

MODELLING AND ANALYZING OF AN ACTIVE MAGNETIC BEARING

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A report submitted in partial fulfilment of the requirements

For the award of the degree of

Bachelor of Mechatronic Engineering

Faculty of Manufacturing Engineering

UNIVERSITY MALAYSIA PAHANG

JUNE 2013

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project report and in my opinion this project is satisfactory in terms of scope and quality for the award of Bachelor for Mechatronic Engineering.

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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 :

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Dedicated to two most important persons in my life, the one without hesitation towards me, the one with full faith on me,

My beloved parents

ACKNOWLEDGEMENTS

First and foremost, I am most thankful to The Almighty for granting me such a lifetime opportunity. I am heartily thankful to my supervisor, PM. Dr. Ajisman Apen, whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject. This thesis would not have been possible without their review and correction of my many mistakes, accompanied by the countless valuable suggestions.

I would like to acknowledge the staff of Faculty of Manufacturing Engineering of University Malaysia Pahang for providing the physical necessities of completing the project as well as generous access to unlimited support, either of internal or external resources. It is an honour for me to thank the educators and professors for all the theoretical and life lessons learnt this whole time.

I owe my deepest gratitude to my parents for their undeniable love, understanding and sacrifice throughout my life. It is a pleasure to thank my beloved family for their continuing encouragement and moral support at the time I needed the most. I am sincerely grateful to my fellow colleagues for the willingness of going through all the ups and downs together. Lastly, I offer my regards and blessings to all of those who supported me in any respect during the completion of the project.

ABSTRACT

This project presents a model of an active magnetic bearing which is design and analyzed using COMSOL Multiphysics and also analysis of an active magnetic bearing control system by using MatLab SimuLink. Magnetic flux from an active magnetic bearing is produced when a current is flowing in winding of the ferromagnetic core. To calculate this magnetic flux, the COMSOL Multiphysic is able to automatically calculate with just inserting the input of parameters. From this calculation, simulation of 2D magnetic flux density can be produce by following the step from COMSOL software guide. For control system of an active magnetic bearing, the Newton's law and the Kirchhoff's law are applied in order to obtain the right transfer function for the project. Graph resulting PID control for controlling the force, current and position is being plotted by comparing linear system and also non-linear system.

ABSTRAK

Projek ini membentangkan model aktif magnetik bearing yang di reka bentuk dan dianalisis menggunakan COMSOL Multiphysics dan juga analisis sistem kawalan aktif magnetik bearing dengan menggunakan MATLAB Simulink. Magnetik fluks daripada aktif magnetik bearing terhasil apabila arus elektrik terinduksi dengan penggulangan wayar tembaga kepada teras magnet yang merupakan bahan ferromagnet.. Untuk mengira fluks magnet ini, pengiraan diperlukan tetapi dengan bantuan COMSOL Multiphysic pengiraan ini secara automatik dikira dengan hanya memasukkan input parameter ke dalam COMSOL Multiphysic ini. Dari pengiraan ini, simulasi 2D ketumpatan fluks magnet boleh terhasil dengan hanya mengikuti beberapa langkah dari panduan perisian COMSOL. Bagi sistem kawalan aktif magnetik bearing, undang-undang Newton dan undang-undang Kirchhoff adalah penting untuk mendapatkan rangkap pindah yang akan digunakan. Graf akan terhasil melalui kawalan PID di dalam MatLab yang akan mengeluarkan graf bagi membandingkan perbezaan sistem linear dan juga sistem bukan linear.

TABLE OF CONTENTS

	Page
SUPERVISOR'S DECLARATION	ii
STUDENT DECLARATION	iii
DEDICATION	iv
ACKNOWLEDGEMENTS	v
ABSTRACT	vi
TABLE OF CONTENTS	ix
LIST OF TABLES	xii
LIST OF FIGURES	xiii

CHAPTER 1 INTRODUCTION

1.1	BACKGROUND OF PROJECT	1
1.2	PROBLEM STATEMENT	4
1.3	OBJECTIVE	4
1.4	SCOPE OF PROJECT	5
1.5	THESIS OVERVIEW	5

CHAPTER 2 LITERATURE REVIEW

2.1	INTRODUCTION	7
2.2	ACTIVE MAGNETIC BEARINGS (AMB'S)	7
2.3	THE SHAPE DESIGN OF THE ACTIVE MAGNETIC BEARING (AMB) STATOR	8
2.4	HOW ACTIVE MAGNETIC BEARINGS (AMBS) SYSTEM WORK?	10
2.5	THE HARDWARE PARTS	13
2.6	SUMMARY	14

CHAPTER 3 RESEARCH METHODOLOGY

3.1	INTRODUCTION	15
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3.2	PROCESS FLOW	15
3.3	PROJECT METHODOLOGY	16
3.4	CALCULATION INVOLVED IN MODELING AND ANALYSIS OF AN ACTIVE MAGNETIC BEARING	17
	3.4.1 OPTIMAL DESIGN	17
	3.4.2 MODELING THE MAGNETIC CIRCUIT	17
	3.4.3 OPTIMIZING THE PARAMETER	21
3.5	COIL DESIGN	21
3.6	CONTROL SYSTEM OF AN ACTIVE MAGNETIC BEARING	21
	3.6.1 OPEN LOOP CONTROL SYSTEM AND CLOSED LOOP CONTROL SYSTEM	22
	3.6.2 CLASSIFICATION OF CONTROLLERS	22
	3.6.3 MAGNETIC BEARING CONTROL	24
3.7	SUMMARY	27
 CHAPTER 4 RESULTS AND DISCUSSION		
4.1	INTRODUCTION	28
4.2	MODELING AND ANALYSIS OF AN ACTIVE MAGNETIC BEARING USING COMSOL MULTIPHYSIC	28

4.3	ANALYSIS OF CONTROL SYSTEM OF AN ACTIVE MAGNETIC BEARING USING MATLAB (1 POLE LEVITATES)	31
CHAPTER 5 CONCLUSION AND RECOMMENDATION		
5.1	INTRODUCTION	37
5.2	CONCLUSION	37
5.3	RECOMMENDATION	38
	REFERENCES	39
	APPENDIXES	41
A1	GANTT CHART FYP	41

LIST OF TABLES

Table 1.1: Thesis overview with chapters	6
Table 3.1: Transfer Function Method compare with State-variable method	25
Table 4.1 Input parameters taken into design	29

LIST OF FIGURES

Figure 2.1: AMB pole represented by 2 nd order curves	9
Figure 2.2: AMB pole represented by 3 rd order curves.	9
Figure 2.3: AMB stator with six poles (a) standard form, (b) rounded external pole part, (c) rounded internal pole part, and (d) proposed form with rounded corners.	10
Figure 2.4: Operation of control loop	11
Figure 2.5: Radial bearing includes four electromagnets and four sensors	12
Figure 2.6: Schematic diagram of a single axis AMB system.	13
Figure 3.1 Flowchart of project	16
Figure 3.2 Magnetic Circuit	18
Figure 3.3 Equivalent of an electric (DC) circuit	18
Figure 3.4 Ideal magnetic model	18
Figure 3.5: Magnetic flux density (T) x Magnetic Force (N) graph.	20
Figure 3.6: Split flux winding	21
Figure 3.7: un-split flux winding	21
Figure 3.8: Open loop system	22
Figure 3.9: Closed loop system	22

Figure 3.10: Active Magnetic Bearing system	26
Figure 3.11: Spring mass damper system	26
Figure 3.12: Block diagram of PD controller with current control	27
Figure 3.13: Block diagram of PID controller with current control	27
Figure 4.1 The FEM result on the meshing design	30
Figure 4.2 2D Magnetic flux density result for $T = 0.2$	31
Figure 4.3 Electromagnet model	32
Figure 4.4 Linear system with PID controller	34
Figure 4.5 Non-linear Plant system with PID controller	35
Figure 4.6: Result of comparing PID control to get the control effort for both systems	35
Figure 4.7: Result of comparing PID control to get the current (i) for both systems	36
Figure 4.8: Result of comparing PID control to get the position x for both systems	36

CHAPTER 1

INTRODUCTION

1.1 Background Of Project

It is an old dream of mankind to levitate a body hover without any contact by using magnetic forces. As early as 1842, the British minister and nature philosopher, Samuel Earnshaw (1805 - 1888), examined this question and stated a fundamental proposition known as Earnshaw's theorem. The essence of this theorem is that it is impossible for an object to be suspended in a stable equilibrium purely by means magnetic or electrostatic forces. First technical applications of levitation by magnetic field were proposed in 1937, when Kemper applied for a patent for a hovering suspension, while Beams and Holmes were working on electromagnetic suspension. This experiment was the predecessor of the later magnetically levitated vehicles. The most familiar levitation vehicle nowadays is the MAGLEV (derived from magnetic levitation), which uses the electromagnetic principle, is suspended without any contact by several magnets from the iron track. Later, in the sixties a principle of magnetic bearings was used in space technology for the magnetic suspension of momentum-wheels to control the attitude of satellites. First industrial applications appeared in the late seventies mainly for turbines and for high-speed machine tools. Because of the magnetic bearing offer a novel way to solve classical problems of rotor dynamics by

suspending a spinning rotor with no contact, wear and lubrication, and controlling its dynamic behaviour

An Active Magnetic Bearings (AMBs) is largely used nowadays in many industries, mostly in oil and gas industry since it can sustain high temperature with a constant high speed. Active magnetic bearings (AMBs) are experiencing an increased use in many rotating machines (e.g., compressors, milling spindles, flywheels, etc.) as an alternative to conventional mechanical bearings such as fluid film and rolling element bearings. An AMB provides a non-contact means of supporting a rotating shaft through an attractive, magnetic levitation force. The magnetic force is generated or controlled by passing an electric current through a coil wound around a stator made of ferromagnetic material (i.e., an electromagnet).

