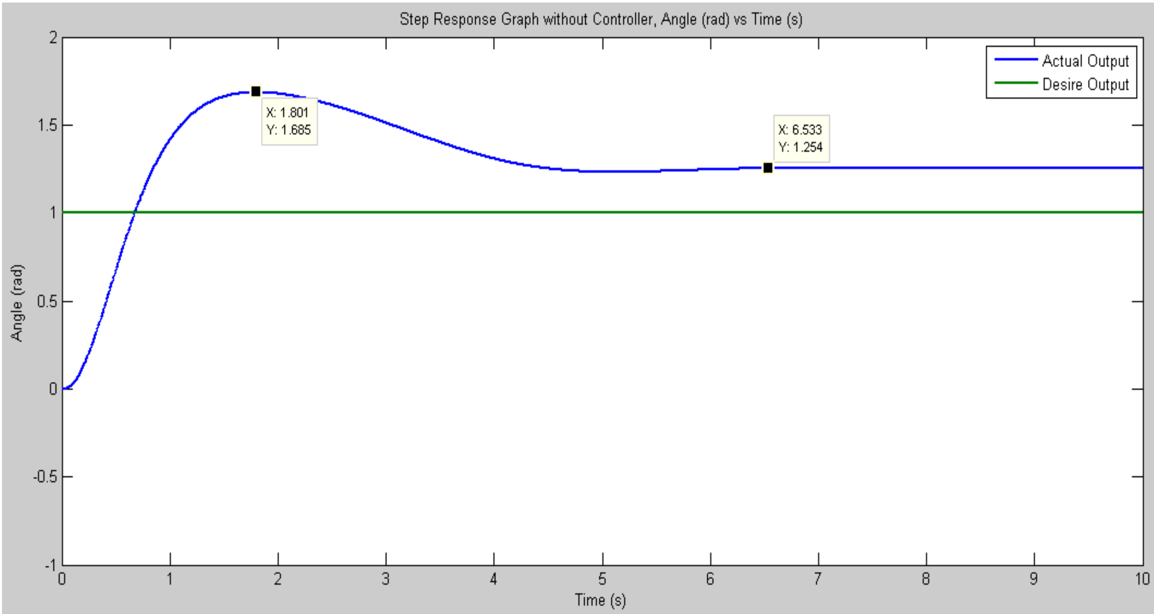

Figure 4.4: Step response graph of angle (rad) vs time(s)

Table 4.1: Step response result data

Specification	**Value**
Overshoot, OS	68.2%
Steady State Error, ESS	0.254 rad
Peak Time	1.801 s
Settling Time, Ts	6.533 s
Rise Time, Tr	0.06878 s

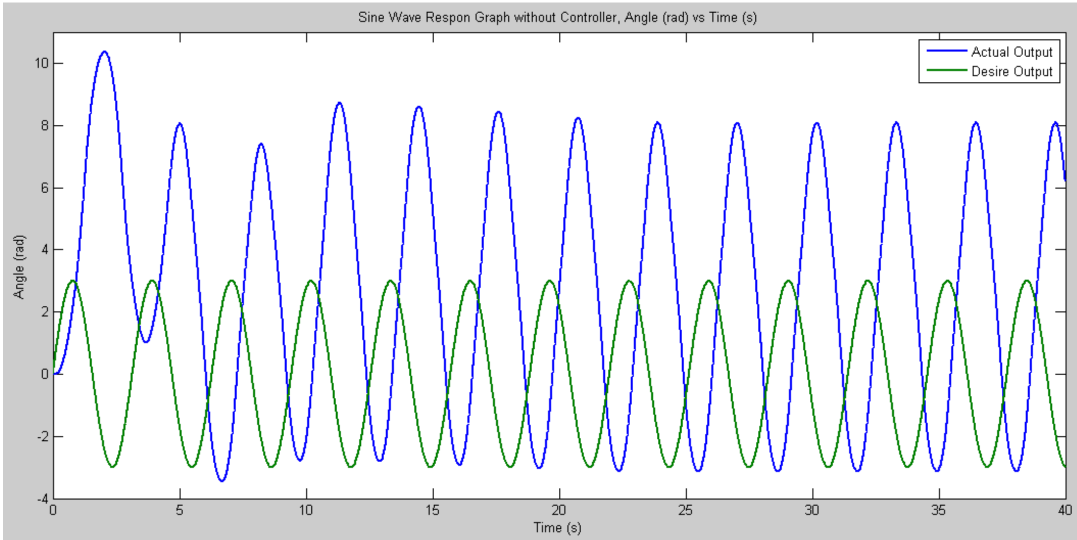

Figure 4.5: Sine wave response graph angle (rad) vs time(s)

Table 4.2: Sine wave response result data

Specification	**Value**
Amplitude, A	10.38 radian
Frequency, ***f***	0.3125 hertz
Angular Frequency, ***w***	1.963 rad/s
Overshoot , OS	245.7%

4.4.3 Discussion

For step input, the overshoot value of single link flexible manipulator without controller angle is 68.2% than the desired value. The steady state error value is 0.254 radian which the highest angle displacement value. Next values of the graph are peak time, settling time and rise time which are 1.1801 second, 6.027 second and 0.06878 second to reach steady state.

For sine wave input, the input is setup to 3 amplitude but the system unstable. The output is 10.38 radian. The time cycle is different with desired output. The frequency for this system is 0.3125 Hz by counting the 12.5 complete cycle in range of time (40 seconds). Apart from that, we can get the angular frequency, which give value 1.963 rad/s. The overshoot of the graph is 245.7% from peak of actual result to peak of desired.

4.5 SYSTEM WITH PROPOTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROLLER

In this part, the block diagram of the system, the PID tuning, the result of the system and the discussion of the system result will be show.

