CONTROLLERS FOR MAGNETIC LEVITATION SYSTEM

A DISSERTATION

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IN

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Submitted By

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(2K17/C&I/15)

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DECLARATION

I, REETESH, Roll No.2K17/C&I/15 of M.Tech. (Control and Instrumentation), hereby declare that the project dissertation entitled "Controllers for Magnetic Levitation System" is submitted to the Department of Electrical Engineering, Delhi Technological University, Delhi, India in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "Controllers for magnetic levitation system'' by Reetesh Verma, Roll No. 2K17/C&I/15, Department of electrical engineering, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted or full for any Degree or Diploma to this University or elsewhere.

APPROVAL FOR SUBMISSION

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ABSTRACT

The Ball and Magnetic levitation system is viewed as one of the unsteady and nonlinear electromechanical framework. For the specialist and control engineers adjusting of the nonlinear control framework has become a major test. Ball and Magnetic levitation control framework is viewed as one of the standard issue in control engineering. There are a few regulators, for example, PD regulator, PID regulator and vigorous LQR regulator which have been recognized in the writing and steadiness is likewise broke down for the Ball and attractive levitation framework. Design of regulator has become the significant perspective while designing and modelling of the system and it is likewise critical to dole out an appropriate to provide proper gain to the regulator. In this theory, execution of few control procedures that involve traditional, current and wise regulator for ball and Magnetic levitation framework with an examination among these regulators has been contemplated. LQR being a cutting edge regulator is a full state criticism regulator. The motive behind utilizing LQR calculation is to diminish the calculation burden of the framework. This proposition portrays the exchange work and numerical displaying of the proposed framework. The model of the framework is additionally linearized to be utilized with the direct regulators. Plan of the regulators and its usage is followed utilizing MATLAB/SIMULINK. PID has also been simulated for our control system in MATLAB/SIMULINK. Every individual controller performance is compared and analysed on the basis of common input criteria of step response.

ACKNOWLEDGEMENT

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Date: REETESH

(2K17/C&I/15)

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CHAPTER: 1 INTRODUCTION

Model The Maglev arrangement fills in as a straightforward model of gadgets, which are getting an ever increasing number of mainstream lately for example Maglev trains and attractive direction. Maglev trains are as of late tried and a few lines are as of now accessible as in Shanghai. Attractive heading are utilized in turbines for a similar explanation as Magnetic levitation trains are being constructed, with less grating in the actual. Effectively numerous turbines are utilized industrially where the turning shaft is suspended with attractive motion. Some other attractive direction uses incorporate siphons, rotating and other pivoting instruments. The attractive levitation frameworks are engaging for their extra chance of dynamic vibration damping. This should be possible by different control calculations usage and with no changes to the mechanical pieces of the entire framework. Lately the Maglev arrangement fills in as a basic model of gadgets which are getting increasingly well known. The magnetic suspension ball system is a typical uncertain nonlinear system, and is the foundation and platform for the study of other complex magnetic levitation system, Which have become very common in these years, i.e. Trains and magnetic bearings with Magnetic levitation.The Maglev unit takes into consideration the plan of various regulators and tests progressively utilizing Matlab and Simulink climate.

CHAPTER: 2 PROBLEM FORMULATION

The objective of thesis is mathematical modelling of ball and plate balancing system and design of various controllers such as PD, robust LQR for positioning control and their implementation. A simplified model of ball and Magnetic Levitation system is obtained by linearization process in order to implement the linear controllers. Controller and dynamic performance of ball position is determined through using MATLAB/Simulink. Stability of open loop ball and plate system is discussed using simulation response. The bode plot, root locus and Nyquist plot are plotted to discuss the open loop behaviour of ball plate system. We assume the angle of the x-axis motor will only affects the ball movement in the x direction. Similarly, for the y ball motion. Therefore, in the thesis we derive mathematical modelling of falling ball balancing system for open loop and with feedback with suitable controllers.