Due to the non-contact nature of the bearings and rotor, AMBs have the unique ability to suspend loads with no friction, eliminate wear, allow the operation of rotors at higher speeds, and operate under environmental conditions that prohibit the use of lubricants. Furthermore, since AMBs can be actively controlled, they offer other advantages over mechanical bearings such as eliminating rotor vibration through active damping, adjusting the stiffness of the suspending load, compensating for rotor misalignment and changes in rotor speed, and providing an automatic rotor balancing capability.

For my project, there are 2 main software that I used to design and analyse of an active magnetic bearing which is Comsol Multiphysics to analyse the design of an active magnetic bearing and MatLab to see how an active magnetic bearing work by using the principle of magnetic levitation.

COMSOL Multiphysics is a finite element analysis, solver and Simulation software / FEA Software package for various physics and engineering applications, especially coupled phenomena, or multiphysics. COMSOL Multiphysics also offers an extensive interface to MATLAB and its toolboxes for a large variety of programming, preprocessing and postprocessing possibilities. The packages are cross-platform (Windows, Mac, Linux). In addition to conventional physics-based user interfaces, COMSOL Multiphysics also allows for entering coupled systems of partial differential equations (PDEs). The PDEs can be entered directly or using the so-called weak form (see finite element method for a description of weak formulation). An early version (before 2005) of COMSOL Multiphysics was called FEMLAB.

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:

1. Math and computation
2. Algorithm development
3. Modeling, simulation, and prototyping
4. Data analysis, exploration, and visualization
5. Scientific and engineering graphics
6. Application development, including Graphical User Interface building

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non-interactive language such as C or FORTRAN. The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects, which together represent the state-of-the-art in software for matrix computation. MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis. MATLAB features a family of application-specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others.

1.2 Problem Statement

Nowadays, bearing is used widely in a rotating machines (e.g., compressors, milling spindles, flywheels, etc.) to support the load. Mechanical bearing is used in many applications but it creates friction loss. For example in high temperature place like turbine at oil and gas, the bearing will get wear easily and need to change them often due to the high temperature. Beside that for a place which use vacuum a normal bearing such as mechanical bearing can't perform here due to the vacuum suck air out from the place which mean oil from bearing will get suck out and make the friction between shaft and bearing will be high. The solution here is with an Active Magnetic Bearings (AMBs) the friction that create will be gone since an Active Magnetic Bearings (AMBs) is a no contact bearing which suspended by an electromagnet.

There are several questions on how to make the Active Magnetic bearings (AMBs), What is the type of core need to be used as a stator and what is the type of windings need to be used to produce an electromagnetic field. Beside that a duly formulae of megnetomotive force is needed to know whether it is sufficient to float/balance the shaft in the middle of stator/core.

This study investigated the entire problem about designing and analyse of an active magnetic bearing such as what is the type of core needed, how much windings need to be used, how much current flow need for each coil, and also how the system to levitate is working.

1.3 Objective

To develop and simulate a model of an active magnetic bearing.

To design and simulate a control system for controlling the current to levitate an object.

To analyze the active magnetic bearing.

1.4 Scope of Project

This thesis specifically has three scopes.

- (i) Design an Active Magnetic which can produce the sufficient magnetic flux density to levitate an object.
 - There will be 8 poles for the windings to be attached according to the north and south which will produce the magnetic flux.

- (ii) Program a control system in Matlab to see how an active magnetic bearing works.
 - There will be several transfer function which based on Newton Law's and Kirchhoff's Current/Voltage Law.

- (iii) Design a circuit for levitation
 - Circuit will consist of a component which will act as a Gate to allow several current flow to activate the magnetic bearing and also a sensor which will be suitable to sense current.

1.5 Thesis Overview

Modeling and analyzing of an active magnetic bearing final thesis is a compilation of 6 chapters that contains and elaborates specific topics such as the Introduction, Literature Review, Methodology, Architecture, Result and Analysis, Conclusion and Further Development that can be applied in this project.

Table 1.1: Thesis overview with chapters

Chapters	Content	Remarks
Chapter 1	Introduction	Basically about the background and introduction of this project.
Chapter 2	Literature Review	Describe about the literature review for the development of the solar based monitoring workstation cited from related sources.
Chapter 3	Methodology	Discuss on the full methodology of this project
Chapter 4	Systems Architecture	Discuss about the architecture of the project that consist of the hardware design and the software implementation.
Chapter 5	Results and Data Analysis	Discuss all the results obtained and the limitation of the project. All discussions are concentrating on the result and performance of the Active Magnetic Bearings (AMBs)
Chapter 6	Conclusion	Discuss the conclusion and further development of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explains the capabilities and features of the existing Active Magnetic Bearings (AMBs) described in the literature that were reviewed. The aim of this literature review is to acquire great understanding of how to design an Active Magnetic Bearings to support a rotating load that have been implemented and are already use in similar situation which will be useful for my research. The suitable features examined will be considered to be incorporated into the proposed system.

The objectives of this chapter are:

- To understand how an Active Magnetic Bearings (AMBs) work
- To select the appropriate components, device or circuit related to this project.
- To understand the formulae and transfer function for this project.

2.2 Active Magnetic Bearings (AMBs)

The term "**bearing**" comes ultimately from the verb "to bear" and a bearing is thus a machine element that allows one part to bear another. A bearing is any of various machine elements that constrain the relative motion between two or more parts to only the desired type of motion. This is typically to allow and promote free rotation around a fixed axis or free linear movement; it may also be to prevent any

motion, such as by controlling the vectors of normal forces. Bearings may be classified broadly according to the motions they allow and according to their principle of operation, as well as by the directions of applied loads they can handle. But the problem with normal mechanical bearing is that it had a friction loss and also easy to get wear which will be need to change more often. With **Active Magnetic Bearings (AMBs)** is the best solution which can give a zero friction by having a no contact to the rotor/shaft. Besides that, AMBs can operate in high speed with a high efficiency while giving low noise. Magnetic bearing is an active system, thus it provides several advantages over a passive one. The controller can compensate unbalance and control the rotor behaviour actively at critical speeds. System monitoring is then possible by using the AMB as a sensor, which provides indications about the changes in shaft dynamics. This system diagnosis enables to reduce the maintenance cost by increasing the intervals between engine services.

2.3 The Shape design of the Active Magnetic Bearing (AMB) stator

According to Adam Pilat (2010), Computer-aided design (CAD) software in the modeling process is the standard design method used to design the shape of the AMB bearing core. The designs consist of graphical primitives like lines and arcs with fixed properties. There are 2 method for choosing the design which is based on mathematical analysis and representation of the AMB stator by curve. There are many main components of the AMB which need to be considered in designing AMB which are stator for windings, coils, power actuators, control system with appropriate control strategy and rotor as a target object of control.

The main focus which illustrate by Adam Pilat is the stator construction which has a number of rectangular poles where coil windings are mounted. The connected coils and stator core compound an electromagnet that precisely generates attractive force acting on the rotor under controller supervision which is a microcontroller. The stator is manufacture with laminated metal plates produced in the cutting process using blanking die method, laser tools or CNC machines. The design procedure requires analytical and numerical calculations of the electromagnetic forces beside tend to be optimal in the case of pole numbers and their location. There are 2 designs which being

consider to design AMB stator based on curves which is AMB pole represented by 2nd order curves and AMB poles represented by 3rd order curves.

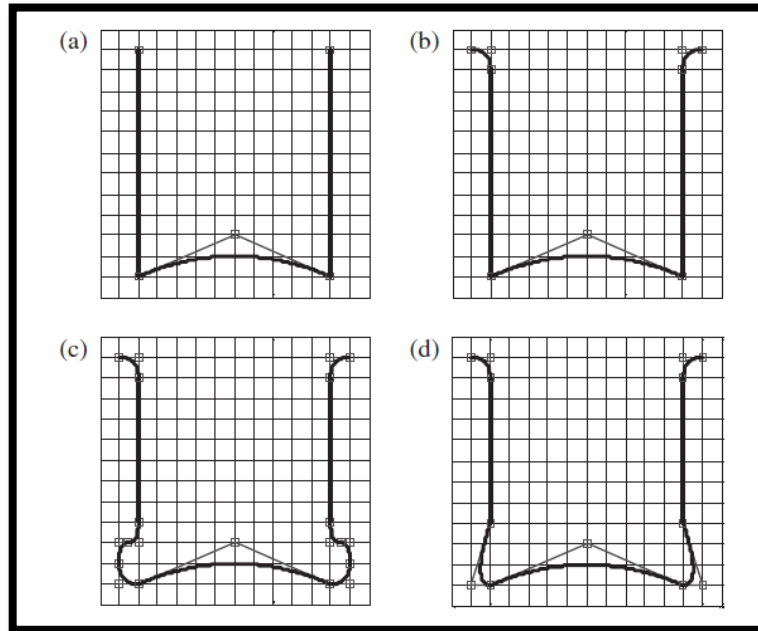


Figure 2.1: AMB pole represented by 2nd order curves.

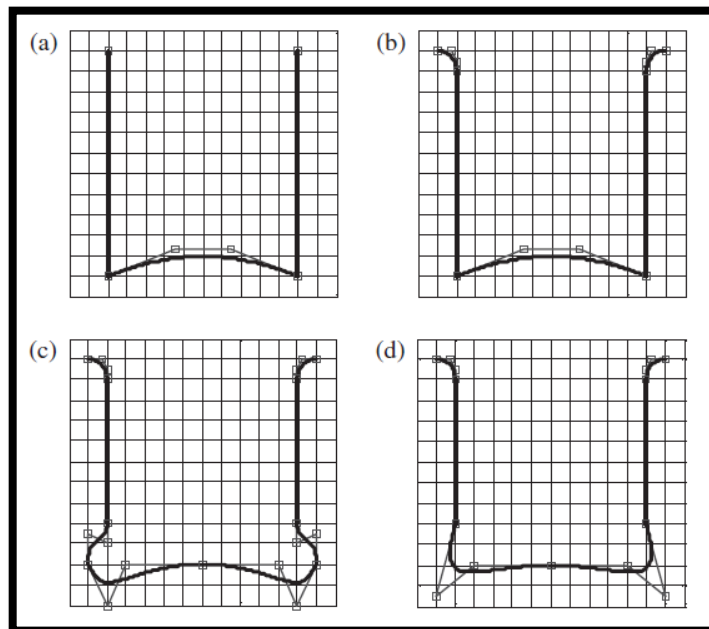


Figure 2.2: AMB pole represented by 3rd order curves.