4.5.1 Block Diagram

PID controller is combining in the system without controller as Figure 4.6. PID is easy to tune by set a value for Kp, Ki and Kd. The error is measured by adding a feedback line to the input from the single link flexible manipulator output block diagram. The result from step and sine wane input will be analyzed.

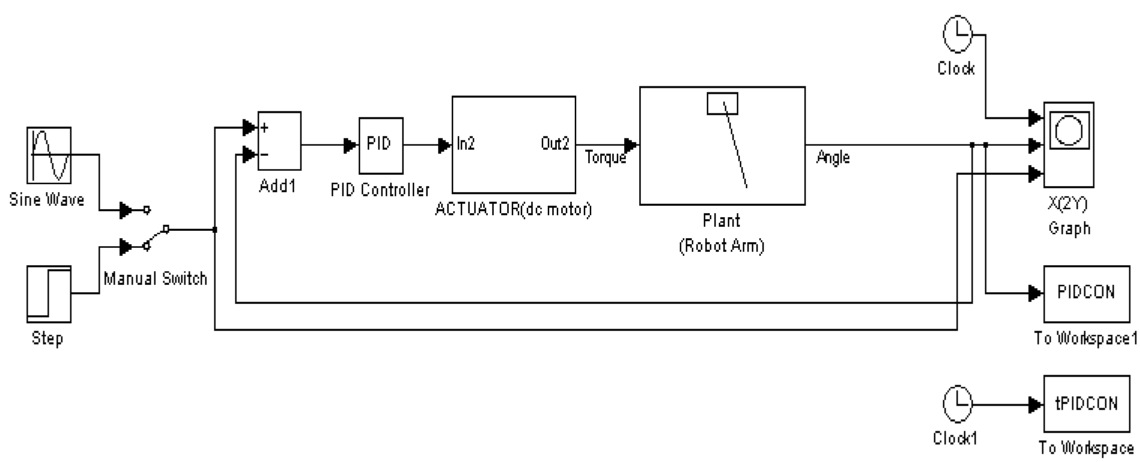

Figure 4.6: System with PID controller block diagram

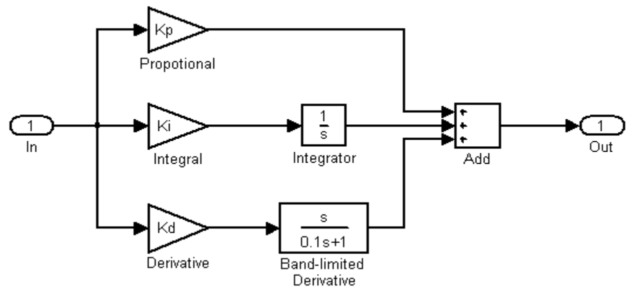

Figure 4.7: PID subsystem block diagram

4.5.2 Tuning PID

Figure 4.8 and 4.9 show the graph of the system with PID controller. It was done two time in order to have a good result.

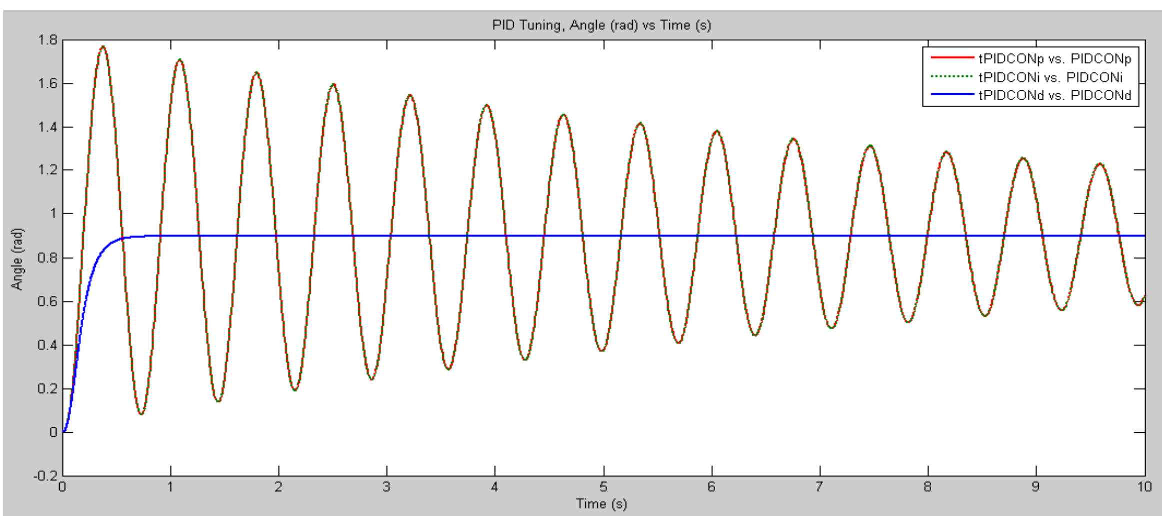

Figure 4.8: Graph of PID controller first tuning

Proportional, Kp : 8

Integral, Ki : 0.01

Deriavative, Kd : 1.5

The PID controller is easy to implement and robust stability. In this section, the result of closed loop system with PID controller is discussed. The PID tuning is determined by using try and error method. It is important to understand what is the effect of PID value is so the actual result can be tune as desired.

The result shows that the system with PID controller is better than without PID controller. The value of PID parameters for the first tuning is Kp = 8, Ki = 0.01 and Kd = 1.5. However, this PID parameter will not be use because of low value of Kp. Higher Kp value is needed to reduce the steady state error. Current steady state error is 0.102 rad.

