Controller design for magnetic levitation system

Thesis · May 2015

1 author:

Abhishek Nayak
Indian Institute of Technology Delhi

Controller Design for Magnetic Levitation System

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF TECHNOLOGY

in

Control and Automation

by

Abhishek Nayak
Roll No: 213EE3309

Under the Guidance of
Prof.Bidyadhar Subudhi

Department of Electrical Engineering
National Institute of Technology, Rourkela
Rourkela-769008, Odisha, India
2013-2015

Dedicated to my family

and my friends

Department of Electrical Engineering
National Institute of Technology Rourkela
Rourkela-769008, Odisha, India.

Certificate

This is to certify that the work in the thesis entitled "**Controller Design for Magnetic Levitation System**" by ***Abhishek Nayak*** is a record of an original research work carried out by him under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology with the specialization of **Control & Automation** in the department of **Electrical Engineering**, National Institute of Technology Rourkela. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

Place: NIT Rourkela
Date: May 2015

Prof. Bidyadhar Subudhi
Dept. of Electrical Engineering
NIT Rourkela

ACKNOWLEDGEMENTS

I am grateful to numerous local and global peers who have contributed towards shaping this thesis. At the outset, I would like to express my sincere thanks to Prof. Bidyadhar Subudhi for his advice during my thesis work. As my supervisor, he has constantly encouraged me to remain focused on achieving my goal. His observations and comments helped me to establish the overall direction of the research and to move forward with investigation in depth. He has helped me greatly and been a source of knowledge.

I am really thankful to my all friends and especially Abhilash, Manas, Deepthi ,Pavan, Sudipta, Upasana, Karmila and Debasis. My sincere thanks to everyone who has provided me with kind words, a welcome ear, new ideas, useful criticism, or their invaluable time, I am truly indebted.

I must acknowledge the academic resources that I have got from NIT Rourkela. I would like to thank administrative and technical staff members of the Department who have been kind enough to advise and help in their respective roles.

Last, but not the least, I would like to dedicate this thesis to my family, for their love, patience, and understanding.

Abhishek Nayak

213EE3309

Contents

Abstract

Magnetic Levitation is a method by which an object is suspended in air by means of magnetic force. Earnshaw stated that static arrangements of magnet cannot levitate a body. The exception comes in case of diamagnetic and superconducting materials in magnetic field and by controlling magnetic field by control method.

Here the problem of controlling the magnetic field by control method is taken up to levitate an object. The control problem is to supply controlled current to coil such that the magnetic force acting on the levitated body and gravitational force acting on it are exactly equal. Thus the magnetic levitation system is inherently unstable without any control action. It is desirable to not only levitate the object but also at desired position or continuously track a desired path.

Here a linear and two nonlinear controllers are designed for magnetic levitation system. First a robust adaptive backstepping controller is designed for the system and simulated. The simulation results shows tracking error less than 0.0001m. The immeasurable state present is estimated by Kreisselmeier filter. The Kreisselmeier filter is a nonlinear estimator as well as preserves the output feedback form. However the control output is too high. To counteract the above problem discrete backstepping controller is designed for the system by taking Euler approximate model of the system. The controller output is well within the range of 0.5~1 voltage. The reference tracking is also verified in simulation and the tracking error comes in range of 0.00015m. A linear controller is also designed for magnetic levitation system as the region of operation of magnetic levitation setup is too small. A two degree freedom (2DOF) PID controller is designed satisfying a desired characteristics equation. The controller parameters are obtained by pole placement technique. The 2DOF PID controller is simulated and experimentally validated and it is seen that better result are obtained in 2DOF PID than 1DOF PID controller.

List of Figures

List of tables

Table 4.6.1: Comparison of experimental results of 2DOF PID and 1DOF PID.

List of Acronym

1.	MagLev	:	Magnetic Levitation
2.	IR	:	Infra Red
3.	DOF	:	Degree Of Freedom
4.	CLF	:	Control Lypunov Function
5.	SPA	:	Semiglobally Practically Asymptotic

CHAPTER 1

INTRODUCTION

- INTRODUCTION
- HISTORY OF EVOLUTION
- TYPES OF MAGNETIC MATERIAL
- MAGNETIC FIELD BASIC
- MAGNETIC LEVITATION CONCEPT
- APPLICATION OF MAGNETIC LEVITATION
- SCOPE OF WORK
- MOTIVATION
- LITERATURE REVIEW
- OBJECTIVE
- THESIS ORGANISATION
- CHAPTER ORGANISATION
- CHAPTER SUMMARY

1.1 INTRODUCTION

Magnetic levitation is a method by which an object is suspended in the air with no support other than the magnetic field. However difficulty in stably levitating an object by using inverse square law is studied by Samuel Earnshaw in 1842 [1]. Earnshaw's Theorem states that a point charge cannot have stable equilibrium position when a static force is applied following the inverse square law. This theorem is also applicable to the magnetic force of the permanent magnet. Werner Braunbeck extended the analysis to uncharged dielectric bodies in electrostatic fields and magnetic bodies in magnetostatic fields in 1939. This phenomenon was also studied by Papas in 1977. It was observed that for diamagnetic material, super conducting body and conducting body with eddy current induced on them can have stable equilibrium point.

1.2 HISTORY OF EVOLUTION

Work on using permanent magnet can be date back to 1890. Application to shafts of wattmeter or spindles was carried out by S.Evershed (1900) [2];Faus (1943) and Ferranti (1947) [3][4]. The first demonstration of levitating bodies by using superconducting effect was studied by Arkadiev (1945, 1947) [5][6]. Kemper (1937, 1938) suspended an electromagnet using active control [7]. Holmes in 1937 developed controlled ac supply electromagnet to suspend rotor of ultra-high speed using speed centrifuges and Beams in 1937 [9][10] developed electromagnetic suspension system using control ac electromagnet. Magnetically levitated gyroscope was demonstrated by Simon (1953) [11] and levitating a superconducting sphere over different arrangement of electromagnets was demonstrated by Culver and Davis (1957) [12][13]. Levitation of a vehicle over a superconducting rail was proposed by James R. Powell (1963).James R. Powell and Gordon T. Danby (1966) proposed attaching a super conductor to base of a vehicle and levitate it over a conducting rail [14]. The duo were granted U.S patent for their magnetic levitation train model. There were several proposal of using transportation mode by using magnetic levitation was proposed in 1960s and 1970s. Japan and Germany are two countries which actively took research on mass transportation using magnetic levitation. Germany model basically suspends the train on the underside way of guideway using attraction between the electromagnet on the train and the rail plate on the underside of the carriage. However in Japanese model the train surrounded by guideway wall and track, where the center of guideway is above the superconductor situated under the train. In April 2004 Shanghai Transrapid system began commercial operational which uses the German method and in March 2005, HSST "Linimo" started commercial operational.

1.3 TYPES OF MAGNETIC MATERIAL

Classification is made depending on the different type of material behavior towards the magnetic field.

1.3.1 Ferromagnetic material:

These are the materials in which magnetic moments of atoms or molecules align in a regular pattern with all moments pointing in same direction in the magnetic field.

Example: Iron, Nickel, Cobalt, Steel etc.

1.3.2 Anti Ferromagnetic material:

These materials have magnetic moments of atom or molecule align in a regular pattern with all moments pointing in the opposite direction to neighboring moments.

Example: transition metal compounds especially oxides, Hematite, Chromium, Iron Manganese etc.

1.3.3 Diamagnetic material:

Diamagnetic materials, when applied to magnetic field create a field in the opposite direction to the applied field. Diamagnetism is a quantum mechanical effect that occurs in all materials. When only contribution of magnetism is considered then it is called as diamagnetic material.

Example: Copper, Carbon Graphite, Lead etc.

1.3.4 Paramagnetic material:

Paramagnetic materials are attracted towards the magnetic field and magnetic fields induced are in direction of magnetic field applied. The magnetic property is lost when magnetic field is removed.

Example: Sodium, Manganese, Lithium etc.

1.3.5 Ferrimagnetism:

Ferrimagnetic materials have magnetic moments opposite as in antiferromagnetism but the opposing moments are unequal in ferromagnetic materials.

Example: Yttrium iron garnet, Cubic ferittes composed of iron oxide etc.

1.4 MAGNETIC FIELD BASICS

The magnetic field at a certain point can be given by Biot Savart law (1820). The law state that a current carrying element ' dl ' carrying current ' i ' contributes magnetic field ' B ' at a point ' P ' which is normal to plane of ' dl ' with vector ' r ' is given by

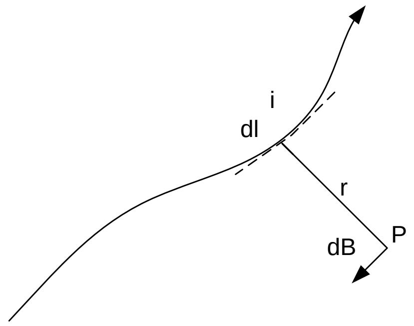

Figure 1.1 Current carrying wire exerting magnetic field at point P

$$dB = \frac{\mu_0 \text{ i dl } \sin\theta}{4\pi r^2}$$

Where

μ_0	is permeability constant in free space
i	is current in the element
B	is magnetic field
dl	small section of wire carrying current
r	vector from the element to the point 'P'

Whereas in magnetic levitation system mostly electromagnetic coil are used to produce the magnetic field. Magnetic field inside solenoid is given by

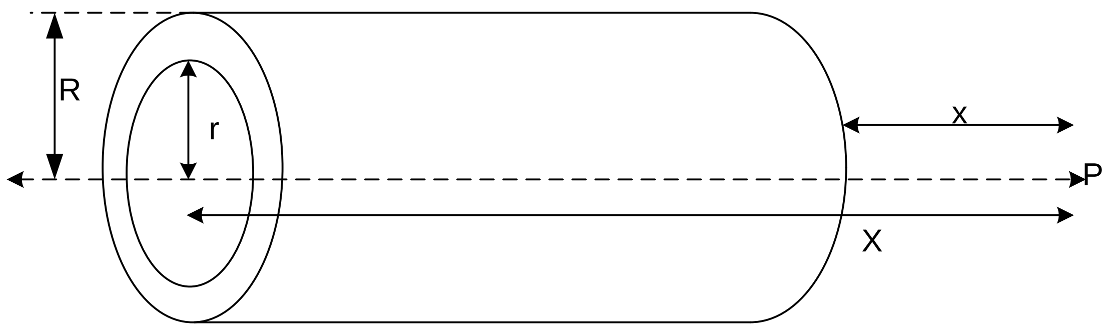

Figure 1.2 Magnetic force exert by solenoid at appoint P

$$B = \frac{\mu_0 in}{2(R-r)}\left[X\ln\frac{\sqrt{R^2+X^2}+R}{\sqrt{r^2+x^2}+r} - x\ln\frac{\sqrt{R^2+X^2}+R}{\sqrt{r^2+x^2}+r}\right]$$

Where

B, μ_0, i stands same as above

n number of turn in per unit length in solenoid

R, r outer and inner radii of solenoid respectively

X, x distance between the ends of solenoid to point where the magnetic field is measured.

However we use directly energy balance concept to find out the force acting on the levitating body [26]. The magnetic force is derived latter on.

1.5 MAGNETIC LEVITATION CONCEPT

Magnetic levitation is an electromechanical coupling concept [35]. The magnetic field is created by electromagnet coil which is electrical part attracts the magnetizable material or object. The magnetic force is controlled by controlling the current in the coil. When the object moves to close the magnet the current in the coil is decreased and vice versa.

1.6 TYPES OF MAGNETIC LEVITATION

Magnetic Levitation can be classified according to magnetism as

a) Levitation by attraction:

This works on the principle that when two magnets are placed end to end with opposite pole facing each other.

b) Levitation by repulsion

This works on the principle that when two magnets are place end to end with same pole facing each other.

Magnetic levitation can be classified according to principle by which levitation is made as [41]

i) Levitation by repulsive force between magnets of fixed strengths
ii) Levitation by magnetic field on diamagnetic materials
iii) Levitation by superconducting surface
iv) Levitation by eddy current induced on conducting surface due to magnetic field
v) Levitation by force acting on current carrying conductor in magnetic field
vi) Levitation by controlled DC or AC supply to electromagnetic coil by control algorithm
vii) Mixed μ systems where μ system are materials where some place the permeability is less than 1 and in some place more than 1.

1.7 APPLICATION OF MAGNETIC LEVITATION

Magnetic levitation systems have advantages of friction less movement, isolation of environment and high precision. Some of the application of magnetic levitation are stated below:

1.7.1 Magnetic levitation train:

Magnetic **Lev**itation (MagLev) train have been the most important usages of magnetic levitation technology. The train move along the guide way with the help of magnetic field which help the train to levitate and propel. In March 2004 first MagLev commercially implemented was Sanghai's Transrapid system which uses German model and in April 2005 Japan implemented its own HSST 'Limino'.at relatively slow speed than Shanghai one. The fastest train 'Lo' Japan is the fastest train till recorded of speed 603km/hr.

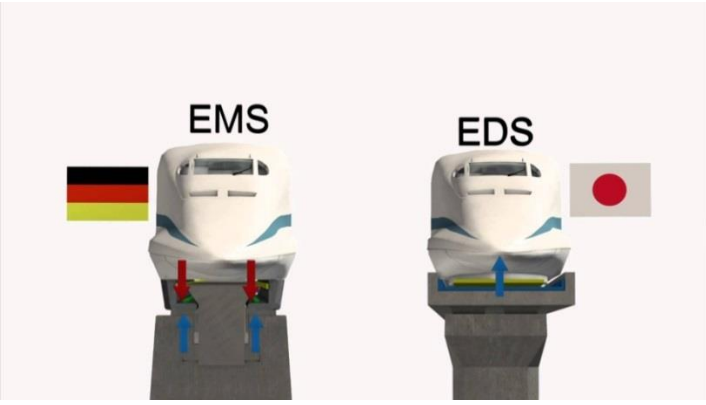

Figure 1.3 Two different model of MagLev train concepts [36].

1.7.2 Magnetic Bearing:

Magnetic bearing use rotor to levitate and rotate with magnetic flux interaction. Since no contact thus no friction, no drag and no wear and tear of parts. Magnetic bearing are used in flywheel as energy storage device, as blood pump, micro positioning system and semi conductor industries.