With the presented design method of the stator shape, it opens a new features for modeling, optimization and analysis of the magnetic field interaction in the AMB based machinery. The highest accuracy gives is by the 3rd order curve. Figure 2.3 below show the complete form of the AMB stator shape.

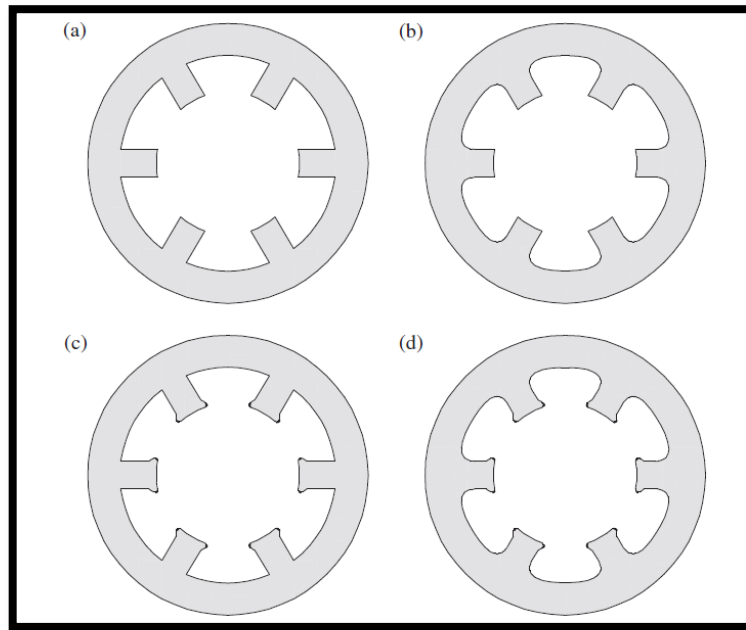


Figure 2.3: AMB stator with six poles (a) standard form, (b) rounded external pole part, (c) rounded internal pole part, and (d) proposed form with rounded corners.

2.4 How Active Magnetic Bearings (AMBs) system work?

How it works? **H. Habermann and G. Liard (1980)** said that Actidyne active magnetic bearing system is the basic principle of design and operation. The advantages of this system are due to the absence of mechanical contact, obviating the need for lubrication, and to the high accuracy of shaft position. The idea of making a suspension of a rotating shaft in a magnetic field without mechanical contact and without lubrication is an old idea from 1842 which was introduced by Earnshaw to make a passive magnetic suspension and the first description of a totally active magnetic suspension system was only issued in 1957 as a French patent assigned to the Hispano-Suiza Company. During the last ten years electric control has been sufficiently

developed to make the design of an active magnetic for industrial application is possible. Industrial application, particularly for large machinery with shafts weighing several tons.

The principle of the Actidyne active magnetic bearing system is that the body is supported and the rotor is held in the desired position relative to the stationary body while the stator by electromagnetic control. The sensors used for this system is a highly accurate inductive sensors to monitor the position continuously. After amplification, currents are induced in the windings of the electromagnets of the stator and the magnetic and magnetic force is produced serve to restore the rotor to the desired position so that stable centering is achieved. The interaction between the bearing and the control is shown in figure below

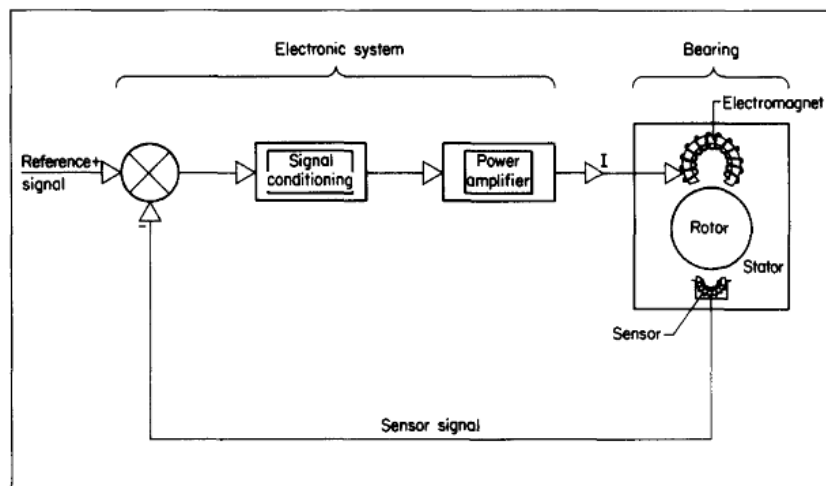


Figure 2.4: Operation of control loop

According to H. Habermann and G. Liard also the principle operation of a radial bearing includes four electromagnets and four sensors. Ferromagnetic lamination without windings is used for the rotor and is supported by magnetic forces. The rotor will keep it in the desired position. Figure below show the example:-

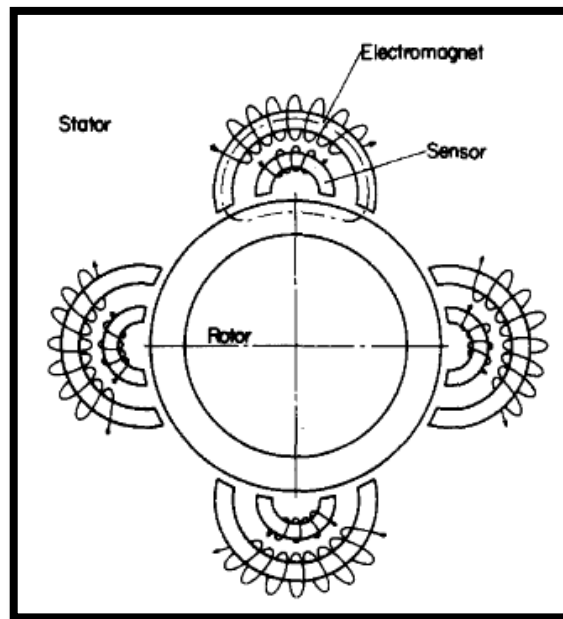


Figure 2.5: Radial bearing includes four electromagnets and four sensors.

According to **Hada Chang and Sung-Chong Chung (2002)**, the size, the controller and power amplifier affect the performance of active magnetic bearing (AMB). Good stiffness, damping and stability, simultaneous consideration on the AMB itself and characteristics of the controller and the power amplifier should be required to design optimal AMB systems. A radial active magnetic bearing (AMB) system supports a rotor without having any mechanical contact by electrically controlling the electromagnetic force. The rotor will be floated in the air gap and get rid of the mechanical breakdown caused by wear or friction and there is no need for lubrication and sealing which will be save on money and time of workers. AMB system can be designed so that it has adjustable stiffness and damping. A high-speed and high-precision rotating motion can be implemented and this is why AMB systems referred to have big potentiality in the industry. Figure below show the schematic diagram of a single axis AMB system which is designed by the author:-

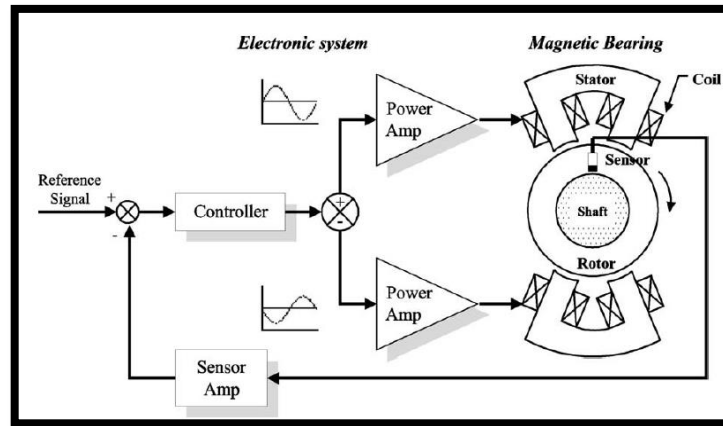


Figure 2.6: Schematic diagram of a single axis AMB system.

2.5 The Hardware parts

There are 6 parts in building hardware for Active Magnetic Bearings (AMBs) said **Dr. Luc BURDET (2006)**. The first main part is the core for AMB. Iron core is the best material to be used. What is an Iron core? Iron core is a material conducting the magnetic field to the air gap. It's magnetic permeability and its magnetic saturation has to be high. Eddy current losses is need to be minimize, In order to minimize it, the core usually consist of insulated lamination sheets. Next is the Windings, The current through the winding is the source of magnetic field. It is made of an insulated conductor wound on the soft magnetic core. In order to improve the efficiency of the AMB, the conductor has to have a low electrical resistance and must be wound with a high fill factor. The best material considered to be the best for windings is nickel-copper or copper. For the author, it used different type of windings since it need the best material to be handle a high temperature for the research.

The 3rd parts being used is the rotor. The rotor, in standard constructions, is realized with a lamination packet shrinked on a non-magnetic shaft. Tight manufacturing tolerances are needed in order to avoid unbalances in the weight of shaft. It is important to make sure the mechanical property of the rotor lamination is good this is because to overcome the centrifugal stress due to high speed rotation. The 4th part is the position sensors. Since AMBs are actively controlled regarding to the sensor signal,

the control performance strongly depends on the sensor performance. Other types of sensor usually used in AMBs are inductive, eddy current, capacity and optical displacement sensors.

Last but not least, a microcontroller. Nowadays controllers are mainly based on digital technology. Great flexibility and high computation is provided by the controllers. Digital controllers enable principally an adaptive control, unbalance compensation and provide a great tool for system diagnosis. AMBs are controlled in a close –loop. Different method such as PD or PID, optimal output feedback or observer based state feedback is in use. Lastly is the Power Amplifiers. Why use Power Amplifiers? It is because amplifiers convert the control signal from PID hardware into control currents. Switching amplifiers are usually used because of their low losses. The amplifier is often the limiting component in an AMB system.