A new PID value had been tried with Kp = 41, Kd = 0.0001 and Kd = 5.3. The new parameter had reduced the steady state error to 0.0213 rad with 79.1% improvement. This new parameter will be use as PID step input for the comparison with no controller and AFC-PID controller system.

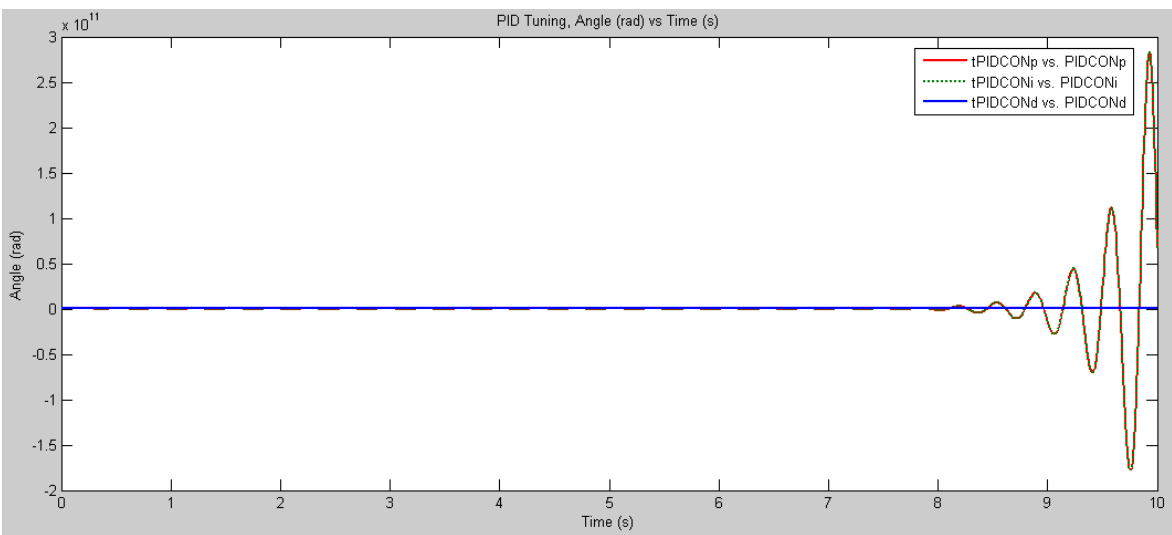

Figure 4.9: Graph of PID controller second tuning

Proportional, Kp : 41

Integral, Ki : 0.0001

Derivative, Kd : 5.3

4.5.3 Result of Step and Sine Wave Response with System with PID Controller

Figure 4.10 and 4.11 show the result for the system without controller. The green line show desire output and blue line show actual output. The result will be discussed in the discussion.

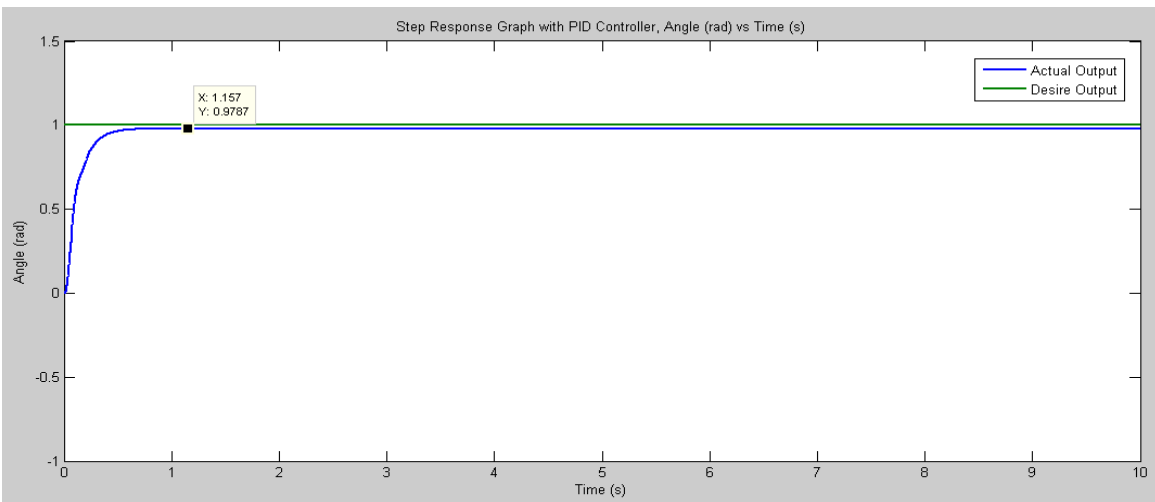

Figure 4.10: Step response graph of angle (rad) vs time(s)