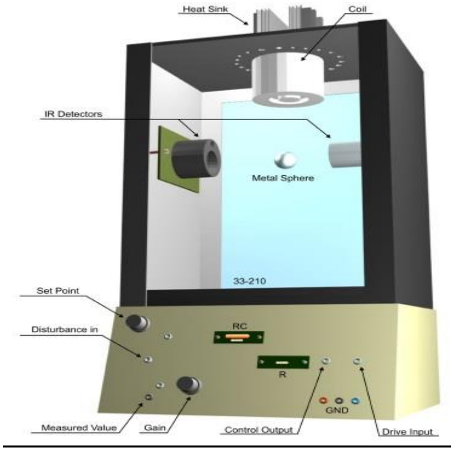

Fig :1 General structure of falling ball Magnetic Levitation System

The undertaking is shown up at by planning a model of a non-direct MIMO system. The Nonlinear framework in general model of maglev framework get linearized at the balance co-ordinates and mathematical model is acquired from it. The Magnetic levitation framework are engaging for their expansion probability of dynamic vibration damping. This is possible by various regulators like PID. The Maglev unit takes into consideration the plan of various regulators and test progressively utilizing MATLAB and Simulink Environment.

CHAPTER: 3 LITERATURE REVIEW

The magnetic levitation framework presents minimal in the method of an economically feasible item, aside from maybe as an activity in control frameworks education. In that pursuit, nonetheless, there are as yet a few earlier projects that track a similar way as this system. While exploring different projects, and extra search was made for plans or innovation identified with this framework. This, nonetheless, yielded no frameworks related or comparable in activity to this undertaking in the postings of secured research and designs. The magnetic levitation framework is a nonlinear and also open-circle flimsy framework [1]. There are various methods for nonlinear system control, such as back stepping control, sliding mode control, neural network control and adaptive control etc. Magnetic suspended structures are extremely unpredictable and not stable. The magnetic levitation device is made and the PID and LQR are configured to monitor the system [2]. Both controllers are designed and tested in real time in MATLAB. The rise in time, peak overshoot and settlement time is measured for each controller and the result is reported and compared. LQR regulator is implemented effectively to control the ball coordinates in the attractive levitation framework continuously. This paper examines the displaying and plan of a continuous attractive levitation (maglev) framework. The control plot for the maglev transportation framework has been actualized tentatively and it was checked by the reproductions. Moreover, the recommended framework was performing with three kinds of regulator which are LQR, PID and Lead remuneration [5]. The regulator's sorts have been looked at in term of various boundaries which are overshoot amplitude, time of rising and time of settlement. Besides, the LQR regulator demonstrated higher dependability and reaction in examination with traditional regulator types utilized for all the framework boundaries used. Tentatively, the LQR seemed a 14.6%, 0.199 and 0.0.64 for overshoot, time of settlement time of rising individually. The paper is about the plan of blend of LQR and PID regulator for Maglev framework which has been actualized in [2]. Maglev frameworks with 2-DOF PID remuneration is planned and reproduced in [3]. The utilisation of PID alongside LQR regulator has been planned and executed to Magnetic levitation framework [4], in which re-enactment just as equipment result has been introduced. New idea of Tumult Boundaries Improvement hypothesis with PID regulator has been introduced. Here utilization of LQR-PID approach for adjustment of a magnetic levitation framework is engaged. It is observed LQR giving framework heartiness also the security, Related input following is just executed by PID regulator. Along these lines, a mix of LQR and PID will encourage transient execution and solidness simultaneously The displaying of straight ideal controller for attractive Levitation system in both re-establishment and steady. The Hamilton -Jacobi -Bellman (HJB) condition [5] is used to design the CL ideal control of vast time additionally restricted time Linear Quadratic. Controller. (LQR) system with two degree execution measure or record. To favour the feasibility of proposed controller, it is differentiated and the conventional PID controller between their relative time response and execution records of the structure. Later on, a quick and dirty. In this paper, the ideal LQR controller is arranged using H-J-B condition for both perpetual time and restricted time is proposed for Magnetic Levitation system. From the relative examination, it's observed that the time response and the accompanying introduction of Magnetic levitation structure with the proposed controllers are found to be clearly better than Z-N tuned PID controller both in Simulink and ceaseless environment. The comparative result furthermore shows that the restricted time LQR ideal controller execution is to some degree in a manner that is superior to that of endless time with the genuine assurance of burdens frameworks.