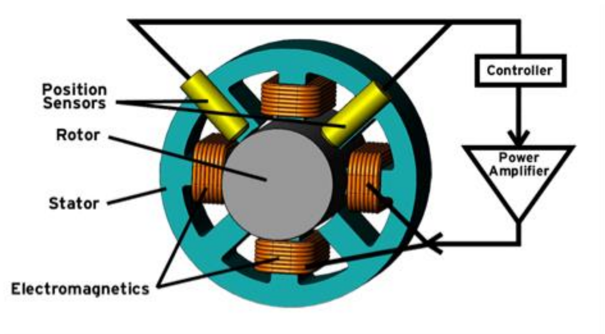

Figure 1.4 Magnetic bearing with controller and position sensing sensor [37]

1.7.3 Launching Rocket:

NASA’s Marshall Space Flight Center at Huntsvhill, Alabama has developed a track to magnetically levitate a space craft and give initial velocity to reach escape velocity of earth. The project is to make space transportation with less cost. The space craft will have 964km/hr when launched from the track without having any fuel consumption.

Figure 1.5 Marshall Space Flight Center at Huntsvhill, Alabama. track of 15 meter long [38].

1.7.4 Electromagnetic Aircraft launch system:

Electromagnetic Aircraft launch system uses magnetically levitated based catapult to launch aircraft in aircraft carrier. This system achieved better acceleration than conventional linear motor as well the stress on air frame of aircraft is also less.

Figure 1.6 U.S Navy model MagLev catapult [39]

1.7.5 MagLev wind turbine:

Guangzhou Energy Research Institute researcher have estimated that magnetically levitated wind turbine can as much 20% more efficient than traditional wind turbine. The proposal is given for colossal wind turbine with vertical blades and supported by neodymium magnets. Since the efficiency is more thus area required to generate same power is much less here than traditional wind turbine.

Figure 1.7 MagLev wind turbine as proposed by Guangzhou Energy Research Institute [17]

1.7.6 MagLev Microrobot

MagLev microrobots are being studied in University of Waterloo for possible application in hazardous environment, for dust free application and micro assembly of hybrid microsystems. Behrad Khamesee have presented a paper on it [40].

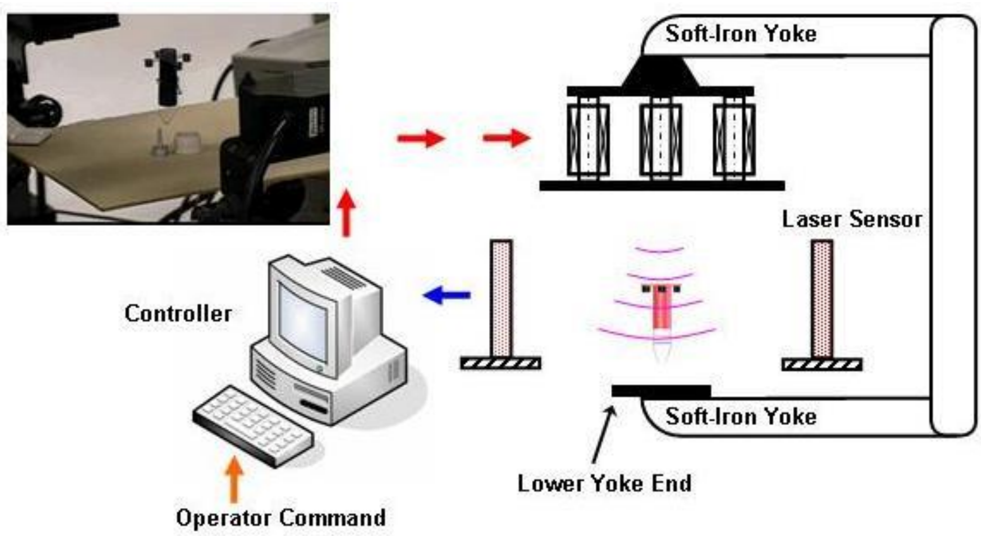

Figure 1.8 Khamesee MagLev microrobot [40]

There are many more application areas which are continuously being explored. MagLev is a new technology which has been an actively research area.

1.8 SCOPE OF WORK

Magnetic Levitation is an open loop unstable system. The whole system is an elctromechanical coupled system. Thus modeling of the system is difficult task which is first carried out. Since the system is nonlinear and unstable thus control problem is challenging. Some nonlinear and linear control techniques are derived to satisfy certain set of performance. The control techniques are then simulated and applied in experimental setup to verify their effectiveness.

1.9 MOTIVATION

MagLev is a non-contact technology thus finds application in high speed transportation system as there is no friction, since there is no friction it can applied to high precision system, also absence of friction gives way to no wear and tear of moving parts which results in high longevity e.g MagLev bearing and also no dust pollution thus creates a clean environment where very high purity is required e.g semi-conductor industry. MagLev also creates environment separation thus one can operate from one environment to another environment eg. Heart pump, in medical industry, in hazardous places. Thus MagLev can be said to be a future technology and it has a vast area of application to be uncovered. All this applicability comes at the cost of either a good design of superconducting magnet (which is inherently stable) or good controller design because fundamentally the levitation by electromagnet is unstable. Here we consider for designing a controller which stabilizes the levitated object through continues monitoring of position and feed-backing it. The MagLev system is a nonlinear and open loop unstable system. Thus it provides an exciting opportunity for controller designer to explore different control algorithm for the system.

1.10 LITERATURE REVIEW

In recent years there has been active research in control of both attractive and repulsive type magnetic levitation. Huang(2000) proposed adaptive backstepping controller for repulsive magnetic force of a MIMO system. The adaptive backstepping controller proposed for decoupling nonlinearities and eliminating uncertainties[3]. Yang et al (2000) controller design method was to stabilizing the position error of levitated object by a PI controller and adaptive robust nonlinear controller (backstepping method) is designed to attenuate the effects of parameter uncertainties, so that a small velocity error is ensured[4]. Lepetic et al(2001) applied a method of fuzzy predictive functional control to MagLev system. First a lead compensator was designed to stabilize the system then fuzzy controller is applied based on TS rule [5]. Nesic et al proposed a method to implement backstepping in realtime where plant is in continuous form and the controller is implemented though computer or digitally, here an Euler approximate model of system is considered and controller is designed accordingly [18]. Dan Cho et al (1993) Jalili-Kharaajoo (2003, 2004), and Fallaha et al. (2005) proposed sliding mode controllers (SMC) for magnetic levitation system [6, 7, 8]. In all previous case the velocity state is obtained by psodifferentiation of position state. Z-J Yang et al (2008) consider K-filter approach to observer the unmeasured state and apply backstepping to the new dynamics. The velocity state is estimated by Kreisselmeier filter as it is not measurable [14, 15]. Yang et al. (2011) investigate controller via a disturbance observer based control (DOBC) approach to address the mismatched uncertainties in system. The author also proposed disturbance compensation based on estimated disturbance. The disturbance estimated are considered as lumped disturbance and the plant considered is a linearized plant [9]. Ghosh et al (2014) designed by using 2-DOF PID controller, the PID parameters are obtained by using pole placement techniques [10]. .Beltran-Cabajal et al (2015) presented an application of MagLev in a mass spring damper system. The tracking of reference is achieved by output feedback controller. The system states are also estimated by an estimator [19].

Thus a brief conclusion is achieved as there is active research going on in designing adaptive, robust and linear controller for magnetic levitation system. Thus MagLev provides a test bed to test different type controller.

1.11 OBJECTIVE

The objective of the work can be directed to design controller considering the linear model as well as nonlinear model. The controller designed is validated by simulating and implementing it on experimental setup..

1.12 THESIS ORGANISATION

The thesis is organized into seven chapters with each chapters has its own subsection. The chapters are briefly described as below

Chapter 1: This chapter briefly introduces the magnetic levitation technology, history of evolution, some application, and motivation of taking the project, literature review of some previous works and objective of work.

Chapter 2: This chapter describes the magnetic levitation setup on which the controller is tested and mathematical modeling of the system.

Chapter 3: In this chapter controller is designed based on the model achieved.

Chapter 4: In this chapter the controller designed is simulated and the result are discussed. The experiment validation of proposed controller is also carried out.

Chapter 5 Conclusion part and future work are discussed in this chapter.

1.13 CHAPTER SUMMARY

This chapter briefly describes the MagLev system working principle, gives a brief history of how the MagLev system explored from time to time, some application of the MagLev system. The chapter also describes the motivation of author to take the project and also the objective which the author set to achieve.

CHAPTER 2

SYSTEM DESCRIPTION AND MODELING

- INTRODUCTION
- FEEDBACK MAGNETIC LEVITATION SETUP
- SET OF EQUIPMENTS
- BLOCK DIAGRAM
- MODELING OF SYSTEM
- CHAPTER SUMMARY

2.1 INTRODUCTION

This chapter gives an idea of the magnetic levitation system provided by “Feedback Company” and other set of equipment required to perform the experiment. The later part of chapter deals with modeling of a magnetic levitation system. In modeling a linear and nonlinear model of the MagLev system is derived. Here magnetic force causing the levitation is also derived.

2.2 FEEDBACK MAGNETIC LEVITATION SETUP

Magnetic levitation setup plant consists of three important parts

a) Electromagnetic coil
b) Infrared light sensors
c) Metal object
d) Analogue and Digital interface
e) Controller from computer

a) Electromagnetic coil: The electromagnetic coils gives necessary magnetic field when current is passed through it. The produced field interacts with the metallic object to produce the necessary lifting force. A heat sink is provide to regulate the temperature of coil after prolong current supply is provided.

b) Infrared light Sensor: There are two parts in IR sensor. One is the transmitter of IR light and other is receiver of IR light. Base on the amount of light fall on the receiver voltage is produced. When object is in levitation position then the some part of the lights are blocked and correspondingly voltage is produced. The amount of the voltage produced gives the position of the object.

c) Metal Object: Here a hollow metallic ball is considered as object. The weight of the ball is around 20 grams.

d) Analogue and Digital interface: The MagLev plant is the interface with a computer via Analogue and Digital interface as the plant is in continuous time domain whereas the computer works in the digital domain. Thus to couple both an interface is needed. Sensor output is feed to analogue to digital converter pin and the control input from the controller in computer feed to digital to analogue converter pin.

e) Controller: The maglev plant is open loop unstable. Thus to perform levitation a controller is needed. The necessary controller is designed in MATLAB or

Simulink and connected to MagLev system via Advantech PCI1711 card. The control output is bounded to be within +5V and -5V [27].

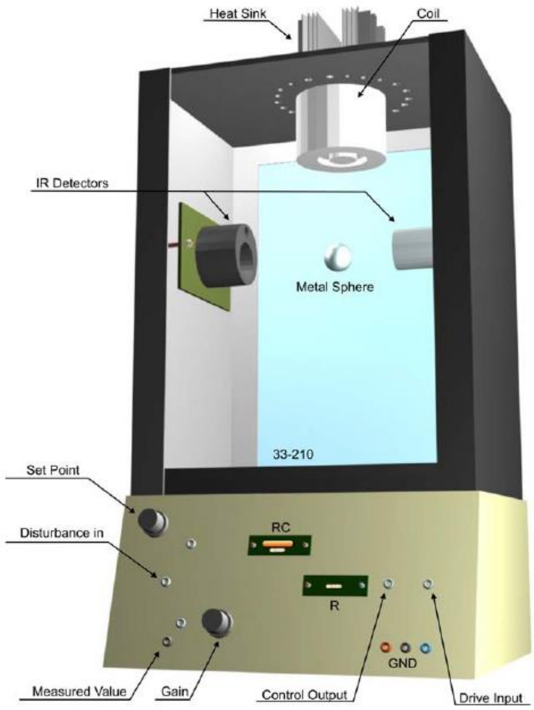

Figure 2.1 Magnetic Levitation mechanical unit

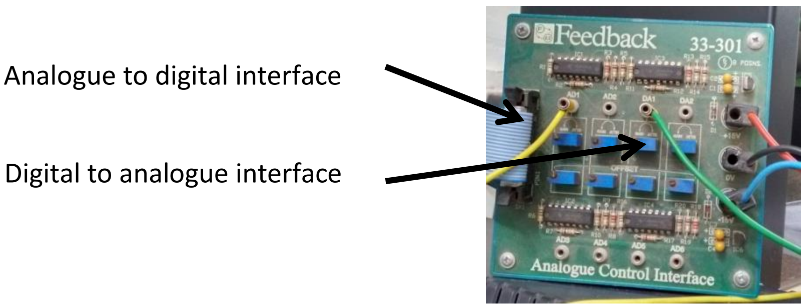

Figure 2.2 Analogue control interface unit

2.3 SET OF EQUIPMENT

Set of equipment required for experiment are as follows [27]

i) Feedback Magnetic Levitation setup
ii) Hollow metallic ball
iii) Feedback Analogue control interface
iv) PC with Windows 2000 or Window XP
v) MATLAB V7.3(R2006b) or later version
vi) MATLAB Toolbox required:

- Real Time Workshop with real time target
- System Identification tool box
- Control tool box

vii) Advantech PCI17111 card

viii) Installation software

2.4 BLOCK DIAGRAM

The block diagram of whole system is given as

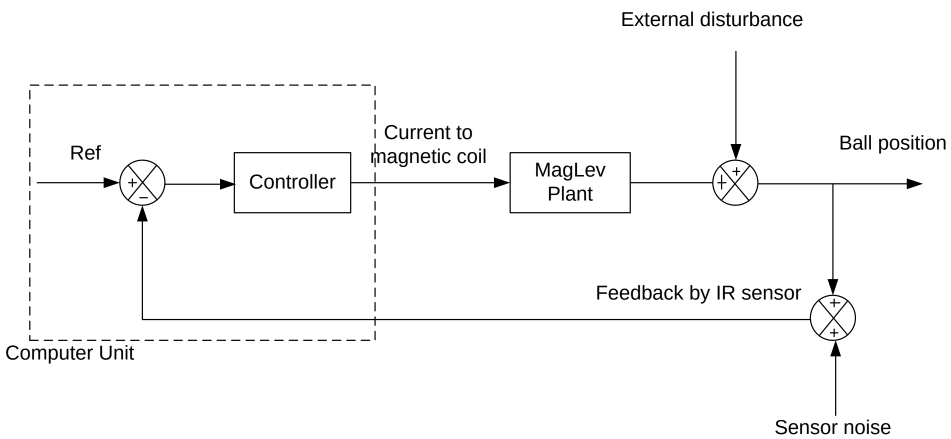

Figure 2.3 Block diagram of Maglev system with controller

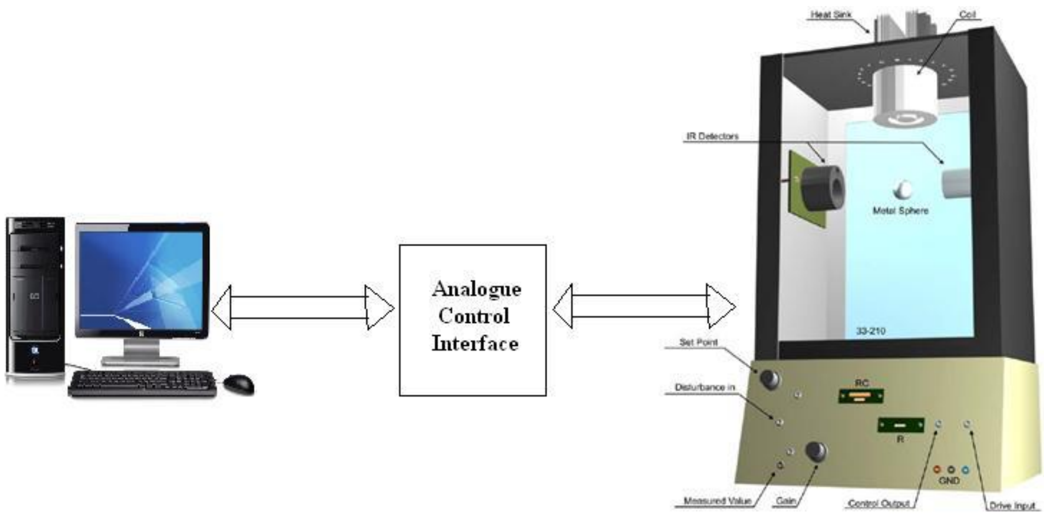

Figure 2.4 Schematic diagram of closed loop system

2.5 MODELING OF MAGLEV SYSTEM

The metallic ball dynamics under equilibrium position, when applied with electromagnetic field is given by Newton law as

$$m.\ddot{x} = m.g - f_e \quad (2.1)$$

Where,

m = mass of the ball

x = position of ball

g = gravitational acceleration

f_e = magnetic force

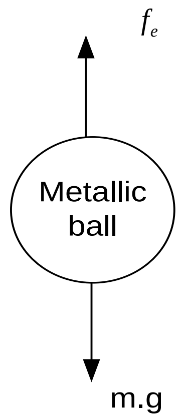

Figure 2.5 Net force acting on metallic ball

The magnetic force is derived as given by J.L Kirtley Jr [26].