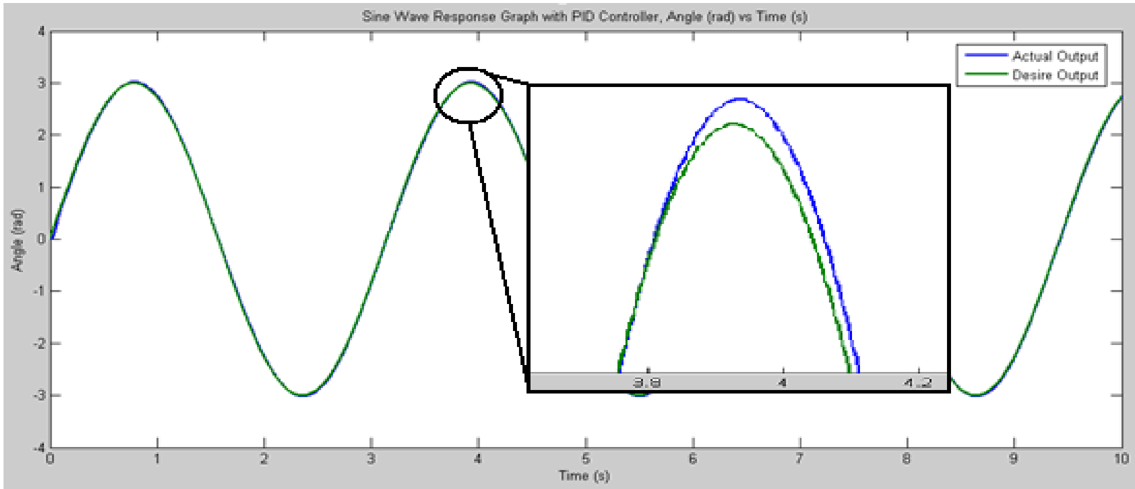

Figure 4.11: Sine wave response graph of angle (rad) vs time(s)

4.5.4 Discussion

By controlling Kp, Ki, and Kd, PID control system the best result as desire output by try and error concept. For the first trial with Kp = 8, Ki = 0.01and Kd = 1.5 with step input, the error result reduce by 56.8% (new undershoot = 11.4%) compare to system without controller. The steady state error is decrease to 0.1027 radian. The new result for settling time and the rise time is 1.0440 s and 0.2876 s.

A new tuning process is done to reduce error. By increasing Kp = 41, the system is try to reach desired point in short time. Then by adjusting Ki = 0.0001 and Kd = 5.3, a new graph result obtain and better than early tuning process. The undershoot is 2.17% and steady state error is 0.0213 radian. Besides, the settling time and rise time are 1.1570 second and 0.6656 second.

Table 4.3: Step response result data

Specification	**1st Trial**	**2nd Trisl**
Proportional, Kp	8	41
Integral, Ki	0.01	0.001
Deriavative, Kd	1.5	5.3
Undershoot, US	11.4%	2.17%
Steady State Error, ESS	0.1027 rad	0.0213 rad
Peak Time	-	-
Settling Time, Ts	1.0440 s	1.1570 s
Rise Time, Tr	0.2876 s	0.6656 s

For the sine wave results, with input Kp = 41 Ki = 0.0001 Kd = 5.3 at PID controller, we can see the value of frequency is non uniform for the set of PID tuning. For the first set of PID data, we can see the value of amplitude is 3.017 radian compared to desired value that is 3 radian. For the frequency, the PID tuning result is 0.35 Hz. The overshoot is 0.56% from peak of actual result to peak of desired.

Table 4.4: Sine wave response result data

Specification	**Value**
Proportional, Kp	41
Integral, Ki	0.001
Deriavative, Kd	5.3
Amplitude, A	3.017 radian
Frequency, ***f***	0.35 hertz
Angular Frequency, ***w***	2,199 rad/s
Overshoot, OS	0.57%

4.6 Active Force Control (AFC) and Proportional-Integral-Derivative (PID) Controller

In this part, the block diagram of the system, inverse process, crude approximation tuning, the result of the system and the discussion of the system result will be show.

4.6.1 Block Diagram

For AFC-PID controller, the block diagram consists of the system and the inverse process. Each block diagram has it function to produce desire output.

4.6.1.1 The system

AFC controller is joins with PID controller to reduce error system and reach desired output (angle). AFC controller relies on measurement and estimation of parameter. Back to literature review, from Newton's second law of motion for rotational bodies, the sum of all torques applied to the system is equal to the product of the mass moment of Inertia (I) and the angular acceleration (α) of the system: $\Sigma\tau = I\alpha$.

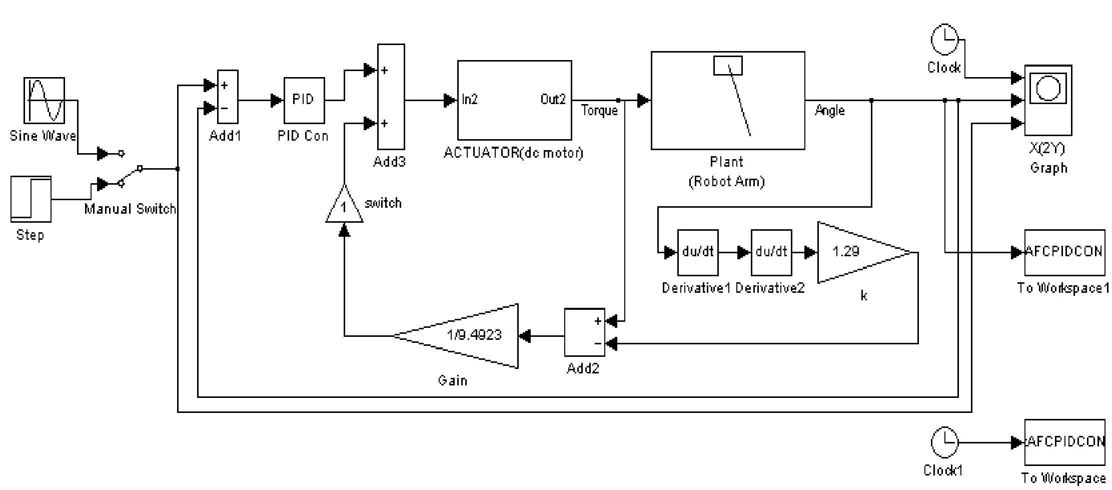

Figure 4.12: System with AFC-PID controller

4.6.1.2 Inverse process

In AFC-PID controller, an inverse value of actuator is needed. Figure 4.13 shows the block diagram to create inverse value for the system. When the sine wave goes through the actuator, a torque graph is plotted. If a number (random value) is times with the actuator's output and make a same graph as the sine wave input (almost same peak value), then the number can be consider as the inverse value. Inverse value this system is 1/9.4923.