2.6 SUMMARY

As a conclusion Active Magnetic Bearing (AMB) is the solution to reduce the cost for changing a bearing if they got wear and having a zero friction. Besides that, AMB can operate in high-speed and high-temperature place which allow oil and gas industries which use turbines to use AMB as their new bearing. Mechanical bearing will only allow more money spend and more time wasting for workers to change it regularly. There are many Computer Aided Design (CAD) programs that can be used in modeling the active magnetic bearing such as CATIA, Solidwork, AutoCAD and Comsol MultiPhysic. MatLab is the best solution in analysis of control system.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will cover about the methodology of Modeling and analyzing of an active magnetic bearing

Objectives of this chapter are:

- To explain the flow chart on How Active Magnetic Working
- To explain the method use in designing, controlling and programming.
- To explain Gantt charts on my progress.

3.2 Process Flow

In this project, the first thing to do is to do the mechanical design, there are several specification that needed to be considered for the design such as the number of turns for each coil. Besides that, I also need to consider the type of core I need to used, as we know iron core with no losses is the most suitable material because it has high magnetic permeability. This is why iron is almost always used for electromagnet cores. When the current in the wire generates its magnetic field, it also induces a field in the iron, which makes the magnetic field of the wire thousands of times stronger. Lastly, you need to considered about the type of wire you need to use by checking into American wire gauge table to see the resistance of copper wire. After that do the analysis on active magnetic bearing control system by using MatLab.

3.3 Project Methodology

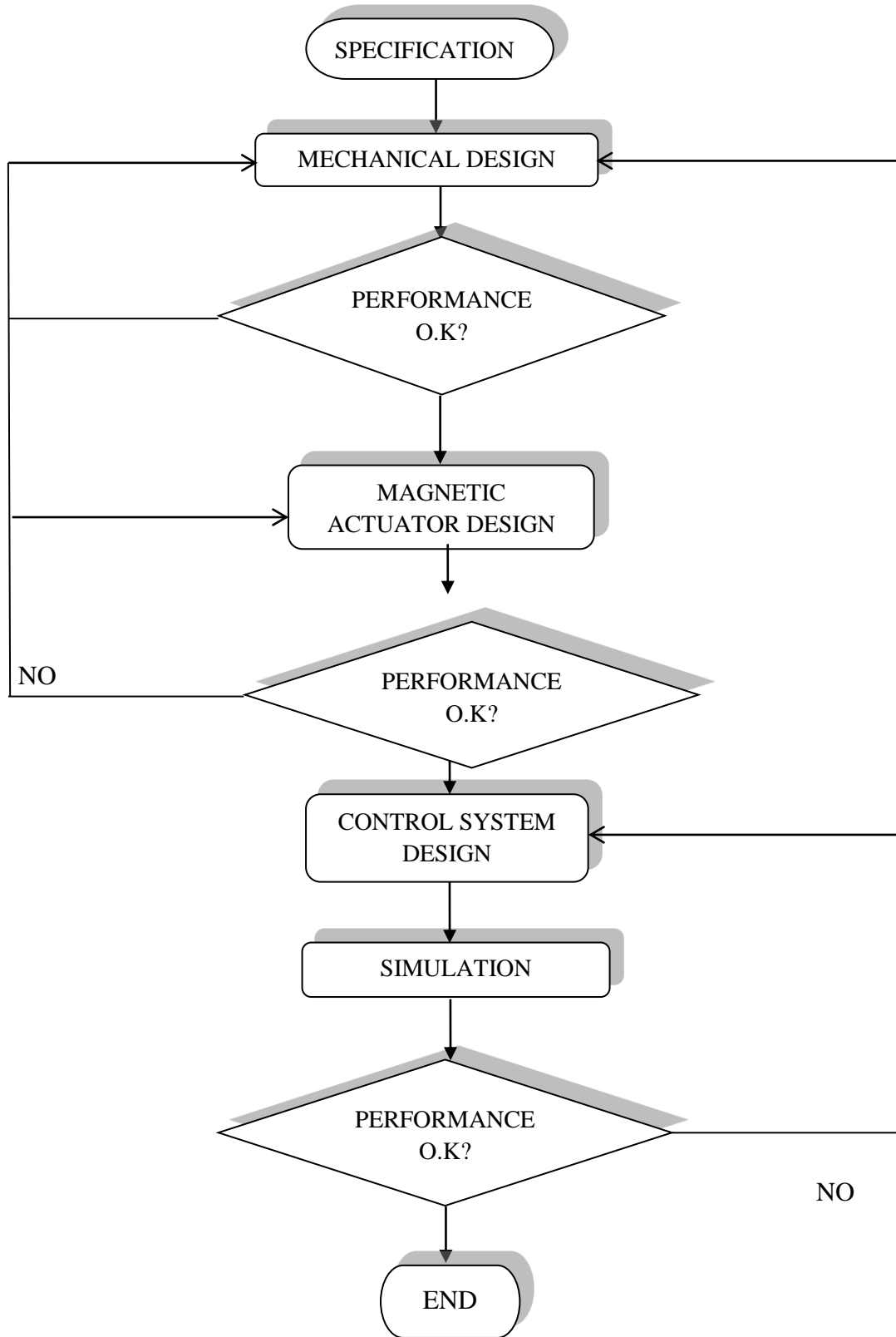


Figure 3.1: Flow chart of project

3.4 Calculation involved in modeling and analysis of an active magnetic bearing

3.4.1 Optimal design

In the design of experiments, optimal designs are a class of experimental designs that are optimal with respect to some statistical criterion. In the design of experiments for estimating statistical models, optimal designs allow parameters to be estimated without bias and with minimum-variance. A non-optimal design requires a greater number of experimental runs to estimate the parameters with the same precision as an optimal design. In practical terms, optimal experiments can reduce the costs of experimentation. The optimality of a design depends on the statistical model and is assessed with respect to a statistical criterion, which is related to the variance-matrix of the estimator. Specifying an appropriate model and specifying a suitable criterion function both require understanding of statistical theory and practical knowledge with designing experiments. Optimal design is carried out in two steps :-

1. Modeling the magnetic circuit to determine the accuracy of achieving objective.
2. Optimizing of the parameters to determine the efficiency of the achieving objective.

3.3.2 Modeling the magnetic circuit

In modeling the magnetic circuit, we need to know the basic of magnetic circuit and the equivalent circuit as shown in figure 3.2 and figure 3.3:-

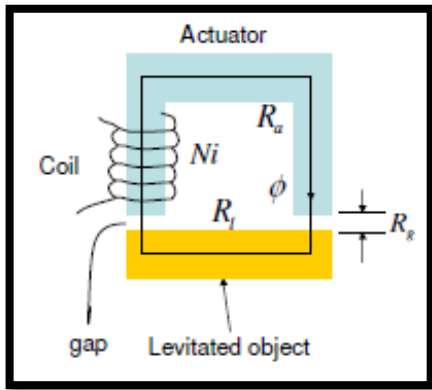


Figure 3.2: Magnetic Circuit

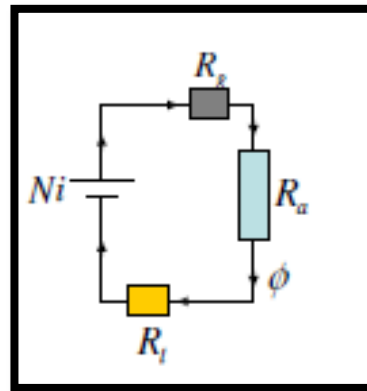


Figure 3.3: Equivalent of an electric (DC) circuit

There are differences analogies between magnetic circuit and electric circuit such as in magnetic circuit we called Magneto motive Force (MMF) but in electric circuit we called it Electro Motive Force (EMF) or can simply be said Voltage (V). Besides that, Electric Current (I) in electric circuit can be defined as magnetic flux (ϕ) in magnetic circuit. Lastly, Resistance (R) in electric circuit is called Reluctance (R).

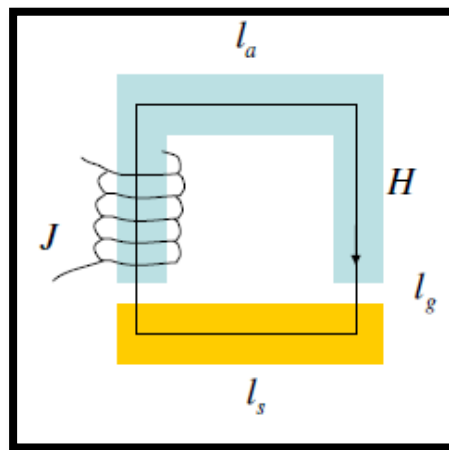


Figure 3.4: Ideal magnetic model

Based on the figure 3.4 the basic law governing the production of a magnetic field by current is Ampere's Law:-

$$\oint H \cdot dl = I_{net} \quad (3.1)$$

Where H is the magnetic field intensity produced by the current I_{net} , and dl is the differential element of the length along the path of integration. In SI units, I_{net} is measured in amperes and H is measured in ampere-turn per meter. In path of integration, I_{net} is then equals to Ni , since the coil of wire cuts the path of integration N times while carrying current i . Ampere's law thus become:-

$$Hlc = Ni \quad (3.2)$$

Therefore,

$$H = \frac{Ni}{lc} \quad (3.3)$$

For the ideal magnetic circuit shown in figure 3.4:

$$2 H_g l_g + H_a l_a + H_s l_s = Ni \quad (3.4)$$

Thus the relation ship between the magnetic field intensity H and the resulting magnetic flux density B produced within a material is given by:-

$$B = \mu H \text{ or } H = B/\mu \quad (3.5)$$

Where,

H = magnetic field intensity.

μ = magnetic permeability of material. = $\mu_o \mu_r$

B = resulting magnetic flux density produced.

From (3.5) equation we can substitute into (3.4),

$$2 B_g l_g + \mu_o \left(\frac{B_a}{\mu_a} l_a + \frac{B_s}{\mu_s} l_s \right) = \mu_o Ni \quad (3.6)$$

if, $\mu_o \left(\frac{B_a}{\mu_a} l_a + \frac{B_s}{\mu_s} l_s \right)$ is neglected.