There are basically two approach of finding the magnetic force i.e Thermodynamic argument (conservation of energy approach) and Field method (Maxwell's field Tensor) method.

Here energy approach is used to find the electromagnetic force. The magnetic field system is considered as conservative system i.e input energy to the system is same as output energy of the system. In the magnetic field system the input is electrical and output is mechanical i.e movement of the object. There no loss of energy in the form of heat or friction.

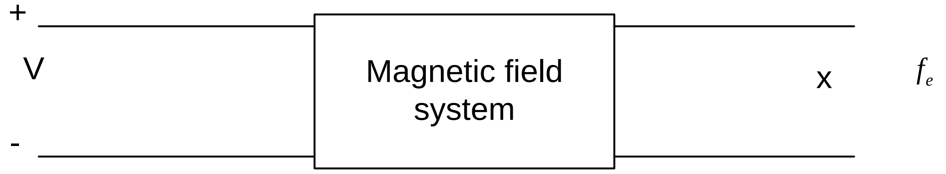

Figure 2.6 Conservative magnetic field system

Since there is no energy loss the energy stored in the magnetic field system. The energy stored in the system depends on two states only i.e flux (λ) or current (i) and mechanical position (x) as seen from Figure 2.6.

Electrical power input the conservative system is

$$P_e = v.i = i.\frac{d\lambda}{dt}$$

Mechanical power out of system can be written as

$$P_m = f_e \frac{dx}{dt}$$

The difference of two is rate of change of energy stored in system

$$\frac{dW_m}{dt} = P_e - P_m$$

$$\frac{dW_m}{dt} = i\frac{d\lambda}{dt} - f_e \frac{dx}{dt} \qquad (2.2)$$

For taking the system from one sate to another, we may write

$$W_m(a) - W_m(b) = \int_a^b i.d\lambda - f_e.dx$$

where

two states are $\begin{array}{l} a = (\lambda_a, x_a) \\ b = (\lambda_b, x_b) \end{array}$

Now the energy stored the system can be written in term of two state variables i.e $\lambda \,\&\, x$ as

$$dW_m = \frac{\partial W_m}{\partial \lambda} d\lambda + \frac{\partial W_m}{\partial x} dx \qquad (2.3)$$

Comparing (2.2) and (2.3) we get

$$f_e = -\frac{\partial W_m}{\partial x} \tag{2.4}$$

$$i = \frac{\partial W_m}{\partial \lambda} \tag{2.5}$$

Now for multiple electrical terminals or multiple mechanical terminals (2.2) can be written as

$$dW_m = \sum_k i_k d\lambda_k - f_e.dx$$

$$\Rightarrow dW_m = \int i.d\lambda - f_e.dx \tag{2.6}$$

Considering inductance as only function mechanical position (x)

$$\lambda(x) = L(x).i \tag{2.7}$$

Now integrating equation (2.6) from λ = 0 to λ and integral over dx is zero we get

$$W_m = \int_0^\lambda i_k.d\lambda$$

From (2.7)

$$W_m = \int_0^\lambda \frac{\lambda(x)}{L(x)} = \frac{1}{L(x)}\int_0^\lambda \lambda(x).d\lambda(x) = \frac{1}{L(x)}\frac{\lambda^2(x)}{2}$$

$$W_m = \frac{1}{2}.i^2.L(x) \tag{2.8}$$

From (2.4)

$$f_e = -\frac{dW_m}{dx}$$

$$f_e = -\frac{1}{2}.i^2.\frac{\partial L(x)}{\partial x} \tag{2.9}$$

Now total inductance in the system can be written as

$$L(x) = L_1 + L_0\frac{x_0}{x} \tag{2.10}$$

Where

x_0 = denote equilibrium position of system

L_0 = denote incremental inductance of ball

L_1 = denote inductance of the coil

From (2.9) & (2.10)

$$f_e = \frac{i^2}{2} L_0 x_{0.} \frac{1}{x^2} = k\frac{i^2}{x^2} \tag{2.11}$$

Where k is constant which depends on system

Now plant dynamics can be written from (2.1) & (2.11) as

$$\ddot{x} = g - k_1 \frac{i^2}{x^2} \tag{2.12}$$

Linearization (2.12) around equilibrium point x_0, i_0

$$\ddot{x} = F(i, x)$$

$$\ddot{x} + \Delta\ddot{x} = \frac{\partial F}{\partial i} di \,|_{(i_0, x_0)} + \frac{\partial F}{\partial x} dx \,|_{(i_0, x_0)}$$

$$= \left(-\frac{\partial f_e}{\partial i} di \,|_{(i_0, x_0)} - \frac{\partial f_e}{\partial x} dx \,|_{(i_0, x_0)} \right)$$

$$= -2.k_1.\left(\frac{i_0}{x_0{}^2} \Delta i - \frac{i_0}{x_0{}^3} \Delta x \right) \tag{2.13}$$

at equilibrium point from (2.12)

$$0 = g - k_1 \frac{i_o{}^2}{x_0{}^2}$$

$$g = k_1 \frac{i_0{}^2}{x_0{}^2} \tag{2.14}$$

From (2.13) and (2.14)

$$\Delta\ddot{x} = -2\frac{g}{i_0}\Delta i + 2\frac{g}{x_0}\Delta x$$

Taking $\frac{2g}{i_0} = K_i$ and $-\frac{2g}{x_0} = K_x$

$$\Delta\ddot{x} = -K_i.\Delta i - K_x.\Delta x$$

Taking Laplace transform

$$s^2.\Delta X = -K_i.\Delta I - K_x.\Delta X$$

$$G(s) = \frac{\Delta X}{\Delta I} = \frac{-K_i}{s^2 + K_x} \tag{2.15}$$

By substituting equilibrium point as $i_0 = 0.8A \,\&\, x_0 = -1.5V(0.009m)$

Transfer function of linearized system around equilibrium point is given as

$$G(s) = \frac{-24.525}{s^2 - 2180} \tag{2.16}$$

The Feedback MagLev system provided has internal circuit to make voltage proportional to current

$$i = 1.05 \times V \tag{2.17}$$

The output from sensor (x_m) is given by

$$x_v = 143.48x_m - 2.8 \tag{2.18}$$

Where

x_m is actual position in meter, with electromagnet end point is considered as 0 meter

The state space model is given as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= g - k_1\frac{i^2}{x_1{}^2} \end{aligned} \tag{2.19}$$

where

x_1 is given as position state

x_2 is given by velocity state

2.6 CHAPTER SUMMARY

This chapter describes the overall system. First the hardware setup description is given by Feedback is discussed. Then the set of equipment is described and block diagram of the overall system with the controller is shown. Lastly, the mathematical model of the system is derived.

CHAPTER 3

CONTROLLER DESIGN FOR MAGNETIC LEVITATION SYSTEM

- INTRODUCTION
- ADAPTIVE BACKSTEPPING CONTROLLER
- DISCRETE MODEL BACKSTEPPING CONTROLLER
- TWO DEGREE FREEDOM (2DOF) PID
- COMPARISION OF THREE CONTROLLERS
- EXPERIMENTAL RESULT
- CHAPTER SUMMARY

3.1 INTRODUCTION:

Since MagLev system is an open loop unstable thus controller design is very critical part of the close system. Since the system is nonlinear, controller design can be carried out by taking nonlinear model as well as linearized model. Since all the states are not measurable a nonlinear estimator is also designed. Here three controller are designed

1) Adaptive backstepping controller.
2) Descrete backstepping controller.
3) Two degree freedom (2DOF)PID controller.

3.2 CONTROLLER DESIGN

3.2.1 Adaptive backstepping controller:

Backstepping control design method was given by "Krstic, Kanellakopoulos, and Kokotovic" circa 1990. Backstepping is a non linear controller which can be applied to nonlinear system having strict feedback form. The control technique is to reduce the system into subsystem and each subsystem is controlled by an auxiliary control input. The auxiliary control follows the stabilizing function. The stabilizing function forms the control Lyapunov function. The original control is achieved by stepping backing from subsystems to last subsystem. Thus the control technique is called backstepping control.

Let a system is given as

$$\dot{x} = f(x) + g(x)\zeta \tag{3.1}$$

$$\dot{\zeta} = u$$

Where $x \in \mathbb{R}^n, \zeta \in \mathbb{R}, u \in \mathbb{R}$

Note $\begin{bmatrix} x \\ \zeta \end{bmatrix} \in \mathbb{R}^{n+1}$ are state of system

u is control input.

Assumptions:

- $f, g : D \to \mathbb{R}^n$ are smooth
- $f(0) = 0$
- ζ is auxiliary input to (3.1). Stabilizing function is given as $\alpha(x)$ where $\alpha(0) = 0$. Also $\exists$ a Lyapunov function $V_1 : D \to \mathbb{R}^+$ such that

  $$\dot{V}_1(x) = \left(\frac{\partial V_1}{\partial x}\right)^T \left(f(x) + g(x).\alpha(x)\right) \le -V_a(x) \ \forall \mathrm{x} \in \mathrm{D}$$

Where $V_a(x): D \rightarrow \mathbb{R}^+$ is positive definite function

Now the error dynamics is defined as

$$Z = \zeta - \alpha$$
$$\dot{Z} = u - \dot{\alpha}$$

Where 'u' satisfying $V = \frac{1}{2}Z^2$

Thus control input is derived.

Objective of controller: The design objective to stabilize the error dynamic. Error dynamic state are of two states. 1st is error between the plant output (i.e) ball position and reference. 2nd is error between the virtual control and stabilizing function. The actual control is backstep by virtual control.

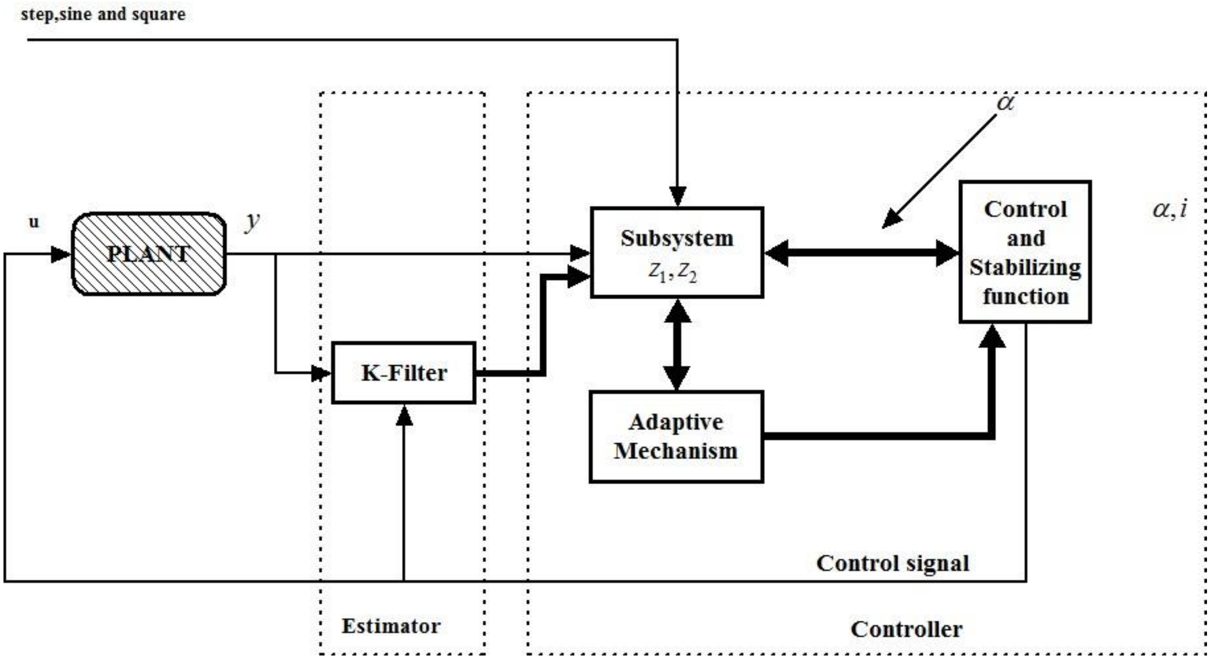

Figure 3.1 Schematic diagram of controlsystem with adaptive backstepping controller

Now from system (2.19) x_1 is only measurable by position sensor but x_2 is not measurable as an extra sensor to measure accurate velocity may not be cost effective and differentiation of x_1 may give noisy output. So we estimate the x_2 by Kreisselmeier filter [28].

Kreisselmeier Filter is given by:

For a system

$\dot{x} = A.x + \phi(y) + F(y,u)^T \theta$

$y = e_1^T.x$

Where $\theta = \begin{bmatrix} b \\ a \end{bmatrix}$ are unknown parameters of system.