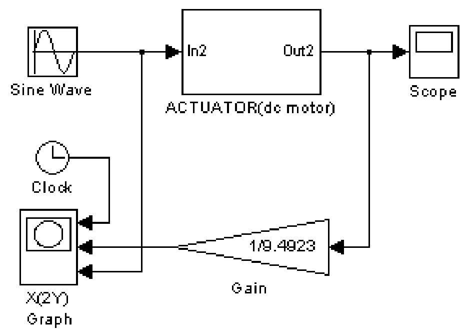

Figure 4.13: Inverse block diagram

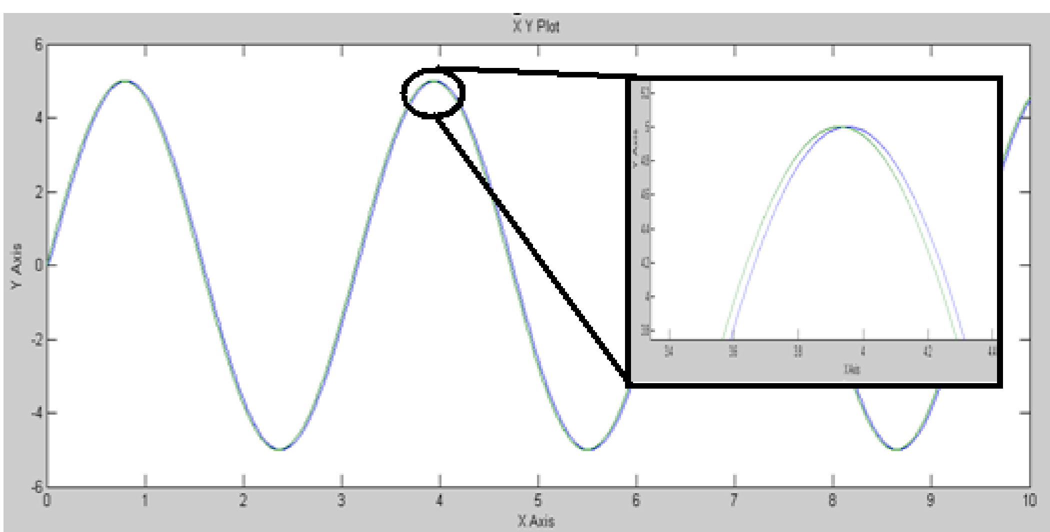

Figure 4.14: Inverse graph

4.6.2 Crude Approximation Tuning

For AFC-PID system, the estimate inertia matrix can be easily acquired by crude approximation, a reference of a look-up table or intelligent methods. It has been shown that the estimated inertia matrix need not be accurately approximated; the only requirement is that it should be within suitable range of values. With a rough estimation, a test of estimated mass is shown below with value 0.2, 1.29 and 2. Estimated mass with value 1.29 give the best response in step and sine wave input.

Figure 4.15 show graph step response. When the value of estimated mass is 0.2, the graph of the system is not stable. When estimated mass value change to 2, the system stable but there is an overshoot. After try and error for estimated mass, value 1.29 makes the graph stable and robust.

For sine wave response, the graph in Figure 4.16 not stable in the first cycle when the estimated mass value is 0.2. The overshoot value is higher when estimated mass value is 2 compare to 1.29. So the best value for estimated mass is still 1.29.