So, the flux density that is used to find the force exerted is

$$B_g = \frac{\mu_o Ni}{2l_g} \quad (3.7)$$

If K_a is added for the $\mu_o \left(\frac{B_a}{\mu_a} l_a + \frac{B_s}{\mu_s} l_s \right)$ as a core loss factor of K_i is added as coil loss factor. Then, The model is reduces to

$$B_g = \frac{\mu_o K_i Ni}{2 K_a l_g} \quad (3.8)$$

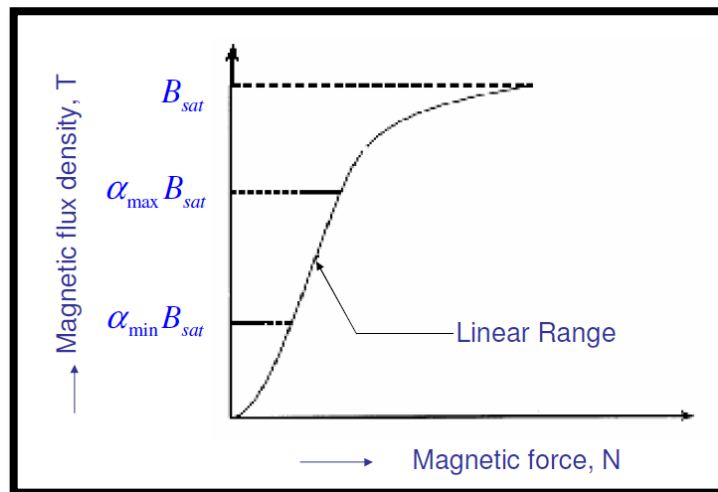


Figure 3.5: Magnetic flux density (T) x Magnetic Force (N) graph.

3.4.3 Optimizing the parameter

For parameters in an active magnetic bearing it is divided into 2, which is known parameters and free parameters. For known parameters are Gap, Inner radius of the bearing and Outer radius of the bearing. For Free parameters it is Inner radius of the coil space, Outer radius of the coil space, Height of the coil space and Current density supplied. All other parameters are dependent on the design.

3.5 Coil design

Admissible coil temperature is determined by the choice of insulation type for the windings or the core. Numbers of turns are chosen such that it generates maximum admissible magneto motive force (MMF) at the maximum current supplied by the power amplifier. The difference between split flux and un-split flux is that split flux only efficient using core rather than un-split flux which cause lower rotating losses and simpler current control

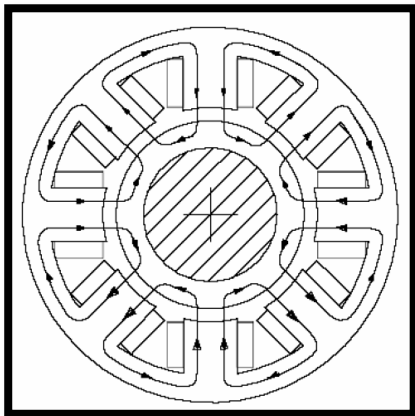


Figure 3.6: Split flux winding

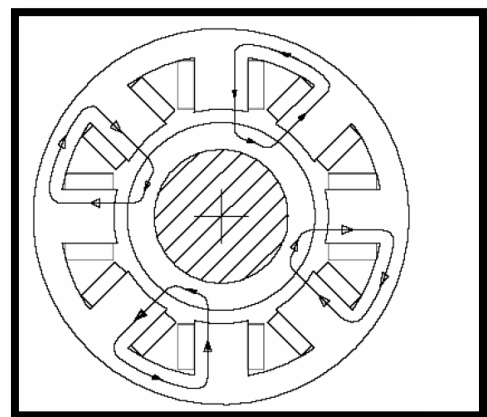


Figure 3.7: un-split flux winding

3.6 Control system of an active magnetic bearing

3.6.1 Open loop control system and Closed loop control system

A control system is divided into 2 which is open loop control system and closed loop control system. The control in which the output of the system has no effect on input is called open loop control. Open loop control is used when the input is known and there are no external disturbances. An example of open loop control is washing machine which works on time basis rather than the cleanliness of clothes. If the control maintains a prescribed output and reference input relation by comparing them and uses their difference as control quantity, it is called feedback or closed loop control. Temperature control of a room is an example of closed loop system. Figure below show the example of both systems.



Figure 3.8: Open loop system

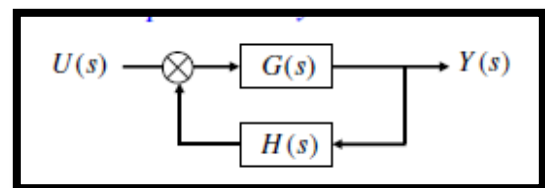


Figure 3.9: Closed loop system

3.6.2 Classification of controllers

According to control action, controllers are classified as :-

1. Two-position or on-off controllers
2. Proportional controllers
3. Integral controllers
4. Proportional-Integral controllers
5. Proportional-differential controllers
6. Proportional-differential-Integral controllers.

For two-position or on-off controllers the output of the controller $y(t)$ will be a maximum or minimum according to the state of error $e(t)$ as below:

$$\begin{aligned}
 y_{(t)} &= y_o \quad \text{for } e_{(t)} = 0 \\
 &= y_i \quad \text{for } e_{(t)} \neq 0
 \end{aligned}
 \tag{3.9}$$

y_o and y_i are minimum and maximum value of output.

For Proportional controllers the output of the controller $y_{(t)}$ is proportional to the magnitude of the actuating error $e_{(t)}$ signal as

$$y_{(t)} = g_p e_{(t)} \tag{3.10}$$

By Laplace transformation:-

$$\frac{Y_{(s)}}{E_{(s)}} = g_p, \text{ which is } g_p = \text{proportional gain} \tag{3.11}$$

For Integral controllers, in integral control action, the value of the controller output $y_{(t)}$ is changed at a rate proportional to the actuating error signal $e_{(t)}$

By Laplace Transformation:-

$$\frac{Y_{(s)}}{E_{(s)}} = \frac{g_i}{s}, \text{ } g_i \text{ is called Integral gain} \tag{3.12}$$

For Proportional-Integral (PI) controllers, control action is a combination of both proportional and integral action.

$$y_{(t)} = g_p e_{(t)} + \frac{g_p}{T_i} \int_0^t e_{(t)} dt \tag{3.13}$$

By Laplace Transformation:-

$$\frac{Y_{(s)}}{E_{(s)}} = g_p \left(1 + \frac{1}{T_i s} \right) \tag{3.14}$$

For Proportional-differential (PD) controllers, The control action is defined by:-

$$y(t) = g_p e(t) + g_p T_d \frac{d e(t)}{dt} \quad (3.15)$$

By Laplace Transformation:-

$$\frac{Y(s)}{E(s)} = g_p (1 + T_d s) \quad (3.16)$$

For Proportional-Integral-Differential (PID) controllers, it has the advantages of all three actions. So this is the most common type of industrial controllers. Mathematical form of PID action is :-

$$y(t) = g_p e(t) + \frac{g_p}{T_i} \int_0^t e(t) dt + g_p T_d \frac{d e(t)}{dt} \quad (3.17)$$

By Laplace Transformation:-

$$\frac{Y(s)}{E(s)} = g_p \left(1 + \frac{1}{T_i s} + T_d s \right) \quad (3.18)$$

3.6.3 Magnetic bearing control

There are 2 methods of design and analysis of controllers. The first method is Transfer function method also known as classical control which contains transient and steady state response analysis, Root locus analysis and frequency response analysis. The second method is state-variable method also called as modern control which contains pole- placement analysis and Linear-quadratic optimization. Table 3.1 below show clearly the differences between both methods.

Table 3.1: Transfer Function Method compare with State-variable method

Transfer Function Method	State-variable method
Classical control method	Modern control method
Used for single input single output (SISO) systems	Used for multi input multi output (MIMO) systems can be used for SISO Also
It is useful for linear and simple systems only	It is useful for nonlinear and Complex systems also.
Frequency domain method	Time domain method
Analysis consists of single higher order differential equation	Analysis consists of system of n first Order differential equations.
Steady state and transient response analysis, Root locus analysis and frequency response analysis are the main methods of design and analysis	Pole-placement method and Linear-quadratic optimization are the main Methods of design and analysis.

For a mechanical spring there will be an equilibrium point where the force resisted by the spring is equal to the force applied on the spring. But for electro magnets there will be a quantity of current corresponding to position of the object and force applied. At this point the gravity force and magnetic force will be equal. A slight movement from this point will cause indefinite movement of the body. This point is called operating point

For linearized formula around the operating point is :-

$$f(x, i) = k_x x + k_i i \quad (3.9)$$

Where,

x = the displacement from the operating position

i = the deviation of current from operating current

k_x = displacement stiffness

k_i = current stiffness

f = instantaneous force

Linearized equation is suitable for most of the applications of magnetic bearings, it is not valid in three occasions which is when $x = x_0$ the rotor touches the bearing magnet, when there are strong currents such that magnetic saturation of the material occurs and when $i = i_0$ or very small currents there won't be levitation of the rotor because of very small magnetic forces. Magnetic bearing system control is made by combining linearized formula with a newton's law $f = m\ddot{x}$ where we will get:-

$$m\ddot{x} - k_x x = k_i i \quad (3.19)$$

Figure below show the Active magnetic bearing system and spring mass damper system.