$F(y,u)^T = \left[\begin{bmatrix} 0_{(p-1)\times(m+1)} \\ I_{m+1} \end{bmatrix} \sigma(y).u \quad \phi(y) \right]$ are the nonlinear terms multiplied with parameter uncertainties

$k = [k_1, ..., k_n]^T$ is chosen such that the matrix $A_0 = A - k \times e^T$ is Hurwitz.

The observed state will be governed by system

$\dot{\tilde{x}} = A_0 \tilde{x}$ where $\tilde{x} = x - \hat{x}$

Estimated state is given by

$$\hat{x} = \xi + \Omega^T \theta \tag{3.2}$$

Filter is

$$\begin{aligned} \dot{\xi} &= A_0 \xi + ky + \phi(y) \\ \dot{\Omega} &= A_0 \Omega^T + F(y,u)^T \end{aligned} \tag{3.3}$$

Now Kreisselmeier Filter deign for the system (2.19)

$e = x_2 - \hat{x}_2$ is the error between the estimated velocity and the actual velocity.

The filter is constructed such that

$\dot{\tilde{x}}_2 = -k \times \tilde{x}_2$ where $\tilde{x}_2 = x_2 - \hat{x}_2$

Now here we estimate x_2 as

$$\hat{x}_2 = \xi + A\zeta + kx_1 \tag{3.4}$$

Where

$$\dot{\xi} = -k\xi - k^2 x_1 + g \tag{3.5}$$

$$\dot{\zeta} = -k\zeta - \frac{i^2}{x_1^{\ 2}} \tag{3.6}$$

The step response for different values of 'k' in shown in Figure 3.2 .It can be seen that as 'k' increases the tracking error decreases but the initial value of x_2 increases by a factor of 10 as k is increased by factor of 10. Thus a oscillatory response is observed in starting in closed loop system with step input. The effect is more prominent in fast changing reference signal like square wave, sine wave. Thus ‘k’ is taken as 10

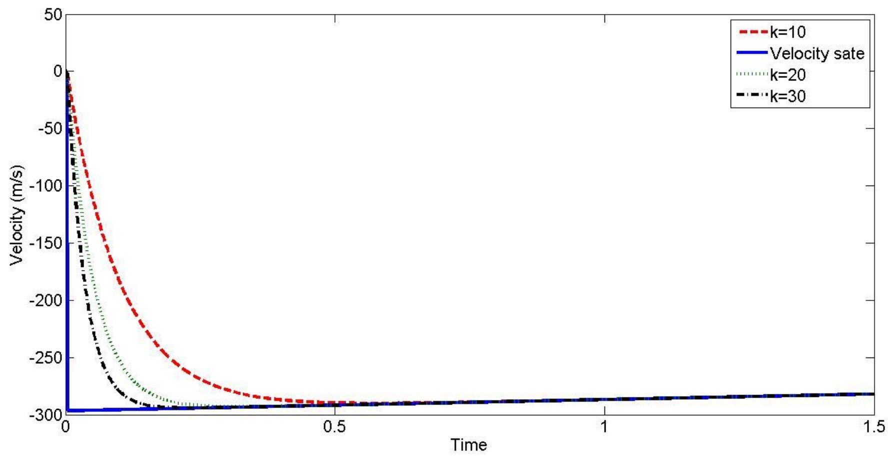

Figure 3.2 Estimation of state x_2 in closed loop for different k with step reference for different k

In system (2) we cannot apply backstepping as x_2 is not measurable

Thus new system is formed as to which we apply backstepping

$$\dot{x}_1 = x_2 \tag{3.7}$$

$$\dot{\zeta} = -k\zeta - \frac{i^2}{x_1^{\,2}} \tag{3.8}$$

Design of backstepping controller for MagLev System

The design objective is to regulate x_1 to a given set point y_r. In the above equations (5) the 1st equation has ζ as virtual control, 2nd equation i is virtual control Thus our goal is to stabilize the error co-ordinate as below.

Error co-ordinate

$$Z_1 = x_1 - y_r$$

$$Z_2 = \zeta - \alpha_1 \tag{3.9}$$

Taking CLF as $V_1 = \frac{1}{2} Z_1$

Finding $\dot{Z}_1$ and stabilizing function α_1

$$\dot{Z}_1 = \xi + kx_1 + A\alpha_1 + AZ_2 - \dot{y}_r + \varepsilon \tag{3.10}$$

Taking $\alpha_1 = \hat{a}\bar{\alpha}_1$

where $a = \frac{1}{A}$

$a = \hat{a} - \tilde{a}$

Thus taking first stabilizing control as

$$\bar{\alpha}_1 = -\xi - kx_1 - c_1 Z_1 - d_1 Z_1 \tag{3.11}$$

Thus resulting Z_1

$$\dot{Z}_1 = AZ_2 - c_1 Z_1 - d_1 Z - A\tilde{a}\bar{\alpha}_1 - \dot{y}_r + \varepsilon \tag{3.12}$$

The term - ξ_1 and $-kx_1$ cancels the same term in (3.12) $-c_1 Z_1$ produces CLF to be negative , $d_1 Z_1$ is introduce to give damping as ε is present. Here $\alpha_1 = \hat{a}\bar{\alpha}_1$ because an unknown term (A) is multiplied with α_1 in $\dot{Z}_1$ expression .The term $-A\tilde{a}\bar{\alpha}_1$ get cancelled in updating law AZ_2 is canceled in $\dot{Z}_2$ which we will get later (3.13).

Now

$$\dot{V}_2 = \frac{1}{2} x_1^{\,2} + \frac{1}{2} x_2^{\,2}$$

$$\dot{Z}_2 = -k\zeta - \frac{i^2}{x_1^{\,2}} - \frac{\partial \alpha_1}{\partial \dot{x}_1}\dot{x}_1 - \frac{\partial \alpha_1}{\partial \xi}\dot{\xi} - \frac{\partial \alpha_1}{\partial \hat{\rho}_1}\dot{\hat{\rho}} \tag{3.13}$$

Here we get control input as i as

$$i = x_1 \sqrt{(-k\zeta + c_2 Z_2 - \frac{\partial \alpha_1}{\partial x_1}(\xi + \zeta\hat{A} + kx_1) - \frac{\partial \alpha_1}{\partial \xi}(-k\xi - k^2 x_1 + g) + \hat{A}Z_1 + d_2(\frac{\partial \alpha_1}{\partial x_1})^2 Z_2 - \frac{\partial \alpha_1}{\partial \hat{a}}\dot{\hat{a}})} \tag{3.14}$$

Where

$-k\zeta - \frac{\partial \alpha_1}{\partial x_1}\dot{x}_1 - \frac{\partial \alpha_1}{\partial \xi}\dot{\xi} - \frac{\partial \alpha_1}{\partial \hat{a}}\dot{\hat{a}}$ terms are used to cancel the same in (3.13), $-c_2 Z_2$ is used to produce negative CLF, $\hat{A}Z_1$ get canceled while considering Z_2 matrix $-d_2(\frac{\partial \alpha_1}{\partial x_1})^2 Z_2$ is used to produce damping which is produce to counteract ε term.

While placing $\dot{Z}_1$ $\dot{Z}_2$ in $\dot{V}_2$

We get extra terms of unknown terms

Now

$$V = V_2 + \frac{1}{2\gamma_1}\tilde{a}^2 + \frac{1}{2\gamma_2}\tilde{A}^2$$

Finding $\dot{V}$ such that it is $-x_1^{\,2} - x_2^{\,2}$

Thus tuning law is obtained as

$\dot{\hat{a}} = -\gamma_1 \bar{\alpha}_1 Z_1$

$$\dot{\hat{A}} = \gamma_2 \left(Z_1 Z_2 - \frac{\partial \alpha_1}{\partial x_1} \zeta Z_2 \right) \tag{3.15}$$

Substituting α_1, i in $\dot{Z}_1, \dot{Z}_2$ we get

$$\begin{bmatrix} \dot{Z}_1 \\ \dot{Z}_2 \end{bmatrix} = \begin{bmatrix} -(c_1 + d_1) & A \\ -A & -\left(c_2 + d_2 (\frac{\partial \alpha_1}{\partial x_1})^2 \right) \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix} + \begin{bmatrix} 1 \\ \frac{\partial \alpha_1}{\partial x_1} \end{bmatrix} \varepsilon + \begin{bmatrix} -A\bar{\alpha}_1 & 0 \\ 0 & Z_1 - \frac{\partial \alpha_1}{\partial x_1} \zeta \end{bmatrix} \begin{bmatrix} \tilde{a} \\ \tilde{A} \end{bmatrix} \tag{3.16}$$

From the above we note that the 1st matrix is a skew symmetric which is a property of backstepping controller, 2nd matrix is error term of x_2 and the last term comes as parameter error terms , from the last term we design the tuning laws as transpose of it.as can be seen in[28].

Assumption

i) Here we consider for modeling plant the internal inductance (L_0) to 5.518125 mH , the initial position (x_0) to be 0.009m . Thus 'A' (the unknown parameter) in model comes to be $1.241578125 \times 10^{-3}$ (for mass (M) =20g).

$$\because \; A = \frac{k_0}{M} \quad \text{where } k_0 = \frac{L_0 x_0}{2}$$

ii) The initial values of $\hat{a}$ & $\hat{A}$ are taken as 1000 and 1×10^{-3} , considering 'A' to be in 10^{-3} range.

Now taking $c_1 = 1000$, $c_2 = 2000$, $d_1 = 2, d_2 = 2, \gamma_1 = 100, \gamma_2 = 100$

The constants value are taken in the guide lines as c_1 less than c_2 because c_1 represents rate of decrease of Z_1 (tracking error)and c_2 represent rate of decrease of Z_2 (auxiliary controller and stabilizing function error), thus for a fast convergence of auxiliary control with stabilizing function the auxiliary controller will control the tracking error. It is seen that with less c_1 value initial error is more. However with more value of c_1 the control action is increased. Thus a tradeoff is made by choosing $c_1 = 1000$, $c_2 = 2000$, d_1 , d_2 are taken small so that the control action will be less. For 'k' value should be large as it decides the rate of convergence of ε but too large will allow more band width thus filter output becomes noisy.

Thus value of $k = 10$ is taken. The values of γ_1, γ_2 are taken as 100 each as the initial values of tuning parameter values are taken too close to the actual values. Taking high values of γ_1, γ_2 will increase computational burden and thus increases the response time.

3.2.2 Discrete backstepping controller:

Backstepping controller technique has very well understood when the plant and the controller both are in continuous form. However for digital implementation of controller the either of two approach can be taken. One is designing controller for continuous time and implementing it directly using sample and hold. A shortcoming of the direct implementation of controller is ignoring the sampling completely. Whereas the other method is to design a controller considering the sampling time by using discrete time model of system. However obtaining exact discrete model in strict feedback form is unrealistic as the plant is in continuous form. Thus sampling destroys strict feedback structure which is necessary for backstepping. Euler approximate model however preserves the .strict feedback structure. Dragan.Nesic proposed a backstepping controller using an Euler approximate model for a nonlinear system[33].

Let a system given as

$$\begin{aligned} \dot{x} &= f(x) + g(x)\xi \\ \dot{\xi} &= u \end{aligned} \tag{3.17}$$

Euler approximate model

$$x(k+1) = x(k) + T(f(x(k)) + g(x(k))\xi(k)) \tag{3.18}$$

$$\xi(k+1) = \xi(k) + Tu(k) \tag{3.19}$$

Where

T is sampling time

Now considering the Theorem given by D.Nesic [33].

Theorem: Consider the Euler approximate model (3.18). Suppose that there exist $\hat{T} > 0$ and a pair (ϕ_T, W_T) that is defined for all $T \in (0, \hat{T})$ and that is a SPA stabilizing pair for the subsystem (3.19) ,with $\xi \in \mathbb{R}$ regarded as its control. Moreover suppose that the pair (ϕ_T, W_T)

has the following properties:

i) ϕ_T and W_T are continuously differentiable for any $T \in (0, \hat{T})$;

ii) there exist $\tilde{\varphi} \in K_\infty$ such that

$$|\varphi_T(x)| \le \tilde{\varphi}(|x|)$$

iii) for any $\tilde{\Delta} > 0$ there exist a pair of strictly positive numbers $(\tilde{T}, \tilde{M})$ such that for all $T \in \left(0, \tilde{T}\right)$ and $|x| \le \tilde{\Delta}$ we have

$$max\left\{\left|\frac{\partial W_T}{\partial x}\right|, \left|\frac{\partial \phi_T}{\partial x}\right|\right\} \le \tilde{M}$$

Then there exists a SPA stabilizing pair (u_T, V_T) for the Euler model (3.18),(3.19). In particular, we take:

$$u_T(x) = -c(\xi - \phi_T(x)) - \frac{\Delta \tilde{W}_T}{T} + \frac{\Delta \phi_T}{T} \tag{3.20}$$

where $c > 0$ is arbitrary,

$$\Delta \phi_T = \phi_T(x + T(f + g\xi)) - \phi_T(x)$$

$$\Delta W_T = \begin{cases} \dfrac{\Delta \bar{W}_T}{(\xi - \phi_T)} & \xi \ne \phi_T(x) \\ T\dfrac{\partial W_T}{\partial x}(x + T(f(x) + d(x)\xi)g(x) & \xi = \phi_T(x) \end{cases} \tag{3.21}$$

$$\Delta \bar{W}_T = W_T(x + T(f + g\xi)) - W_T(\eta + T(f + g\phi_T)) \tag{3.22}$$

And $V_T(x) = W_T(x) + \frac{1}{2}(\xi - \phi_T(\eta))^2$ (3.23)

Thus control law is formulated as above from Theorem.

Objective of Controller: For control law obtained above the control output are too high, so practical implementation is bit difficult as the actuator input are limited. Thus here a controller is designed whose control outputs are bounded. The controller design takes into consideration of Euler approximate model.