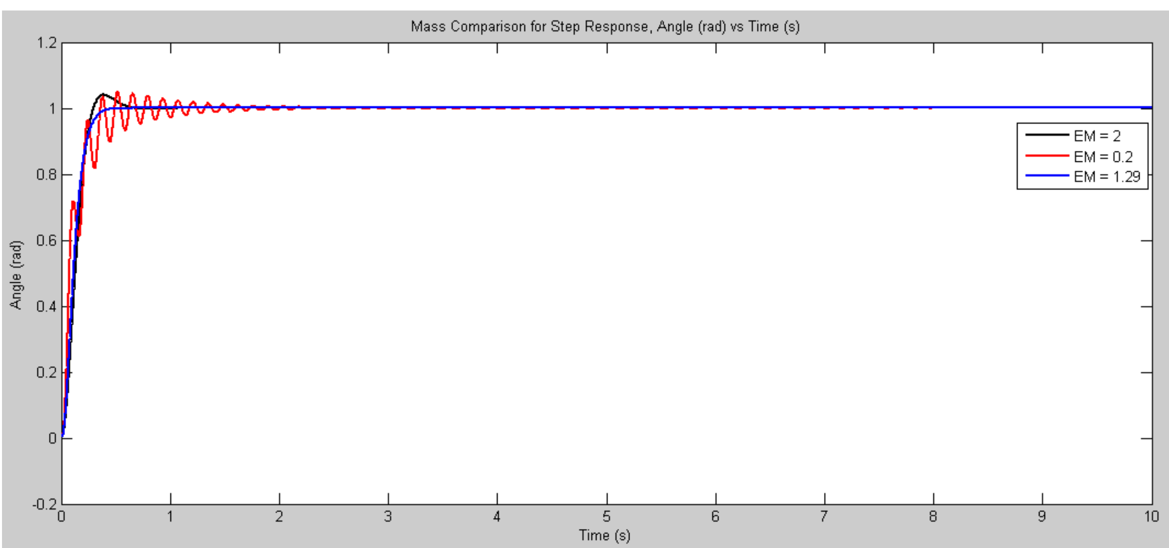

Figure 4.15: Step response with different estimated mass graph

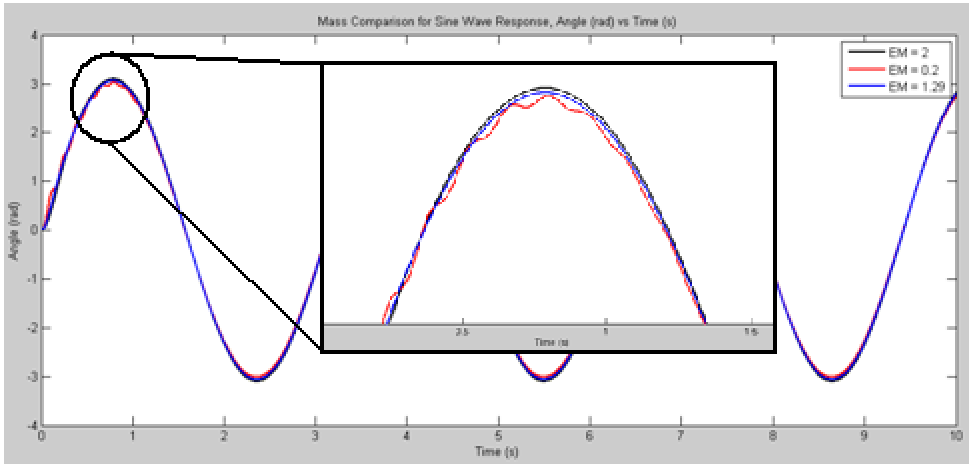

Figure 4.16: Sine wave response with different estimated mass graph

4.6.3 Result of Step and Sine Wave Response with System with AFC-PID Controller

Figure 4.17 and 4.18 show the result of the system with AFC-PID controller. The result with step input reaches the desire output in a short time. The sine wave input result has an overshoot. The detail of the results will be discussed in discussion part.

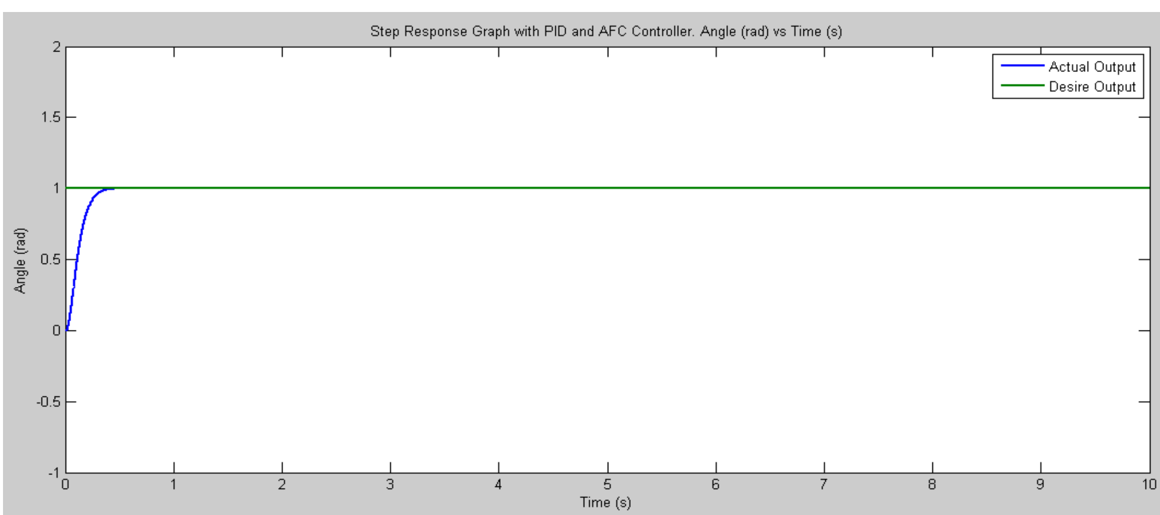

Figure 4.17: Step response graph of angle (rad) vs time(s)

Table 4.5: Step response result data

Specification	Value
Proportional, Kp	41
Integral, Ki	0.0001
Deriavative, Kd	5.3
Estimated Mass	1.29
Overshoot, OS	-
Steady State Error, ESS	-
Peak Time	-
Settling Time, Ts	0.6091 s
Rise Time, Tr	0.2536 s