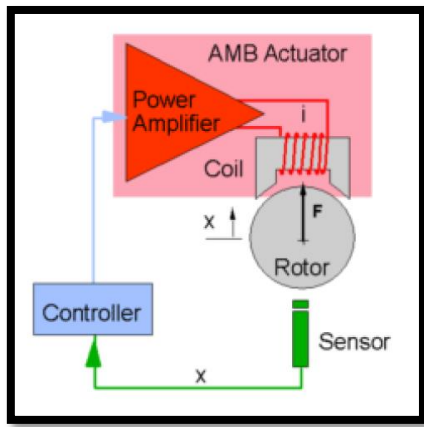


Figure 3.10: Active Magnetic Bearing system

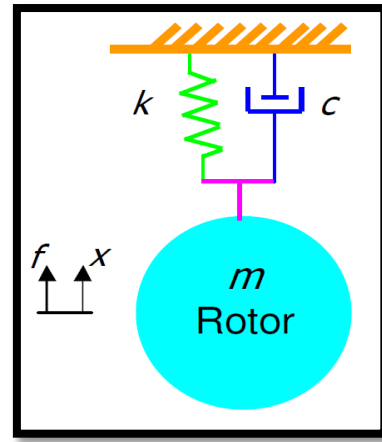


Figure 3.11: Spring mass damper system

From equation 3.10, we can conclude that if the controlling current is zero then $m\ddot{x} - k_x x = 0$ and the response grows exponentially thus the rotor may fall down or touch the magnet. If we supply controlling current such that it becomes like:-

$$i(x) = \frac{k + k_x}{k_i} x + \frac{c}{k_i} \dot{x} \quad (3.20)$$

Then it becomes,

$$m\ddot{x} + c\dot{x} + kx = 0 \quad (3.21)$$

And the response is imitated to a spring mass damper system by the magnetic bearing system.

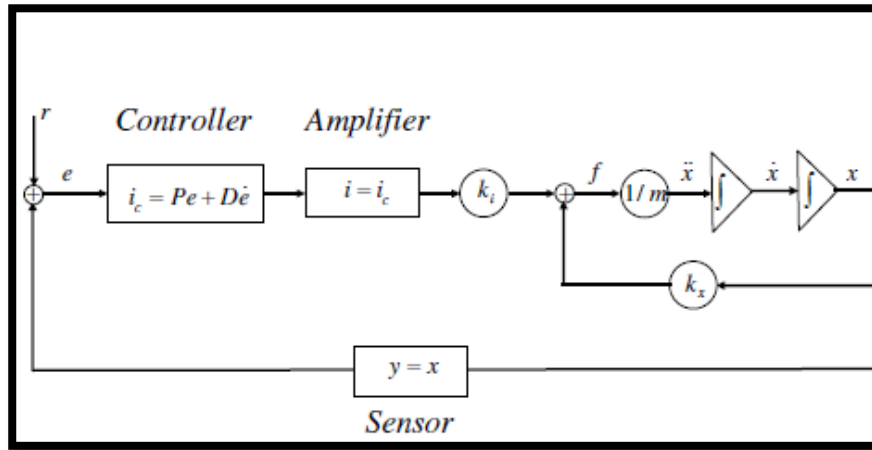


Figure 3.12: Block diagram of PD controller with current control

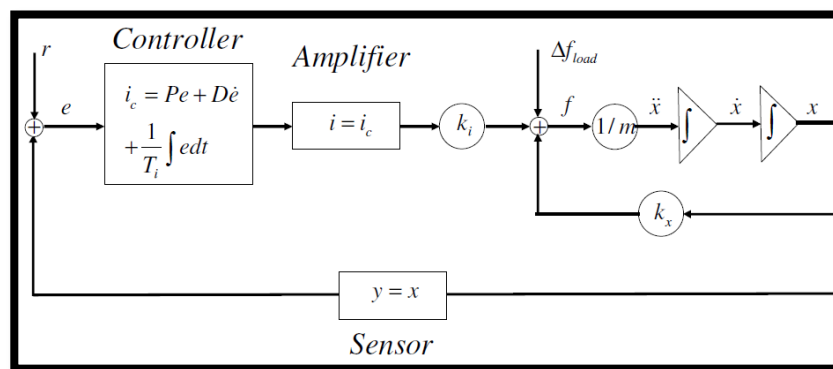


Figure 3.13: Block diagram of PID controller with current control

3.7 Summary

This chapter discussed the method or technique which will be used in this project. The specific understanding of selection, crossover and mutation basic explanation also included in this chapter. The conclusion is that there are several calculations used and mostly is Ampere's law which is important to analyze on the design of an active magnetic bearing to get the magnetic flux density. For control system of an active magnetic bearing we need to know about Kirchoff's law and also Newton's law to produce the transfer function needed. Lastly, to build a real active magnetic bearing is very complicated.

CHAPTER 4

RESULT AND ANALYSIS

4.1 Introduction

Finally, this project has been successfully achieved the scope and objective. Modeling an active magnetic bearing is done in COMSOL Multiphysic software resulting the magnetic flux density in the design had been achieved and showed in simulation. Besides that, all the assuming parameters is being calculated rightly by using all the formulae for magnetic model is done with the help of Electric Machinery and Power System Fundamentals book by Stephen J. Chapman. For analysis on how an active magnetic bearing control system work which is done in MatLab resulting the correct graph for control effort, currents and position x . The control system is done by assuming one pole of actuator to levitate an object. By assuming all the parameters, the result is being compared between linear plant and non-linear plant by using PID control.

4.2 Modeling and analysis of an active magnetic bearing using COMSOL Multiphysic

From chapter 3, the method to model an active magnetic bearing is to modeling a magnetic circuit and to optimizing the parameters. The first step to build an active magnetic bearing is to design the magnetic bearing itself and come out with all the parameters. All the parameters is shown in table 4.1 below:-

Table 4.1 Input parameters taken into design

PARAMETER	VALUE
Inner radius of the bearing	25.00mm
Operating air gap	4.00mm
Operating load	2025N
Variation in the gap	±5%
Variation in the load	±10%
Saturation flux density	1.00T
Remnant flux density of bias magnets	1.2T
Saturation current density	4.0A/mm ²
Maximum outer radius of bearing	120mm
Specific gravity of the stator iron	7.77g/cm ³
Specific gravity of the copper	8.91g/cm ³
Specific gravity of permanent magnet material neodymium-iron-baron	7.5g/cm ³
Coil mmf loss factor	1.394
Actuator loss factor	1.072
Flux leakage factor	0.840
Packing factor	0.85
Maximum allowable coil volume	820mm ³
Maximum height of bearing	70mm

All of the parameter from table 4.1 was used as an input into the COMSOL Multiphysic software. This software was then automatically solve the FEM in the design and also solving for mathematical calculation to simulate a 2 D active magnetic bearing with magnetic flux density. There are several steps that are used to get the result as shown in figure 4.1 and figure 4.2 below. The first step is to open CAD design that had been design into COMSOL Multiphysic software. Next, Input all the parameter in the global definition. After that, define the material to the rotor and stator. For this project, I use iron core for my material and air at every gap. Then, the polarity of magnet is being define which is north and South Pole. After the polarity is being define, mathematical calculation is being input. For this project the calculation mostly used is Ampere's Law. Last but not least the entire variable needed is being input into COMSOL Multiphysic. The last step is to generate the magnetic flux density for $T = 0.2$