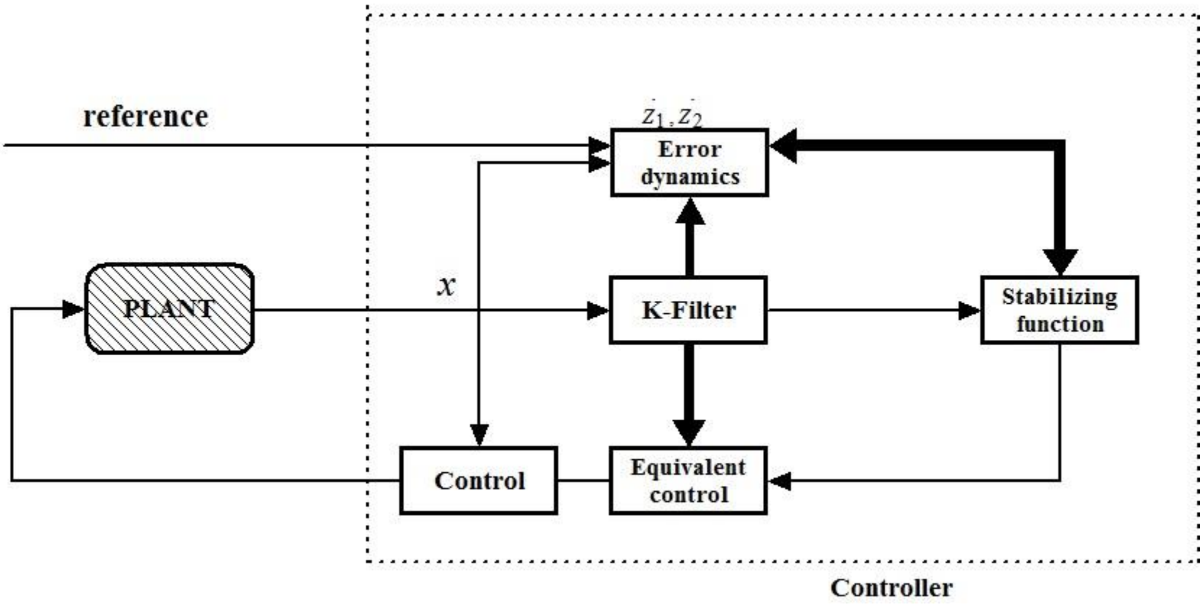

Figure 3.3 Schematic diagram of Backstepping on Euler approximate model

The stabilizing function (α) remains same as derived in (3.11),the K-Filter also remains same as in (3.4),(3.5) and (3.6) and error dynamics also remains same (3.9).

$$\Delta\bar{W}_T = \frac{1}{2}[x_1 + T(\xi + kx_1 + \hat{A}\zeta) - y_r - T\dot{y}_r]^2 - \frac{1}{2}[x_1 + T(\xi + kx_1 + \hat{A}\alpha) - y_r - T\dot{y}_r]^2 \tag{3.24}$$

After solving we get.

$$\Delta\bar{W}_T = T^2\xi\hat{A}(\zeta-\alpha) + \frac{T^2\hat{A}^2}{2}(\zeta^2-\alpha^2) + T^2kx_1\hat{A}(\zeta-\alpha) + 2x_1T^2\xi\hat{A}(\zeta^2-\alpha^2) + 2kx_1\hat{A}T^2(\zeta-\alpha) + 2x_1T^2\xi\hat{A}(\zeta-\alpha)$$
$$\frac{1}{2}T\hat{A}y_r(\zeta-\alpha) + \frac{1}{2}T^2\hat{A}\dot{y}_r(\zeta-\alpha) \tag{3.25}$$

Where $W_T = \frac{1}{2}Z_1^2 = \frac{1}{2}(x_1 - y_r)^2$ is the second stabilizing function.

$\Delta\alpha = \alpha(x(k+1)) - \alpha(x(k))$

Now we form $\Delta\tilde{W}_T$ as given by expression (3.21)

$$\Delta\tilde{W}_T = \begin{Bmatrix} \dfrac{\Delta\bar{W}_T}{\zeta-\alpha} & \text{for } \zeta \neq \alpha \\ T\dfrac{\partial W_T}{\partial x_1}(x_1 + T(\xi + \zeta\hat{A} + kx_1))\hat{A} & \text{for } \zeta = \alpha \end{Bmatrix} \tag{3.26}$$

Equivalent input (U_e)is given by

$$U_e = -c_2(\zeta-\alpha) - \frac{\Delta\tilde{W}_T}{T} + \frac{\Delta\alpha}{T} - AZ_1 \tag{3.27}$$

Solving we get

$$U_e = \begin{cases} -c_2(\zeta-\alpha)-(T\xi\hat{A}+Tkx_1\hat{A}+2T{x^2}_1\hat{A}+2x_1T\xi\hat{A}+\frac{1}{2}\hat{A}y_r+\frac{1}{2}T\hat{A}\dot{y}_r)-(x_1T^2\hat{A}^2+\frac{T^2\hat{A}^2}{2})(\zeta+\alpha)-\hat{a}(c_1+d_1)\hat{x}_2-AZ_1 & \zeta\neq\alpha \\ -c_2(\zeta-\alpha)-x_1(x_1-y_r)(x_1+T(\xi+\zeta\hat{A}+kx_1))\hat{A}+\hat{a}(-k-(c_1+d_1))(\xi+\zeta A+kx_1)-AZ_1 & \zeta=\alpha \end{cases} \tag{3.28}$$

The actual control is given as

$$U = i = \begin{cases} \sqrt{(g-U_e)\frac{{x^2}_1}{A}} & for\ \zeta\neq\alpha \\ \sqrt{(g-U_e)\frac{{x^2}_1}{A}} & for\ \zeta=\alpha \end{cases} \tag{3.29}$$

Constants $c_1, c_2 = 50$., $d_1 = 2$ and $T = 0.001$

3.2.3 Two degree of freedom (2DOF) PID controller design:

PID controller also called as ‘three term controller was introduced by Taylor Instrument Company in 1936. PID controller can be interpreted as ‘P’ depends on ‘present error’, ‘I’ depend on ‘accumulated past error’ and ‘D’ depends on ‘Future’ error. The weighted sum of these three elements is control signal which is applied to plant control input.

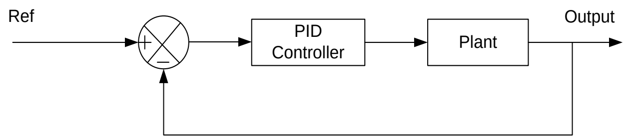

Figure 3.3 Schematic PID controller.

Above controller act only on the error term, thus can be referred as one degree of freedom (1DOF). Whereas if we shift the controller to left of summing point, we will have two controllers i.e one acting plant output and other on reference signal. Thus we have two parameters to control and can be said as two degree of freedom (2DOF). In 2DOF PID we have two section, one controller in the feedback deals with process uncertainties and disturbance and other in feedforward deals with fastness of response to reference signals.

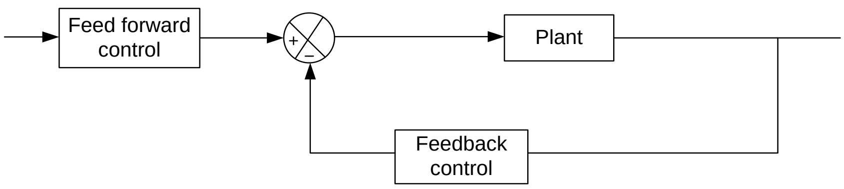

Figure 3.5 Schematic diagram of 2DOF controller

Objective of controller: Previously nonlinear controllers designed are too complicated. Moreover the Magnetic Levitation setup has very small region of operation thus a linear controller can rightfully be applied. Two degree of freedom (2 DOF) has advantage over single degree freedom(1 DOF) as we can separate control problem into two section, one controller in the feedback deals with process uncertainties and disturbance and other in feedforward deals with response to reference signals [25].

2DOF PID design for MagLev system:

Taking the transfer function from (2.16), current and voltage relationship from (2.17) and senor output from (2.18) we obtain the overall transfer function as

$$G'(s) = \frac{\Delta x_v}{\Delta u} = \frac{-3694.78935}{s^2 - 2180} \tag{3.30}$$

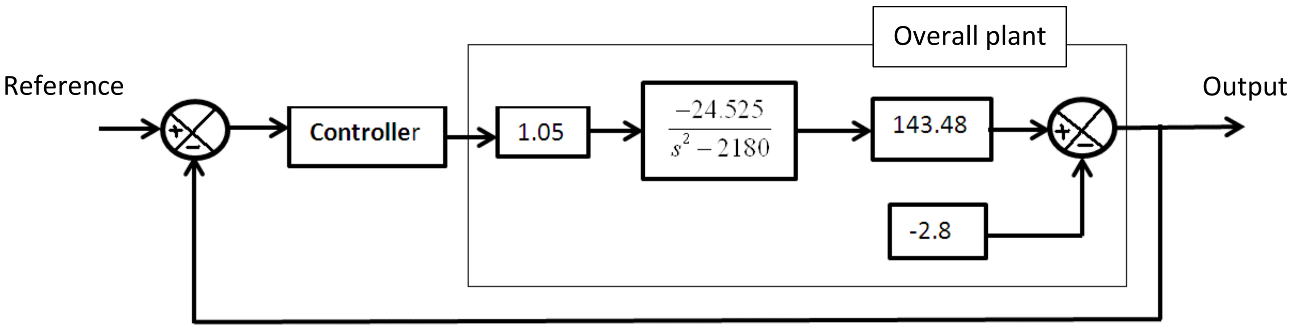

Figure 3.6 Schematic diagram of linear model

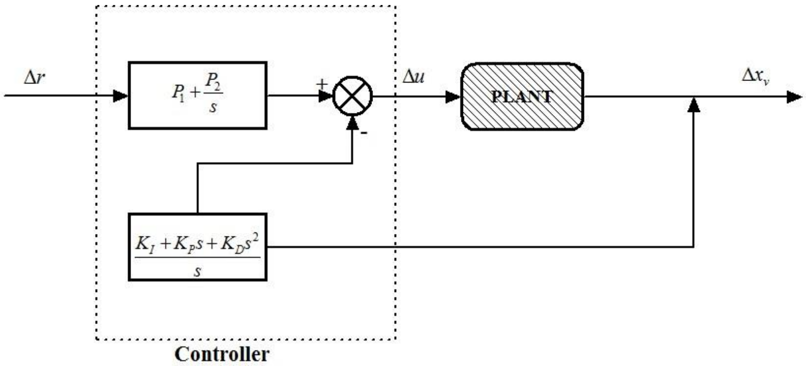

Figure 3.7 Schematic diagram of 2DOF PID

The Plant of Figure is (3.30).

From (3.30) it is found that open loop poles are located at ± 46.69

$$\frac{\Delta x_v}{\Delta r} = \frac{N.(s.P_1 + P_2)}{s^3 + k_d N s^2 + (k_p N - 2180)s + k_i N} \tag{3.31}$$

Where $N = -3694.78935$

Character equation

$$CR_{eq} = s^3 + k_d N s^2 + (k_p N - 2180)s + k_i N \tag{3.32}$$

Values of $k_p, k_i \,\&\, k_d$ value are obtain by pole placement

Desired characteristic equation is designed considering damping ration as $\xi = 0.9$ and settling time as 1 second.

$$CR_{des} = (s+a)(s^2 + 2\xi\omega_n s + \omega^2{}_n)$$

Settling time from CR_{eqn} is

= min(time constant of $(s+a)$,time constant of $(s^2 + 2\xi\omega_n s + \omega^2{}_n)$)

$$= 4 \times \min(\tau = \frac{1}{a}, \frac{1}{\xi\omega_n})$$

Therefore $\frac{1}{a} \ll \frac{1}{\xi\omega_n}$

$$a \gg \xi\omega_n$$

$$t_s = \frac{4}{\xi\omega_n} = 1\sec$$

$$\omega_n = 4.44 rad/\sec$$

Now the desired characteristic equation becomes

$$CR_{des} = (s+a)(s^2 + 8s + 19.75)$$

Loop transfer function is given $L(s) = G(s).C(s) = \frac{(k_d s^2 + k_p s + k_i)}{s} \times \frac{N}{s^2 - 2180}$ same for 1DOF of PID.

S is sensitivity of function $S = \frac{1}{1+G'\times C} = \frac{1}{1+L}$

T is complementary sensitivity function $T = \frac{G'\times C}{1+G'\times C} = \frac{L}{1+L}$

Now pole 'a' is selected such that $\|S\|_\infty < 2 \,\&\, \|T\|_\infty < 2$ thus ensuring good robustness and disturbance rejection

Pole 'a' should be placed far from $\xi\omega_n$.

Taking a=1000 the sensitivity and complimentary sensitivity less than 2 is achieved.

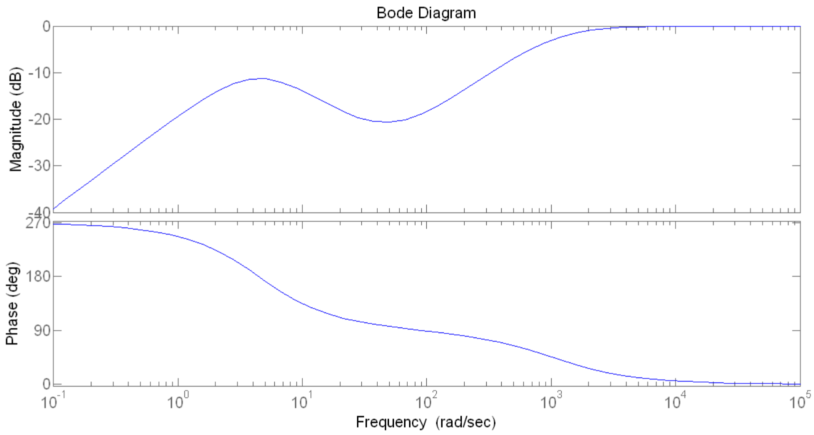

Figure 3.8 (a) Bode plot of sensitivity function. showing magnitude maximum of 0db

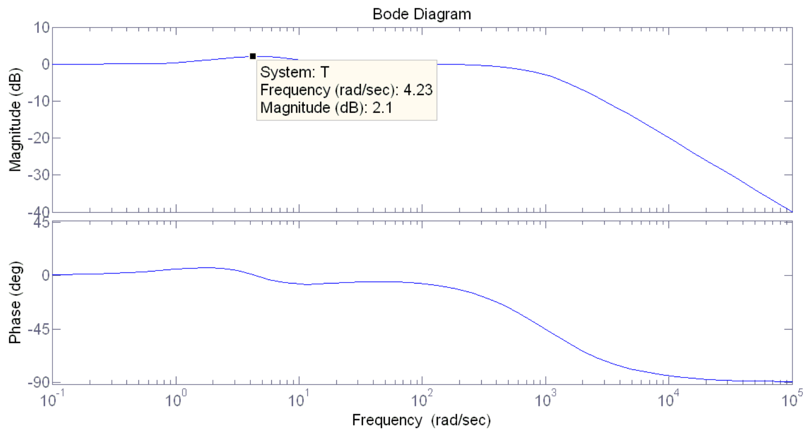

Figure 3.8(b) Bode plot of complementary sensitivity function. The maximum value is 2.1db

Thus the desired characteristic equation becomes

$$CR_{des} = (s+1000)(s^2+8s+19.75)$$

Now for tracking at $t \to \infty$ i.e s=0, $\Delta x = \Delta r$

$$\therefore \left.\frac{\Delta x}{\Delta r}\right|_{s=0} = 1$$

$$\frac{\Delta x}{\Delta r} = \frac{P_2}{k_i}$$

$$\therefore P_2 = k_i$$

Now comparing the desired CR_{des} with plant CR_{eqn} we obtain

$$k_i = -5$$
$$k_p = -2.76$$
$$k_d = -0.2728$$
$$P_2 = k_i = -5$$

Now p_1 is fine-tuned so that we can obtain quick response.