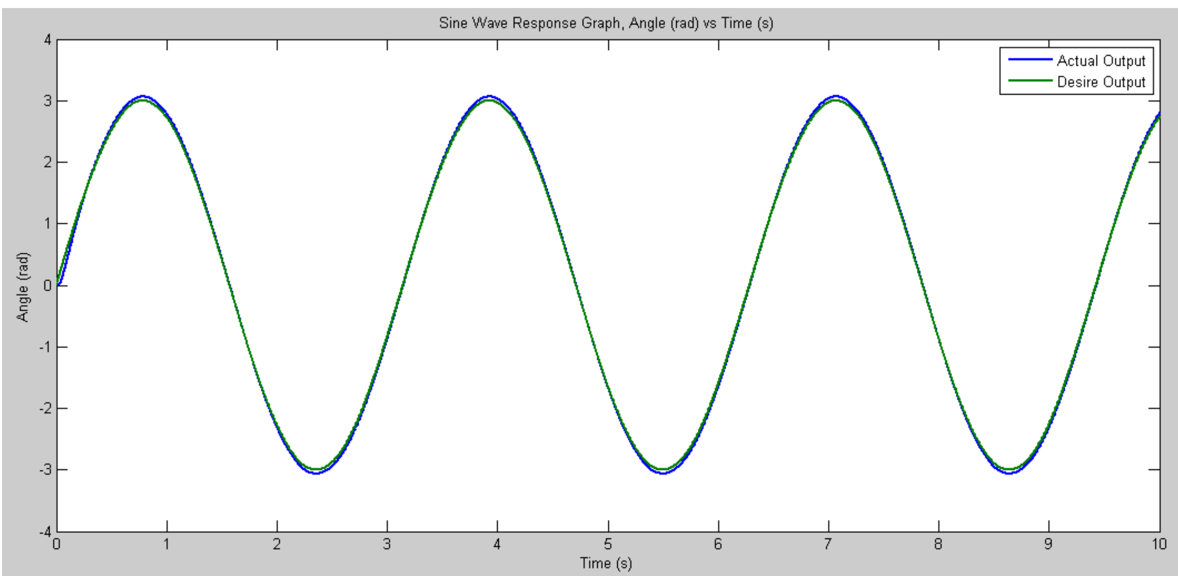

Figure 4.18: Sine wave response graph of angle (rad) vs time(s)

Table 4.6: Sine wave response result data

Specification	**Value**
Value of Proportional, Kp	41
Value of Integral, Ki	0.0001
Value of Deriavative, Kd	5.3
Estimated Mass	1.29
Amplitude, A	3.063 radian
Frequency, $\boldsymbol{f}$	0.35 hertz
Angular Frequency, $\boldsymbol{w}$	2,199 rad/s
Overshoot, OS	2.1%

4.6.4 Discussion

For AFC-PID controller, the graph result of single link flexible manipulator show the actual output is same as desire output for step input. The graph goes smoothly without overshoot/undershoot and steady state error. The rise for the system is 0.2536 second and settling time is 0.6091 second. This controller had minimized the vibration of the single link flexible manipulator. The graph is steady and robust.

For the sine wave results, with input Kp = 41 Ki = 0.0001 Kd = 5.3 at PID controller, we can see the value of frequency is non uniform for the set of PID tuning. For the first set of PID data, we can see the value of amplitude is 3.063 radian compared to desired value that is 3 radian. For the frequency, the PID tuning result is 0.35 Hz. The overshoot is 2.1% from peak of actual result to peak of desired.

4.7 Overall result comparison between all systems

In this part, all result for all system will be combined to show the different and improvement of the result. Table 4.7 and Figure 4.19 are result from step input. Table 4.8 and Figure 4.20 are result from sine wave input.

Table 4.7: Step response result data comparison

Specification	Overshoot/ undershoot	SSE	Rise Time	Settling Time
Without Controller	68.5%	0.2540s	0.6789s rad	6.5330s
PID	2.17%	0.0213s	0.2852 rad	1.1570s
AFC-PID	-	-	0.2818 rad	0.6091s

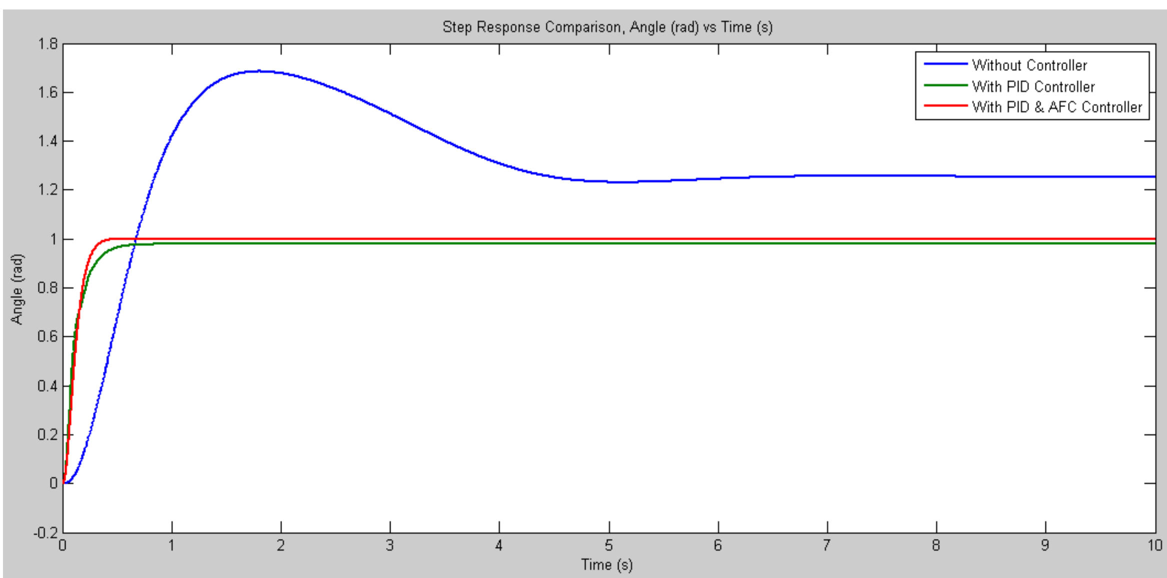

Figure 4.19: Step response graph comparison, angle (rad) vs time (s)

Table 4.8: Sine wave response result data comparison

Specification	Overshoot/ undershoot	Amplitude	Frequency	Angular Frequency
Without Controller	245.70%	10.388	0.3125	2.457
PID	0.57%	3.017	0.35	2.199
AFC-PID	2.10%	3.063	0.35	2.199