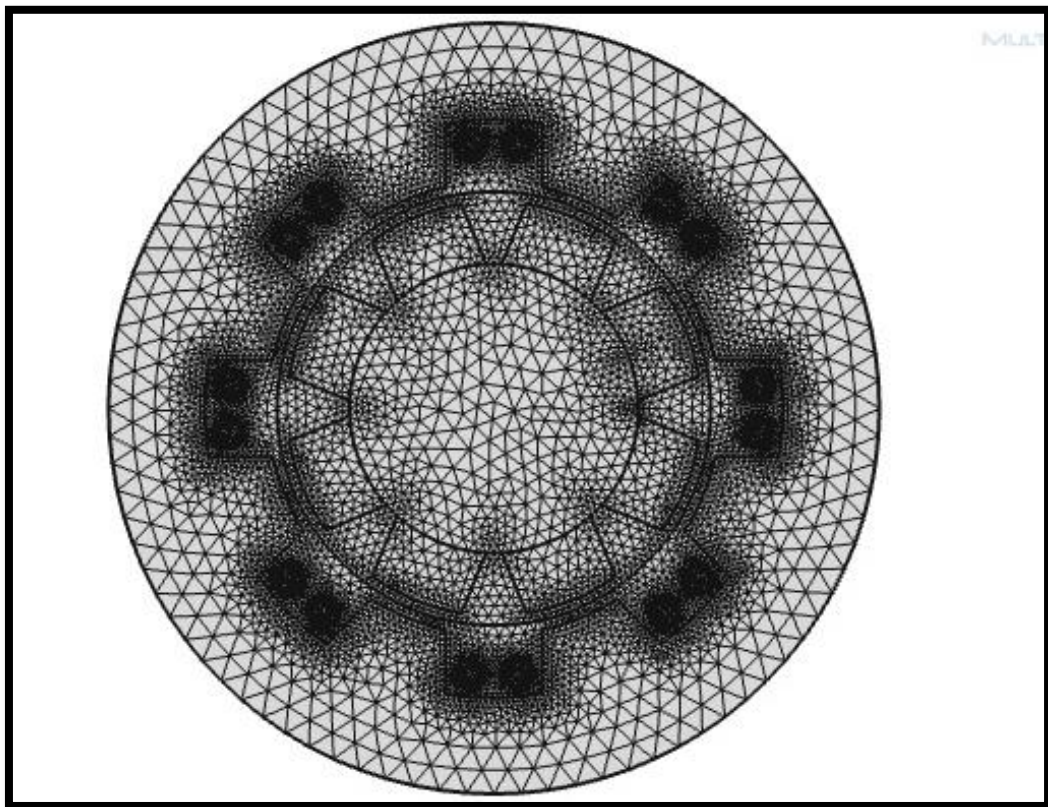


Figure 4.1: The FEM result on the meshing design

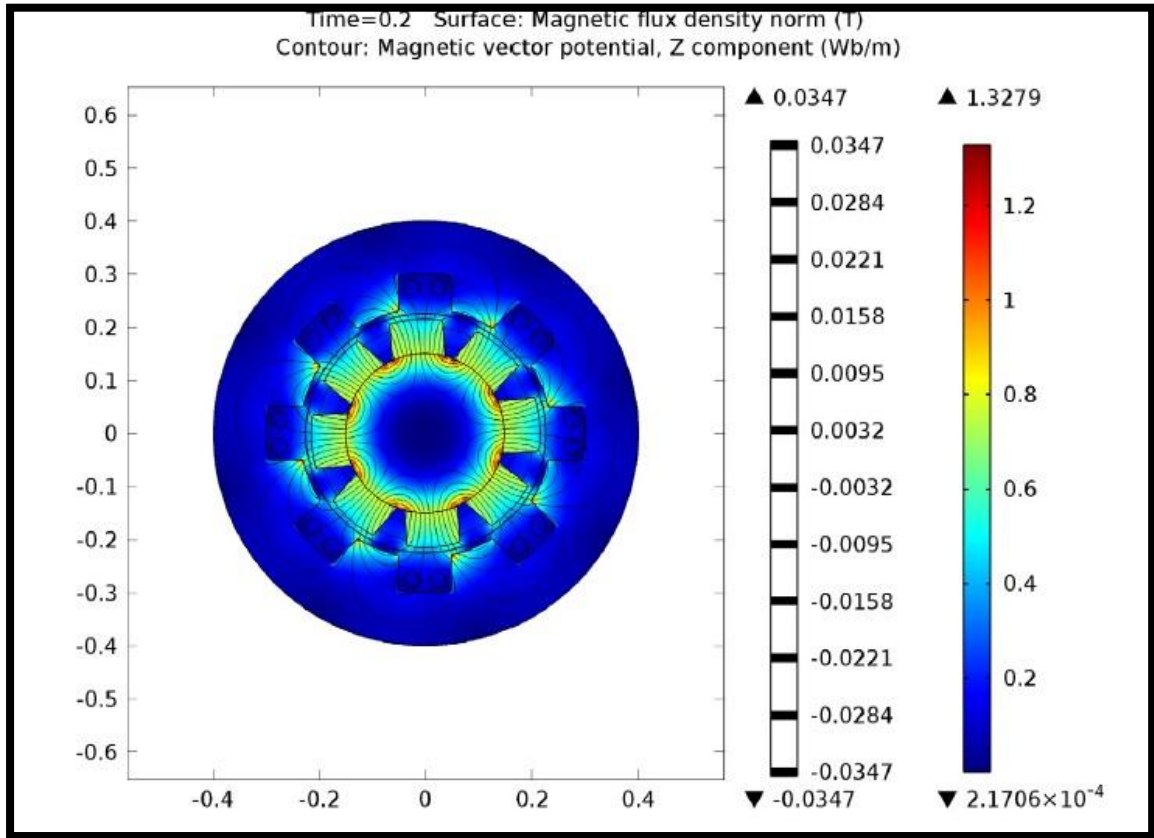


Figure 4.2: 2D Magnetic flux density result for T = 0.2

4.3 Analysis of control system of an active magnetic bearing using MatLab (1 pole levitates)

From chapter 2, we know that an active magnetic bearing is working on the principle of magnetic levitation which will levitate an object to bear it the correct position, x . In this study, I do research on magnetic levitation to levitate an object by using one magnetic actuator which is 1 pole. The first step to do is to get the transfer function by using newton's law based on spring mass damper system.

Assuming, $m = 0.008\text{kg}$

$$g = 9.81$$

$$\bar{x} = 0.0053\text{m}$$

$$\bar{i} = 0.31\text{A}$$

Where,

m = mass of object

g = gravity force

\bar{x} = desire gap between actuator and levitate object

\bar{i} = desire current

$$mg = C \left(\frac{\bar{i}^2}{\bar{x}^2} \right) \quad (4.1)$$

$$= 2.29 \text{ E } -5$$

So,

$$m\ddot{x} = C \left(\frac{2\bar{i}^2}{\bar{x}^3} \right) \hat{x} + C \left(\frac{2\bar{i}^2}{\bar{x}^2} \right) \hat{i} \quad (4.2)$$

Substitute the assuming parameters into equation (4.2):-

$$\ddot{x} = 3695\hat{x} + 63\hat{i} \quad (4.3)$$

So,

$$\frac{\hat{x}}{\hat{i}} = \frac{-63}{(s^2 + 3695)} \quad (4.4)$$

The next step is to get the transfer function by using Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) in an electromagnet model. Figure 4.3 show an electromagnet model which is can be understand clearly for the calculation.

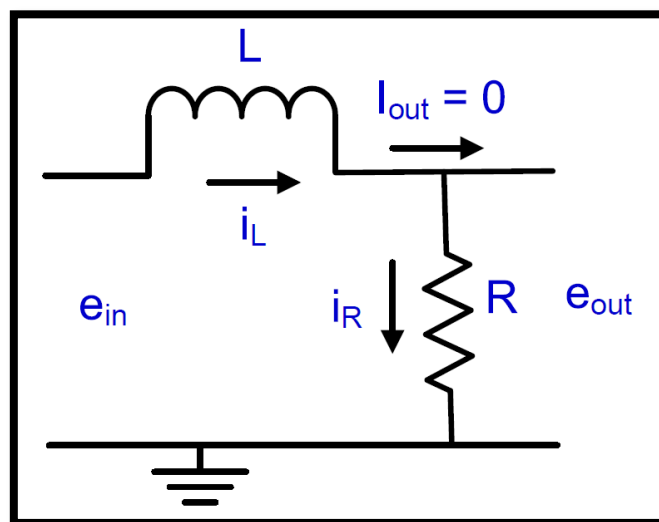


Figure 4.3: Electromagnet model

Assuming $L = 154\text{mH}$ and $R = 34\Omega$,

From KVL,

$$e_{in} - L \frac{di_L}{dt} - e_{out} = 0 \quad (4.5)$$

From KCL,

$$i_L = i_R + i_{out} = i_R + 0 \quad (4.6)$$

Substitute KCL equation into KVL and we get:-

$$e_{in} - L \frac{d}{dt} \left(\frac{e_{out}}{R} \right) - e_{out} = 0 \quad (4.7)$$

So,

$$\frac{L}{R} \frac{de_{out}}{dt} + e_{out} = e_{in} \quad (4.8)$$

$$\frac{L}{R} (De_{out}) + e_{out} = e_{in} \quad (4.9)$$

$$\left(\frac{L}{R} D + 1 \right) e_{out} = e_{in} \quad (4.10)$$

We can conclude that,

$$\frac{e_{out}}{e_{in}} = \frac{1}{\frac{L}{R}D+1} \quad (4.11)$$

So,

$$\frac{i}{e_{in}} = \frac{\frac{1}{R}}{\frac{L}{R}D+1} \quad (4.12)$$

$$= \frac{0.029}{0.0045s+1}$$

Combine both transfer function for Kirchoff's law and Newton's law:-

$$\frac{\hat{x}}{\hat{e}_{in}} = \left(\frac{0.029}{0.0045s+1} \right) \left(\frac{-63}{(s^2+3695)} \right) \quad (4.13)$$

From this transfer function we can get the controller transfer function using root locus to get the Kp, Ki, Kd and N.

Kp = 4784
 Ki = 46798
 Kd = 121
 N = 896.

And the transfer function is,

$$G(s) = \frac{(s^2+38.28s+370.42)}{s(s+896)} \quad (4.14)$$

The control system is built in MatLab to compare the PID control for both Linear and Non-Linear system. Figure 4.4 below show the linear plant and figure 4.5 show the non-linear plant.

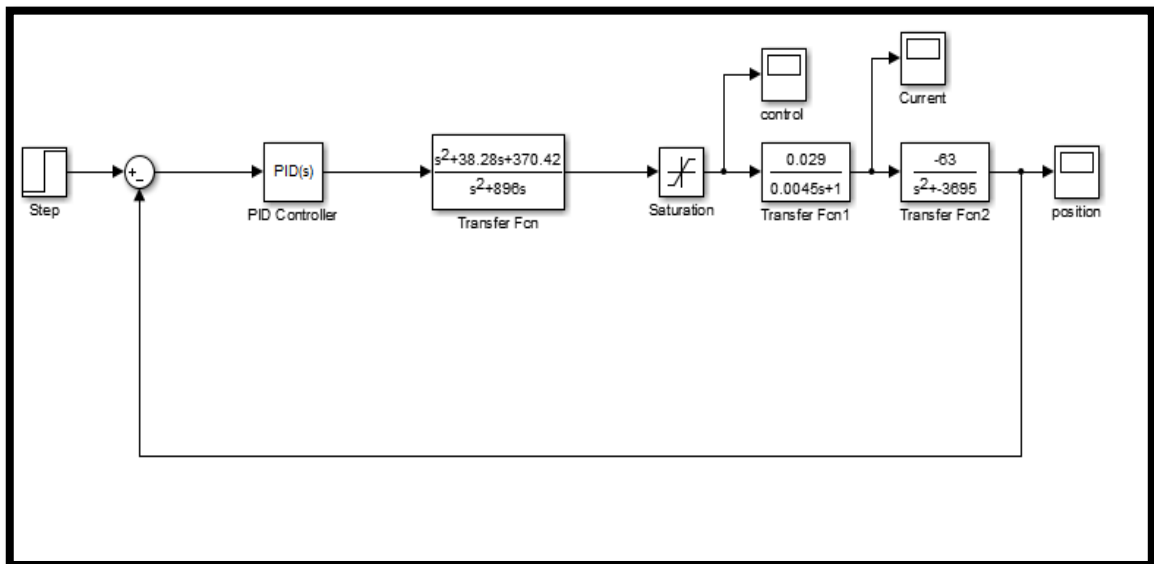


Figure 4.4: Linear systems with PID controller

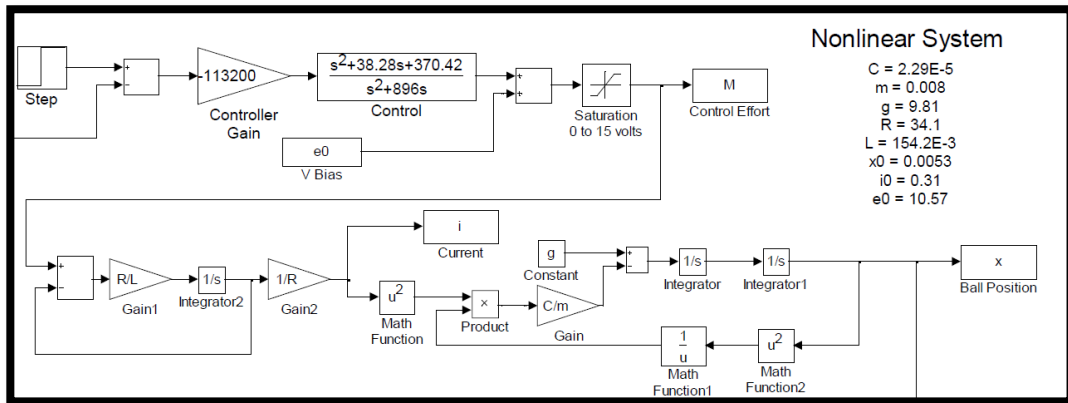


Figure 4.5: Non-linear Plant systems with PID controller

Both results is being compare for control effort, Current and also ball position in figure 4.6, figure 4.7 and figure 4.8.