The controller is validated with p_1 values as 0,1,-1,-2.

3.5 CHAPTER SUMMARY

In this chapter three different controllers has been designed based on nonlinear continuous model, nonlinear discrete model and linear continuous model. A detailed derivation of controllers has been presented.

CHAPTER 4

SIMULATION AND RESULTS

- INTRODUCTION
- SIMULATION OF ADATIVE BACKSTEPPING CONTROLLER ON MAGLEV SYSTEM
- SIMULATION OF BACKSTEPPING ON EULLER APPROXIMATE MODEL OF MAGLEV SYSTEM
- SIMULATION OF TWO DEGREE FREEDOM (2DOF) PID ON MAGLEV SYSTEM
- COMPARISION OF RESULT OF ALL CONTROLLER
- EXPERIMENTAL RESULT OF 2DOF CONTROLLER
- CHAPTER SUMMARY

4.1 INTRODUCTION

While apply a designed controller to real world system it better to study the controller effect on a model which replicate real world system because if some consideration in designing controller is not taken then great damage may made to system. MATLAB Simulink is a tool on which a real world model can be represented and studied the result of controller. If any required changes are required then appropriate changes can be made.

4.2 SIMULATION OF ADATIVE BACKSTEPPING CONTROLLER ON MAGLEV SYSTEM

The Figure 4.1 shows tracking performance of MagLev system for different c_1 and c_2 values. It is observed that with increase of c_1 and c_2 values the tracking error reduces. However it is found that with increase of c_1 and c_2 values the control signal values also increases. Thus a tradeoff is taken between tracking error and control signal values. Thus c_1 and c_2 values are set to 1000 and 2000.

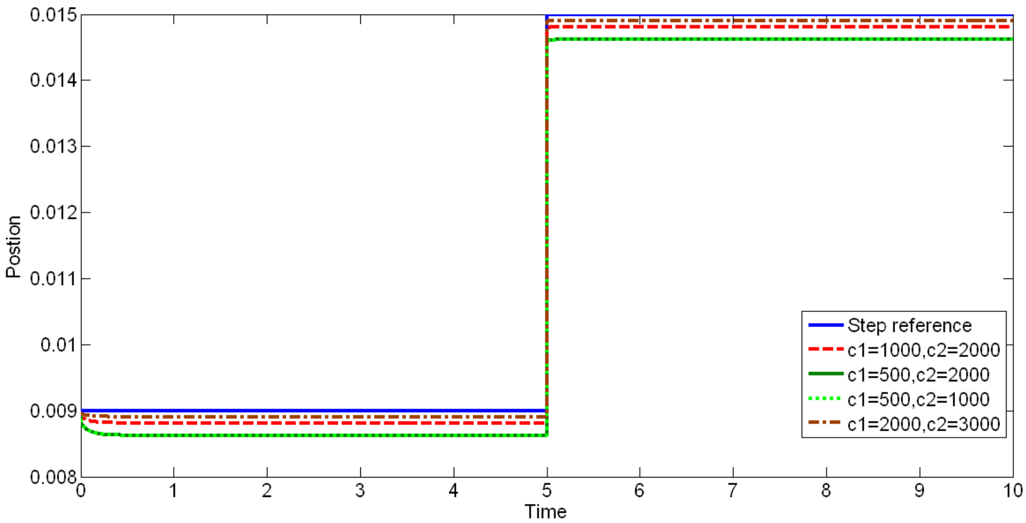

Figure 4.1 Showing tracking response with step as reference for different c_1 & c_2 values

It is also observed from above Figure 4.1 that the there is a baising as the state x_1 doesnot converge with the reference.This can be explained as, from (3.12)it is seen that in the stabilizing function ($\alpha_1 = \hat{a}\bar{\alpha}_1$) the $\hat{a}$ doesnot converge exactly to a .The tunning function (3.15) can give us an idea that, as the initial value of $\hat{a}$ is taken as 1000 then the rate of change of $\hat{a}$ comes in range of 10^{-5}.

Now the MagLev model is tested with different mass of ball and simulated. Mass of ball considered in designing the controller is 20g. Now to test the adaptive nature of controller we test the sytem for double mass of ball i.e 40g and for half mass of ball i.e 10g.

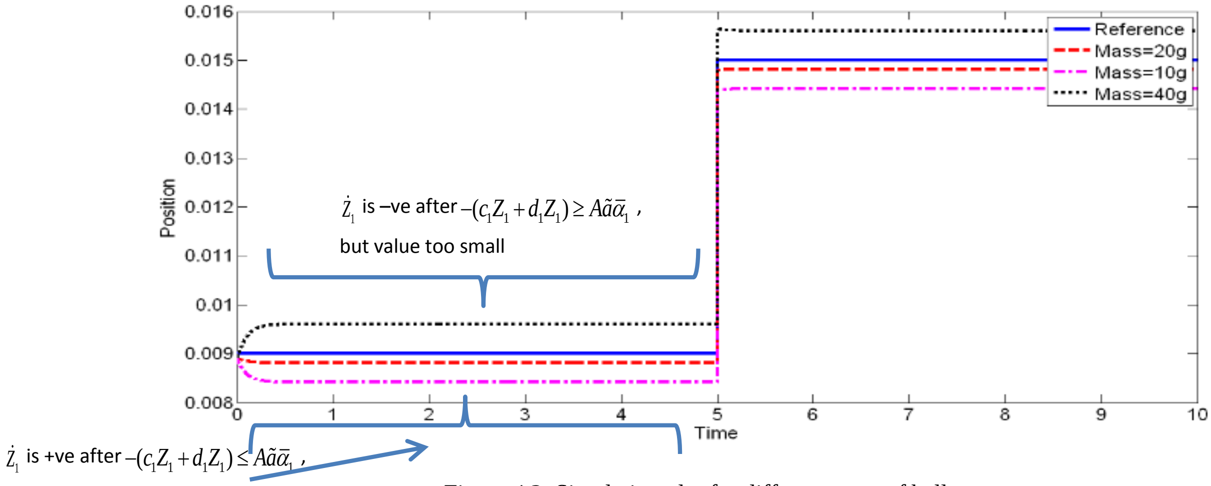

Figure 4.2 Simulation plot for different mass of ball

Now from Figure 4.2 it is observed that there is undershoot for mass 20g & 10g but there is an overshoot for mass 40g.because form(3.12) it is seen that the $\dot{Z}_1$ depends directly on $\tilde{a}$.For mass 40g $\tilde{a}$ is positive thus the slope i.e $\dot{Z}_1$ rises until the term $-(c_1 Z_1 + d_1 Z_1)$ is greater than $\tilde{a}$ but for mass 20g and 10g $\tilde{a}$is negative thus slope initially decreases until $-(c_1 Z_1 + d_1 Z_1)$ is greater.

Simulation result of MagLev system with different reference with $c_1 = 1000, c_2 = 2000, d_1 = 2, d_2 = 2, \gamma_1 = 100, \gamma_2 = 100$:

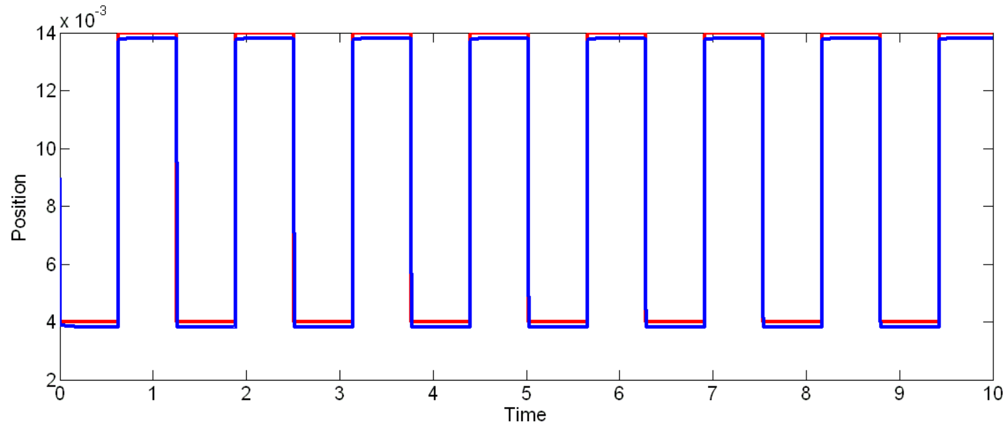

Figure 4.3 Simulation plot of MagLev system with sqaure wave reference

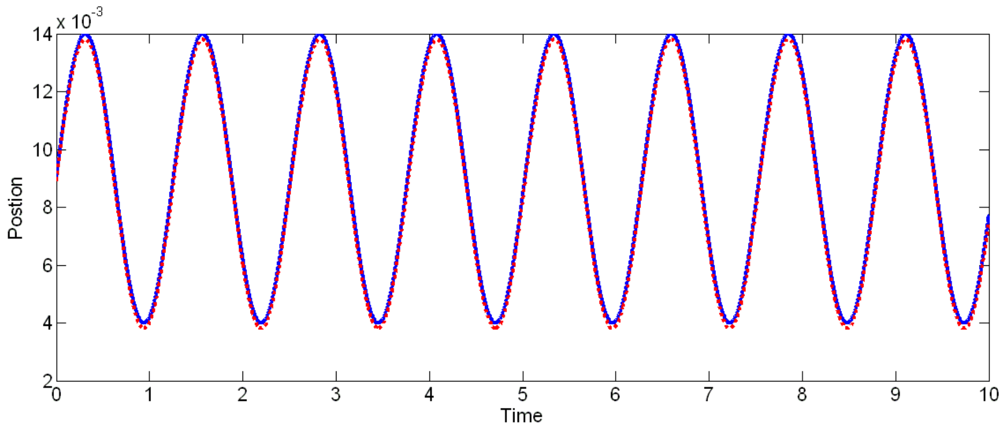

Figure 4.4 Simulation plot of MagLev system with Sine wave reference

However control signal values comes out to be very high in this controller as shown in Figure 4.5 for step reference. During the time of parameter estimating and state estimating the control values comes out to be very high.

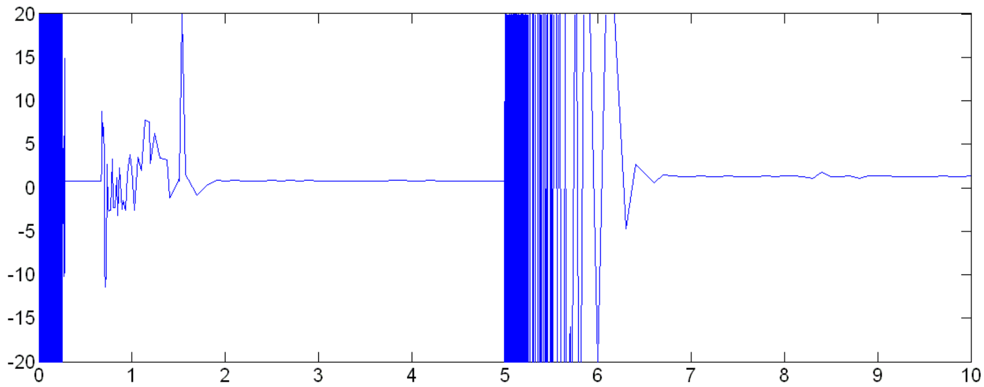

Figure 4.5 Control signal values for step reference.

4.3 SIMULATION OF NESIC BACKSTEPPING CONTROLLER ON MAGLEV SYSTEM

The Figure 4.6 shows tracking performance of MagLev system for different c_1 and c_2 values. It is observed that with increase of c_1 and c_2 values the tracking error reduces. However it is found that with increase of c_1 and c_2 values the control signal values also increases. Thus a tradeoff is taken between tracking error and control signal values. Here c_1 and c_2 values are set much less than previous controller method. The control values also come out to be very less as seen in Figure 4.7.

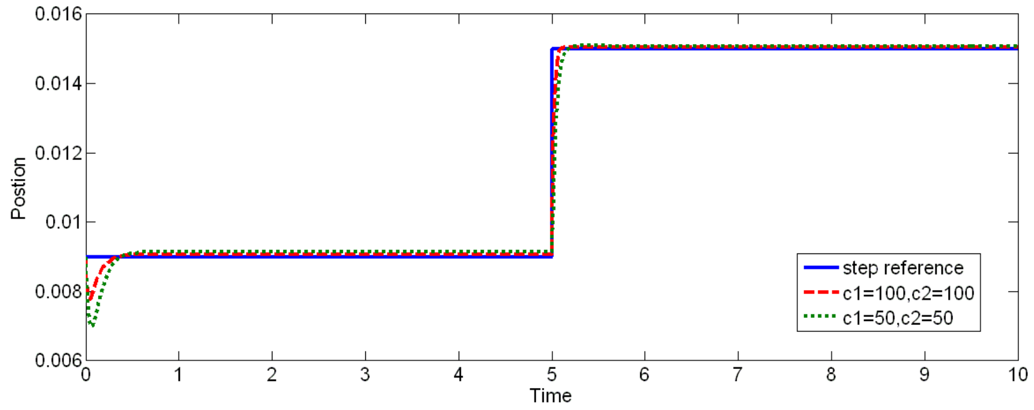

Figure 4.6 Simulation plot for step reference with different c_1 & c_2 values

It is observed that there is an undershoot initially which is reasoned out as the time taken by filter parameter 'ζ' to be same with auxiliary control 'α'.

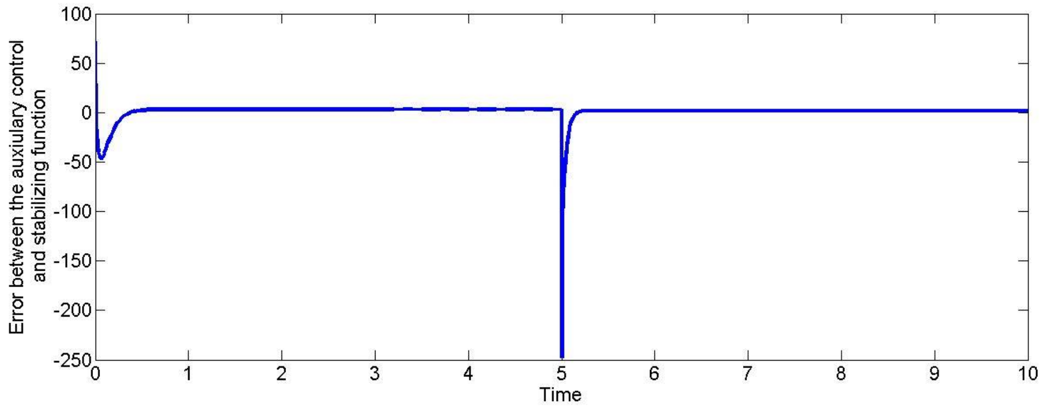

Figure 4.7 Plot of error between auxiliary control and stabilizing function

Now simulation is done for different reference inputs.