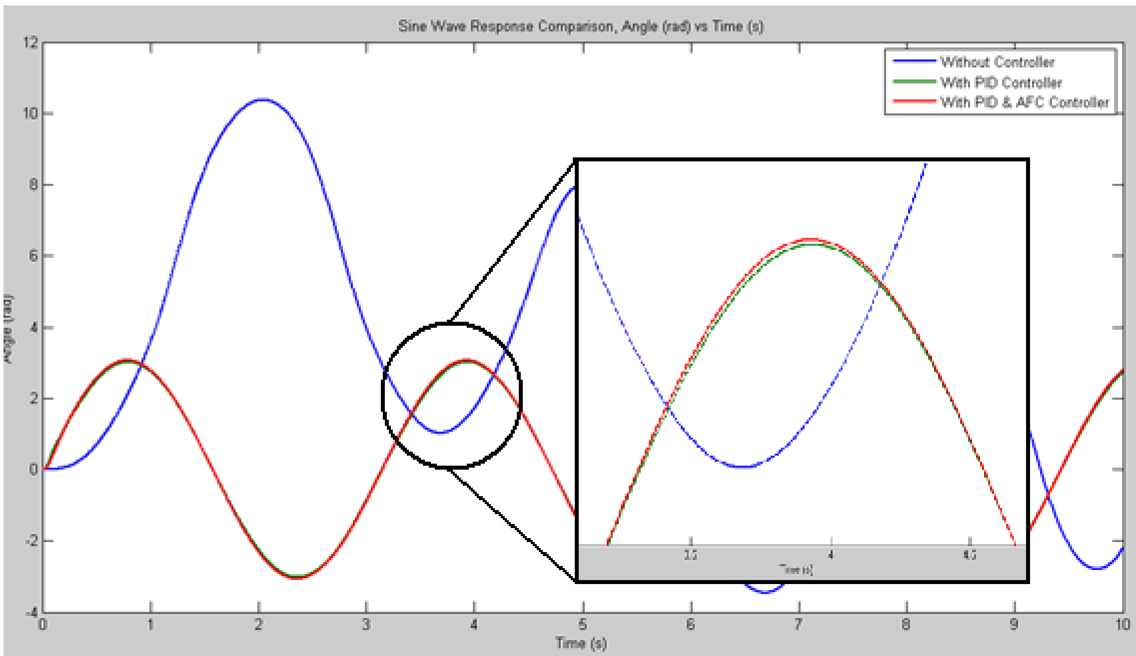

Figure 4.20: Sine wave comparison graph, angle (rad) vs time (s)

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 PROJECT SUMMARY

Every movement produces vibration then reduces the accuracy. For robot arm, as example robot that use to weld car chassis, the end effectors that hold the spark part need to touch target point accurately so the welding process will goes well.

Simulation help engineers to study and predict what things will happen next so they may prepare to counter the problem. There are various conditions that can be setup to study the case without an extra budget, specific space/place and time.

Matlab simulink is use to study vibration control in single link flexible manipulator in simulation as real world situation. It lets you do some complicated calculations quickly, without having to write a whole program. The mathematical equation of single link is transfer into simulation block diagrams, so it can be run, analyzed and compare. Matlab simulink has been proven to be able to solve real-time process control for simple and complex algorithms.

5.2 CONCLUSION

Finally, the objectives of this project to control vibration on the single link flexible manipulator using Proportional Integral Differential (PID) Controller. and Active Force Control controller also will be used with PID Controller to compensate the vibration. have been achieved. Three system with different controller show an improvement from graph result by comparing rise time, overshooting, settling time and steady state error. AFC-PID controller give the best result from those three systems.

5.3 RECOMMENDATION

There are some recommendations for this project for future research.

1) Student should be train how to use the software before do the simulation. It takes a lot of time to study how to use and learn the software.
2) Both simulation and experimental should be done together so student can study different of result-why simulation and experimental result almost have same pattern but not match at the edge.

REFERENCES

M. Benosman, G.L. Vey, Control of flexible manipulators: a survey, Robotica 22 (2004) 533–545.

W. Beres, J.Z. Sasiadek, G. Vukovich, Control and dynamic analysis of multilink flexible manipulators, Proceedings of the IEEE International Conference on Robotics and Automation 3 (1993) 478–483.

R.H. Cannon, E. Schmitz, Initial experiments on end-point control of a flexible one-link robot, The International Journal of Robotics Research 3 (3) (1984) 62–75.

Astrom, K. J. and Hagglund, T. (1995). PID Controllers: Theory, Design and Tuning, Instrument Society of America, Research Triangle Park, 2nd edition.

Astrom, K. J. and Haigglund, T. (2000a). The Future of PID Control, IFAC Work. on Digital Control: Past, present and future, Spain, Terrassa, pp. 19-30.

Ender D. B. (1993). Process Control Performance: not as Good as you Think, Control Engineering, September, pp. 180-190.

Pomerleau, A. and Poulin, E. (2002). A New Approach for TeachingProcess Control, Proc. of IASTED MIC'2002, February, Innsbruck, Austria, pp. 275-279.

Ziegler, J. G. and Nichol,s N. B., (1942). Optimum Settings for Automatic Controllers, Transactions of the ASME, 64, pp. 759-768.

Richard C. Dorf and Robert H. Bishop, 2005. Modern Control Systems**,** Tenth Edition. Prentice Hall.

L.C. Kwek, E.K. Wong, C.K. Loo, V.C. Rao, “Application of active force control and iterative learning in a 5-link biped robot,” *Journal of Intelligent and Robotics System*, vol. 37(2), pp. 143-162, 2003.

W. J. Book, "Recursive lagrangian dynamics of flexible manipulator arms," The International Journal of Robotics *Reseurch*, vol. 3, no. 3, pp. 87-101, 1984

A. Jnifene, A. Fahim, “A computed torque/time delay approach to the end-point control of a one-link flexible manipulator”, Dynamics and Control 7 (2) (1997) 171–189.

D. Wang and M. Vidyasagar, "Transfer fùnction for a single flexible link," 1989 *Proceedings of IEEE International Conference on Robotics and Automation, vol. 2*, pp. 1042-1047, 1989-