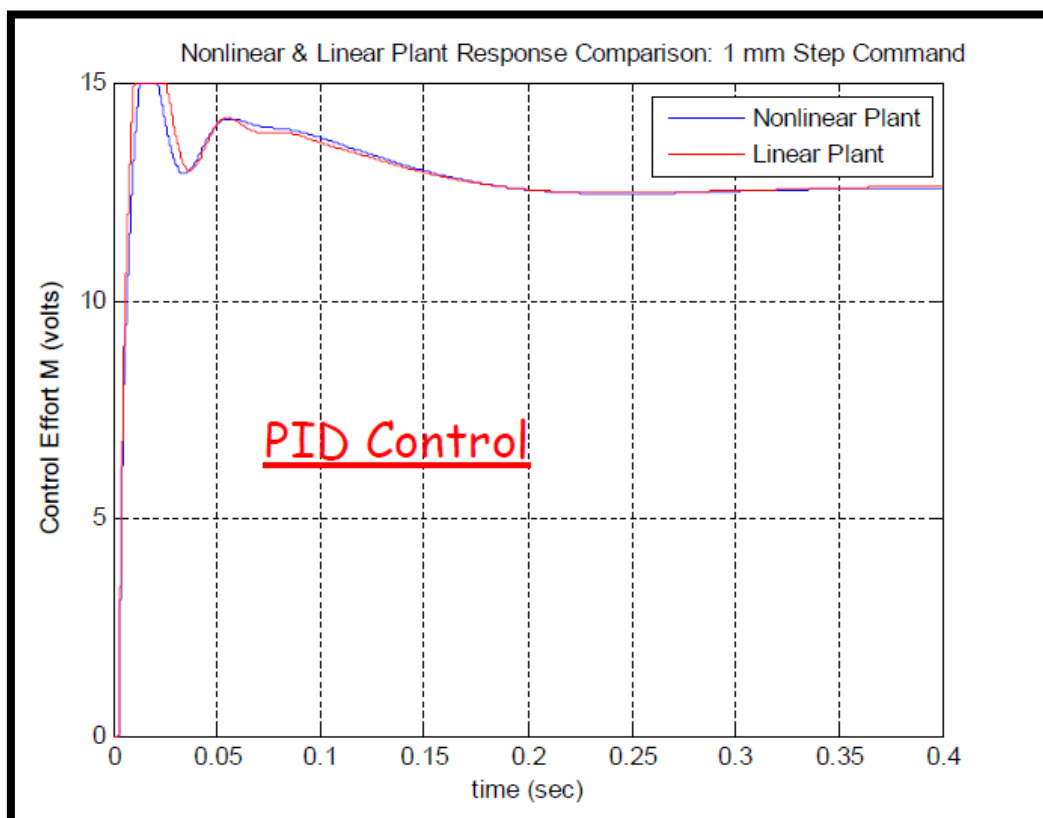


Figure 4.6: Result of comparing PID control to get the control effort for both systems

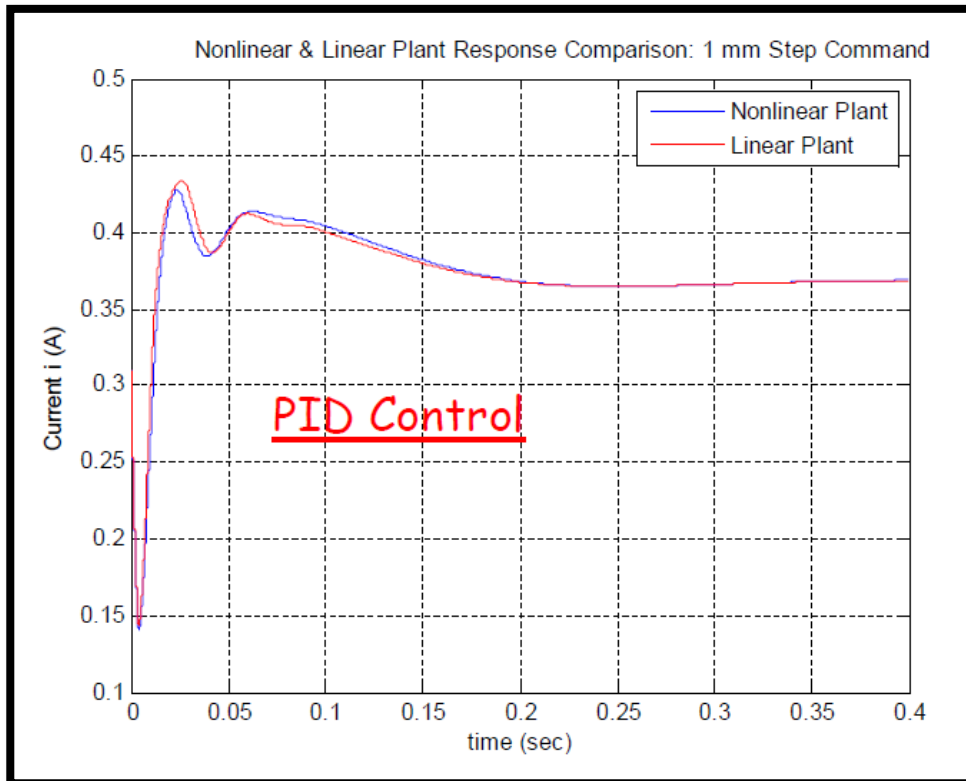


Figure 4.7: Result of comparing PID control to get the current (i) for both systems

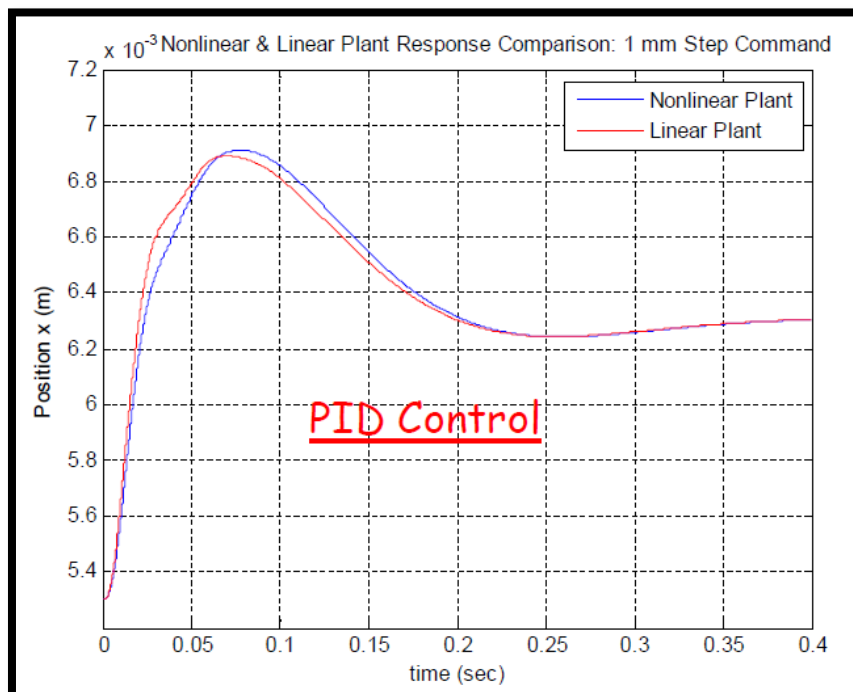


Figure 4.8: Result of comparing PID control to get the position x for both systems

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 INTRODUCTION

This chapter will conclude all the study and research about the topic. The conclusion will be based on the result obtained from chapter 4, nevertheless the result obtained. Any recommendation for further research will also be proposed in this chapter. The proposed recommendation will be based on the experience, observation and analysis of current research. It will be a much of help for further research to obtain or achieved a better quality of the results and understanding in any blurry information on current studies.

5.2 CONCLUSION

As for conclusion, this study has designed and implemented of control system to levitate an object which will be useful for an active magnetic bearing. The important things in doing the design is to know the important parameters which will be need to get the right magnetic flux needed to levitate an object. COMSOL Multiphysic is the easy and useful software for designing and analysis on magnetic bearing. It will calculate automatically just by input several important parameters and calculation which will produce the magnetic flux density. In designing the control system using MatLab function blocks and SIMULINK is the best solution to get the graph result for this

study. The important things to do in designing an active magnetic bearing control system is to get the correct transfer function based on Newton's law and Kirchhoff's Law.

5.3 RECOMMENDATION

For future enhancement of this research, it is recommended to test and compare the result obtain from this data with a real active magnetic bearing. With this, we can get the precise data based on real active magnetic bearing. Besides that, from this study people can make their own active magnetic bearing by milling or wire cut with the desired design and winding it. Other than that, Helicopter blades are rotate by a shaft, if an active magnetic bearing can use there with flywheel in case if the electronic is breakdown. This will help save people life in case anything happened to the helicopter.

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