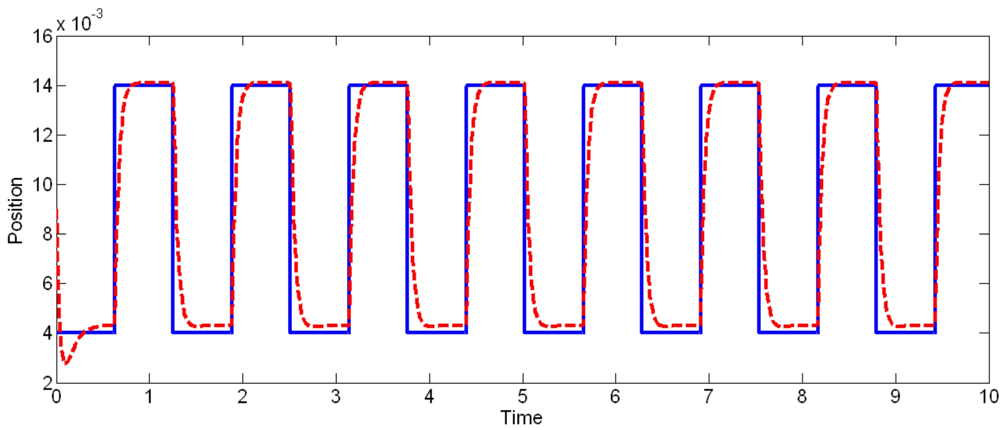

Figure 4.8 Simulation result for square wave reference

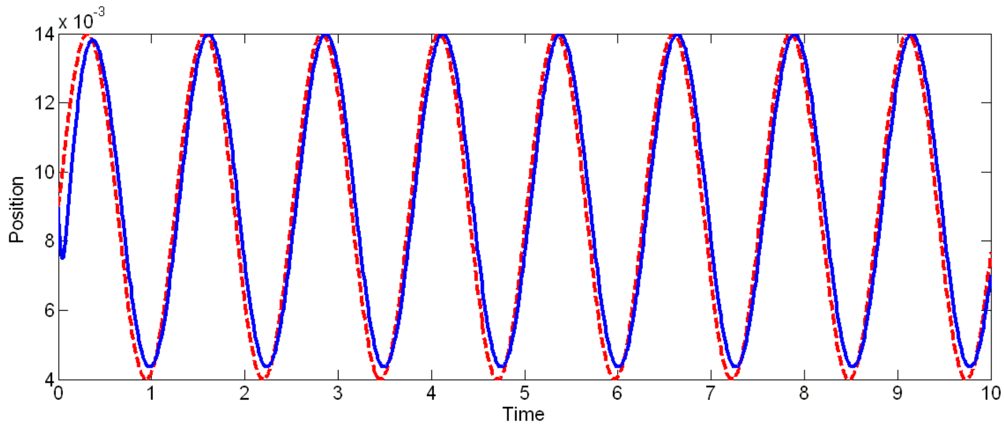

Figure 4.9 Simulation result for Sine wave as reference

4.4 SIMULATION OF MAGLEV SYSTEM WITH 2DOF PID CONTROLLER

The P_1 gain of forward loop PI controller is set so as to achieve fast response. Thus for different values of P_1 the Maglev model with 2DOF PID is simulated.

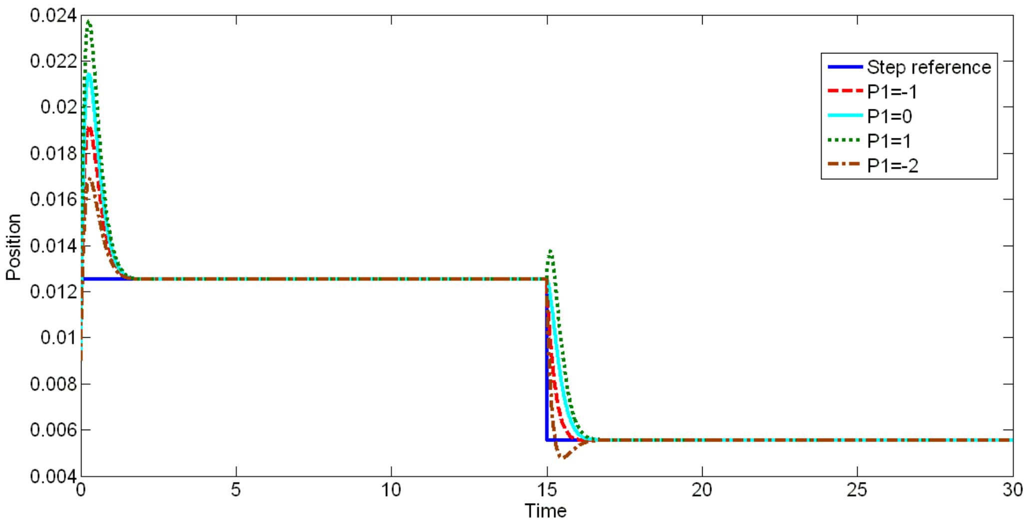

Figure 4.10 Simulation results of MagLev model with different value of P_1

It is seen from Figure 4.10 that there is an initial overshoot which can be reasoned out as sensor offset.

With increase of P_1 value in positive direction the overshoot increases and with increase in negative direction the overshoot decreases but it is seen there is an undershoot as for large negative value of P_1 .

Thus P_1 value is set as -1

Tracking for different reference signal is shown in figure

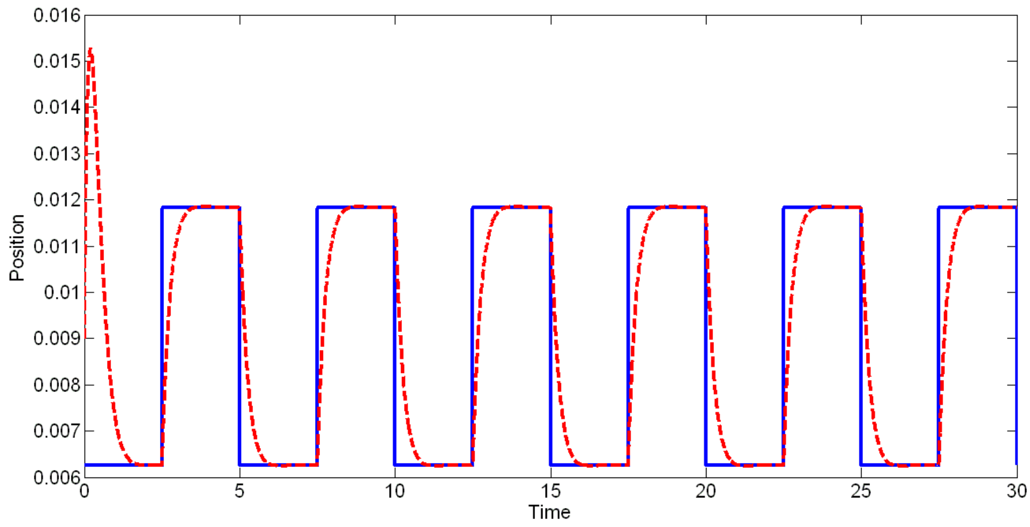

Figure 4.11 Simulation result of MagLev system with square wave reference

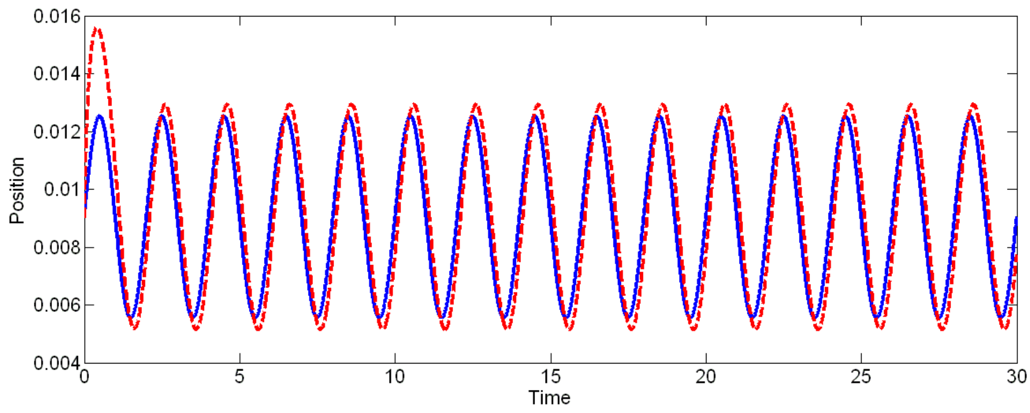

Figure 4.12 Simulation result of MagLev system with Sine wave reference

4.5 COMPARISION OF THREE CONTROLLERS

It is observed from Figure 4.13 that all three controllers have very good tracking performance. However settling time of 2DOF PID is more than other. There is an initial overshoot for 2DOF PID and undershoot for backstepping on Euler approximate model.

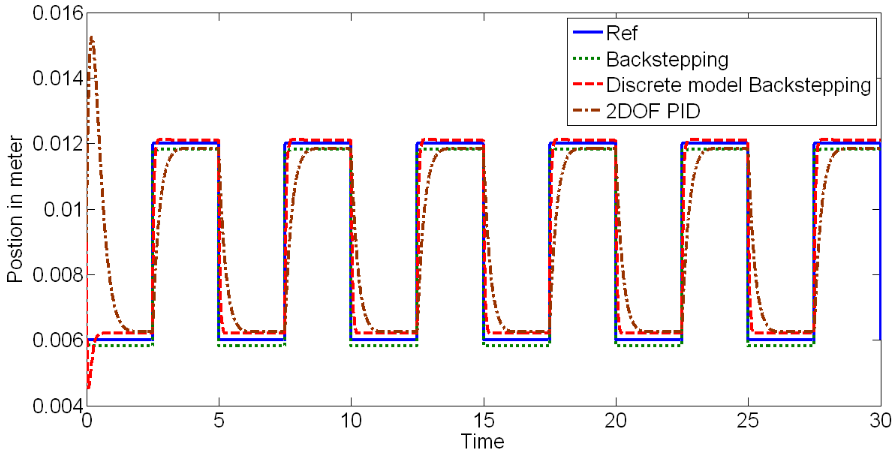

Figure 4.13 Plot of all controller for square wave reference

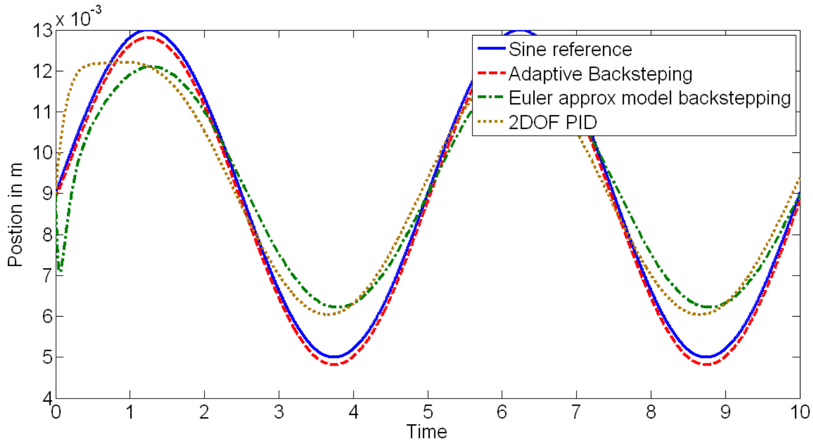

Figure 4.13 Plot of all controller for sine wave reference

The desirable control output from controller is from -5V to +5V. However the control output from backstepping controller is in range of 200 and during parameter tuning the controller output comes in range of 2000. However backstepping based on Euler approximate model it is observed that the controller output comes in range of 0.5. For 2DOF PID also it is observed that the controller output comes in range of 1.

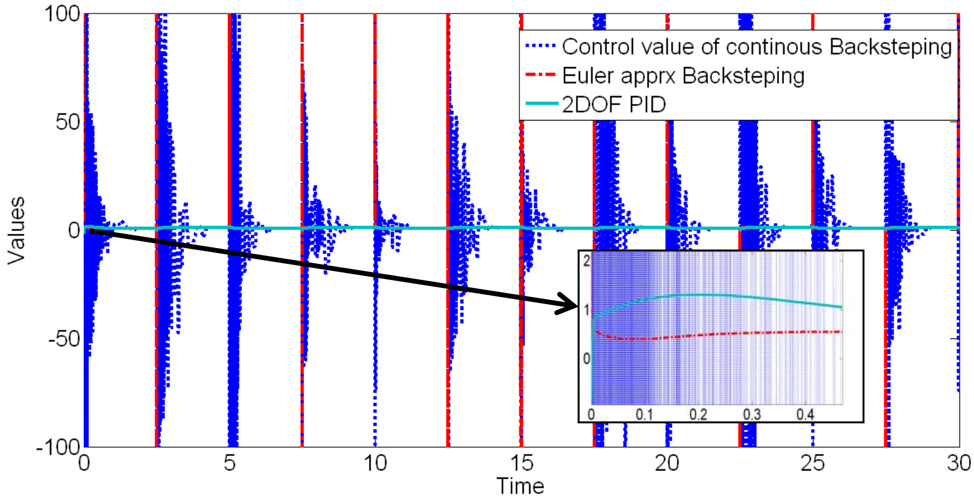

Figure 4.15 Plot of all controller control values

Table 4.5.1 Comparison of all controller performance

CONTROLLER	SETTLING TIME (Seconds)	TRACKING ERROR (millimeter)	CONTROLLER OUTPUT
Adaptive backstepping	0.2	0.1	2000
Nesic backstepping	0.3	0.1	.5
2DOF PID	1	0.1	1

4.6 EXPERIMENTAL RESULT OF 2DOF CONTROLLER

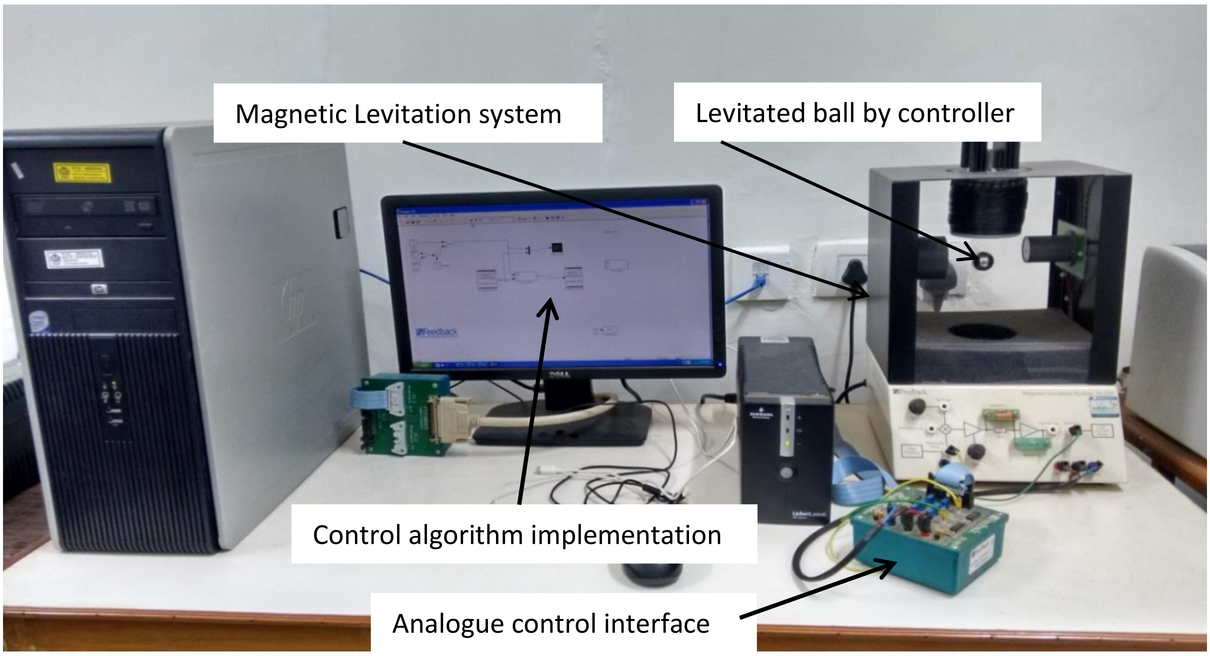

Figure 4.16 Experimental setup

4.6.1 2DOF PID with P_1 values:

2DOF PID is tested with different forward path proportional control values. It is observed that for P_1 values greater than -1 in negative value the undershoot is not being able to control as a result the levitated ball falls down. Similarly for P_1 value higher than 1 , the overshoot is not able to being contained and is attracted to magnet. The Figure 4.17 shows for different P_1 values the MagLev setup response for square wave reference. It is observed that for P_1 =-1 best result is achieved.

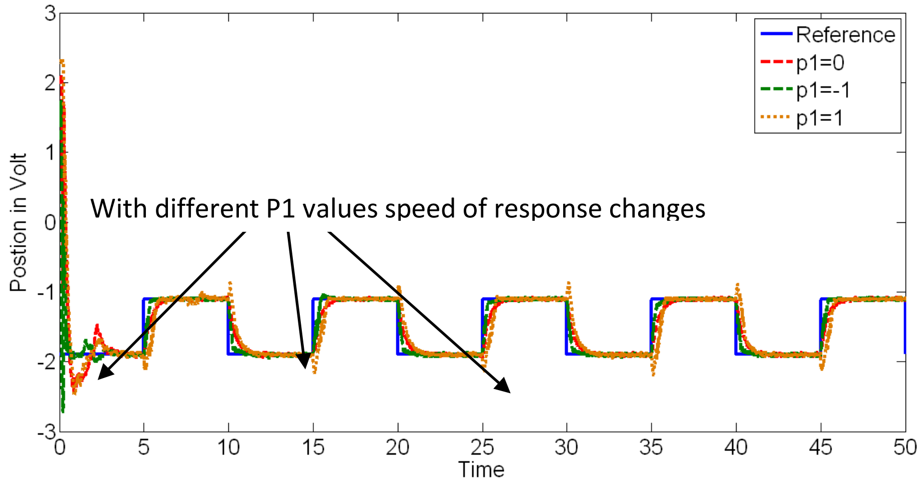

Figure 4.17 2DOF PID with different P_1 values 0,-1,1

4.6.2 Comparison of 2DOF PID with 1DOF PID in experimental setup

Now a 2DOF PID is compared with 1DOF PID where it is observed that for 2DOF apart from the initial overshoot there is no overshoot. However for 1DOF PID it is observed that the overshoots are present. With overshoot the system robustness is also decreased. Thus 1DOF is more venerable to instability than 2DOF PID in case of disturbance. A comparison 1DOF PID is done with 2DOF PID is shown in Figure 4.18.

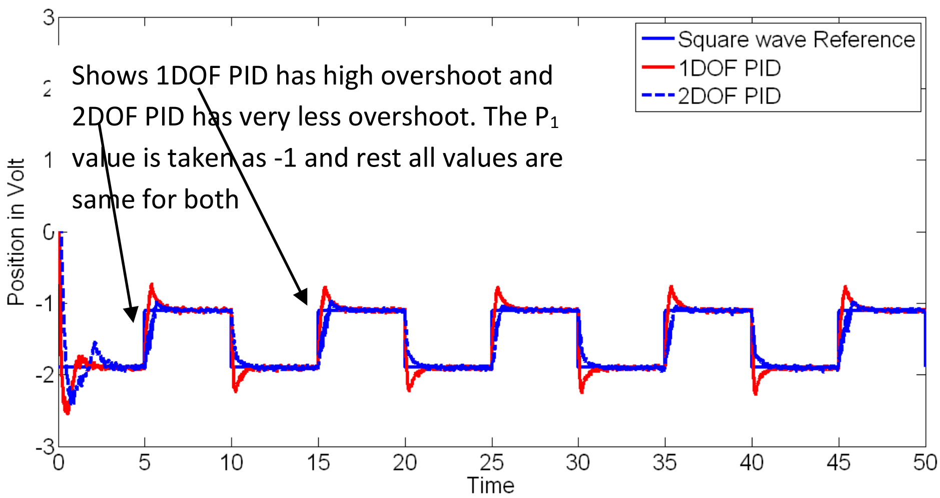

Figure 4.18 Comparison of 2DOF PID and 1DOF PID

Table 4.6.1 Comparison of experimental results of 2DOF PID and 1DOF PID.

CONTROLLER	RISE TIME (Seconds)	SETTLING TIME (Seconds)	TRACKING ERROR (millimeter)	OVERSHOOT (millimeter)
2DOF PID	1	1.5	0	0.5
1DOF PID	0.4	1.5	0	1.3

4.7 SUMMARY OF CHAPTER

In this chapter simulation results of all three controllers are presented. Experimental validation of 2DOF PID controller is done and a comparison with 1DOF PID is done. A detail analysis of performance of all controllers has been done in chapter.

CHAPTER 5

CONCLUSION AND SUGGETION OF FUTURE WORK

- CONCLUSION
- SUGGESTION OF FUTURE WORK

5.1 CONCLUSION

In this thesis a detailed modeling and controller design for MagLev system was carried out. Validation of controller was done in simulation and experiment.

Firstly adaptive backstepping controller was designed. The only output of MagLev system is position of levitated body. Since all sates are not available in output a state estimator was designed. However for backstepping strict output feedback form is required. Kreisselmeier filter was implemented to estimate the immeasurable state. Kreisselmeier filter also preserves the strict feedback form. The filter was able to estimate the state in 0.5 seconds. The simulation result shows excellent tracking performance of the proposed controller. The error in tracking comes out to be less than 0.1milimeter.

It was observed that adaptive backstepping controller has control output more than that of our required control signal i.e +5V and -5V, thus a modification was made to backstepping controller. Backstepping on Euler approximate model shows excellent tracking with control value less than 1V. The error value here comes out be 0.5 millimeter. However it was observed that the controller could not be applied to real time experiment as the real time implementation can be only carried by running the Simulink on "fixed time" solver type with constrain on sampling time as 0.001sec. The proposed controller runs finely with variable time

For real time experiment implementation 2DOF PID controller was proposed. The controller was tested on magnetic levitation setup. The experimental result shows excellent tracking with tracking error of 0.5 millimeter. The controller was also tested with small external disturbance to the levitated ball.

5.2 FUTURE WORK

Controller design which compliments with the all the criteria of implementation in Real time experiment in available hardware.

The magnetic levitation hardware which is provided can be interfaced with computer with Simulink model. The Simulink model has to be run with 'fixed time type solver'. At present the backstepping based on Euler approximate model is running finely in 'variable time type solver' but in 'fixed time type solver' the controller is not being able to track the reference. The controller is only being able to show proper tracking with sampling time of 0.00001 seconds. The problem might be due the estimator which is designed according to continuous time system and the taking Euler approximate of the estimator model. The estimator approximation is not taken into account in designing the controller.

The possible solution can be designing the controller which takes the estimator Euler approximation into account or by designing a new estimator which preserves strict feedback form of backstepping.

Reference

[1] Earnshaw, Samuel (1842). "On the Nature of the Molecular Forces which Regulate the Constitution of the Luminiferous Ether". *Trans. Camb. Phil. Soc.* **7**: 97–112.

[2] Evershed, S., “A frictionless motor meter.” J. Instn elect. Engrs 1900, 29,pp. 743-796.

[3] Faus, H. T, “Magnetic suspension.” U.S. Pat. no. 2315408, 1943 GE (U.S.A.).

[4] Ferranti, S. Z. “Magnetic suspension for electricity meter spindles.” Br. Pat. no. 590292, 1947.

[5] Arkadiev, V. “Hovering of a magnet over a superconductor.” Fiz. Zh. 1945 9,pp 148.

[6] Arkadiev, V. “A floating magnet.” Nature, Lond. 1947 160 (4062),pp 330.

[7] Kemper, H. “Overhead suspension railway with wheel-less vehicles employing magnetic suspension from iron rails.” German Pat. nos. 643316, 64402, 1937.

[8] Kemper, H. “Suspension by electromagnetic forces.” Elektrotech. Z., 1938, 59,pp. 391-395.

[9] Holmes, F. T. “Axial magnetic suspension.” Rev. scient. Instrum. 1937, 8, pp 444-447.

[10] Beams, J. W. “High rotation speeds.” J. appl. Phys. 1973, 8, pp 795-806

[11] Simon, I. “Forces acting on superconductors in magnetic fields.” J. appl. Phys., 1953, 24,pp 19-24.

[12] Culver, W. H. & Davis, M. H. “Application of superconductivity to inertial navigation.” Raud Corp, Santa Monica, U.S.A, 1957, Rep. no. R363.

[13] Davis, L. C. I972 Drag force on a magnet moving near a thin conductor. J appl. Phys. 43, 4256-4257.

[14] Powell, J. R. I963 The magnetic road; a new form of transport. In ASME, Railroad Conference, Papker 63-RR4.

[15] Powell, J. R. & Danby, G. R. I966 High speed transport by magnetically suspended trains. ASME, Publ no. 66WA/RR5.

[16] Yaghoubi Hamid, “Practical Application of Magnetic Levitation Technology” Final report Iran Maglev Technology (IMT), sep 2012

[17] Thornton D. Richard, “Efficient and Affordable Maglev opportunities in the United States” IEEE, 2009 Vol.97

[18] Huang Chao-Hing et al “Adaptive nonlinear control of repulsive MAGLEV suspension systems”,IEEE conference pp 1734-1739, 1999

[19] Yang Zi Jiang et al “Adaptive robust nonlinear control of magnetic levitation system”,Automatica ,pp 1125-1131,2001

[20] Marko Lepetic, “Predictive control based on Fuzzy Model:A case study”,*IEEE Conference*,pp 868-871, 2001

[21] Jalili Kharaajoo Mahadi, “Sliding mode control of voltage controlled magnetic levitation systems” *IEEE Conference* pp 83-86, 2003

[22] Fallaha Charles et al, “Real time implementation of a sliding mode regulator for current controlled magnetic levitation system”, 2005

[23] Cho Dan, “Sliding mode and classical control magnetic levitation system”, *IEEE Control Magazine*, 1993

[24] Yang Jun et al “Robust control of nonlinear MAGLEV suspension system with mismatch uncertainties via DOBC approach ”,*ISA Trans* pp 389-396, 2001

[25] Ghosh Arun et al “Design and implementation of a 2-DOF PID compensation for magnetic levitation system”,*ISA Trans* pp 1216-1222, 2014

[26] Kirtley Jr J.L, “Introduction to Power System” Class note chapter 8 “ElectroMagnetic Forces and Loss Mechanisms”

[27] Feedback Instrument Magnetic Levitation manual

[28] Krstic M.et al “Nonlinear and adaptive control design” (Wiley, New York, 1995)

[29] Yang Z.J: “Adaptive robust output-feedback control of a magnetic levitation system by K-filter approach”, IEEE. Trans. Ind. Electron, 2008, 55, (1), pp. 390–399

[30] Yang Z.J. et al. “A novel robust nonlinear motion controller with disturbance observer”, IEEE Trans. Control Syst. Technol., 2008, 16, (1), pp. 137–147

[31] Yang Z J et al, “Robust non-linear output-feedback control of a magnetic levitation system by K- Filter approach” ,IET Control Theory and Applications,2008.0253,pp 852-864

[32] Mishra Anand Ku et al, “Modeling and Simulation of Levitating Ball by Electromagnet using Bond Graph”, iNaCoMM , 2013,pp 42-48

[33] D.Nesic and A.R.Teel, “Backstepping on the Euler approximate model for stabilization of sampled –data nonlinear systems.” *IEEE Conference*, 2001, pp1737-1742

[34] Beltran-Carbajal F.et al, “Output feedback control of a mechanical system using magnetic levitation”,*ISA Trans*,2015

[35] Herbert, et al, “Electromechanical Dynamics Part II”, Masachusetts Institute of Technology: MIT Open Course,3 Vol

[36] <http://maglevtrainenglishpac.weebly.com/differeneces-between-eds-and-ems.html> ,Accessed online 27/5/2015

[37] <http://www.e-driveonline.com/main/wp-content/uploads/2012/05/a1-300x180.gif> ,Accessed online 27/5/2015

[38] <https://mix.msfc.nasa.gov/IMAGES/HIGH/9906088.jpg> ,Accessed online 27/5/2015

[39] <http://www.foxnews.com/tech/2014/05/14/navy-to-test-electromagnetic-catapult-on-carrier/> ,Accessed online 27/5/2015

[40] <http://www.robotliving.com/robot-news/magnetic-levitating-microbots/> ,Accessed online 27/5/2015

[41] Jayawant.B, “Review Lecture.Electromagnetic Suspension and Levitation Techniques”, Proceeding of the Royal Society of London series”, Mathematical and Physical Science, Vol.416, pp 245-320