CHAPTER: 4 MATHEMATICAL MODELLING

4.1 System Description

The Magnetic levitation system consists of magnetic, electrical and mechanical systems. The dynamic behaviour maglev system can be modelled by the study of Electromagnetic and mechanical sub systems. Maglev arrangement in this segment alludes to the mechanical-electrical part and the control viewpoint.

As demonstrated in Figure 1.1, the Magnetic levitation system comprises of a Interface Board connection with a Mechanical system with a loop present. It also consist an infra red sensor is joined to the registered autonomously PID control applies to both straight time invariant frameworks just as direct time-differing frameworks. The application to straight time invariant frameworks is notable. The application to direct time invariant frameworks empowers the design of linear feedback for non-straight questionable frameworks.

4.1.1 Magnetic Levitation Kit

Fig 4.1 Feedback Magnetic Levitation System Model

The components comprising Separated from the mechanical units electrical units assume a significant part in Magnetic levitation control. It is permitted to estimated signs to be moved to the Personal Computer through an Input/output card. The Interface of controlling is utilized to move control signals from the Personal Computer to Magnetic levitation and return. The moving and electrical units give a full oversight framework arrangement introduced in Figure 1.2.

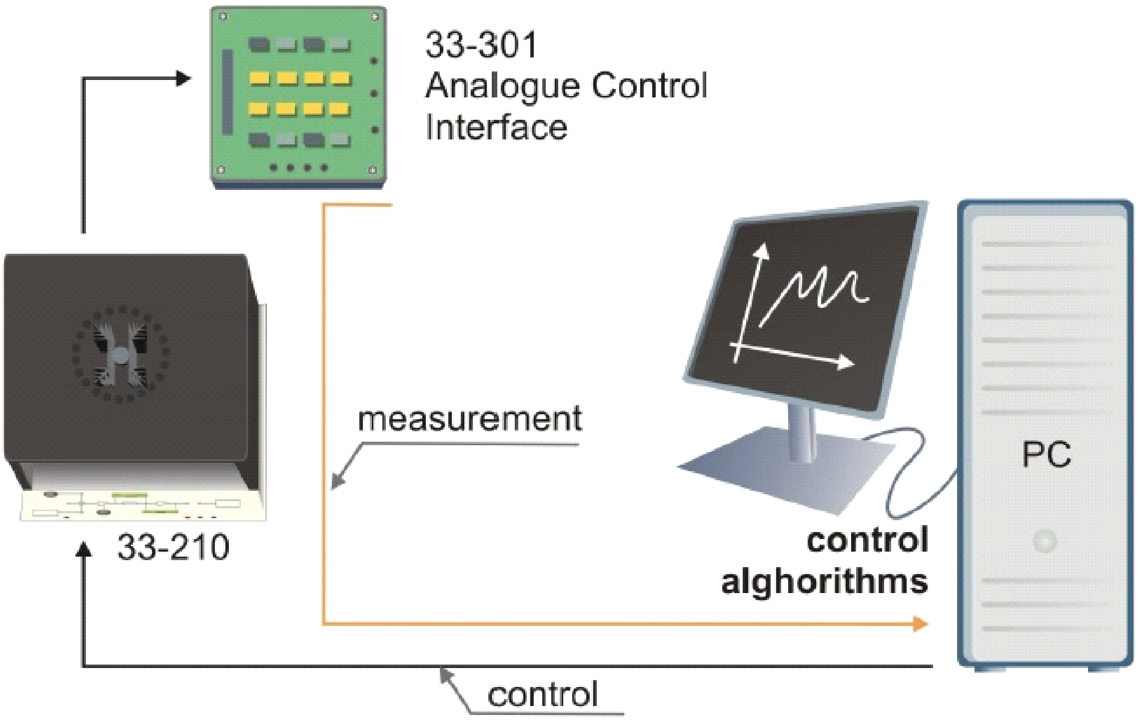

Fig.4.2 Maglev Interface Diagram

Each control project begins with plant displaying, so however much data as could be expected is given about the actual cycle. The mechanical-electrical system of Magnetic levitation is introduced in Figure 4.3.

4.2 Mathematical Modelling of magnetic levitation system

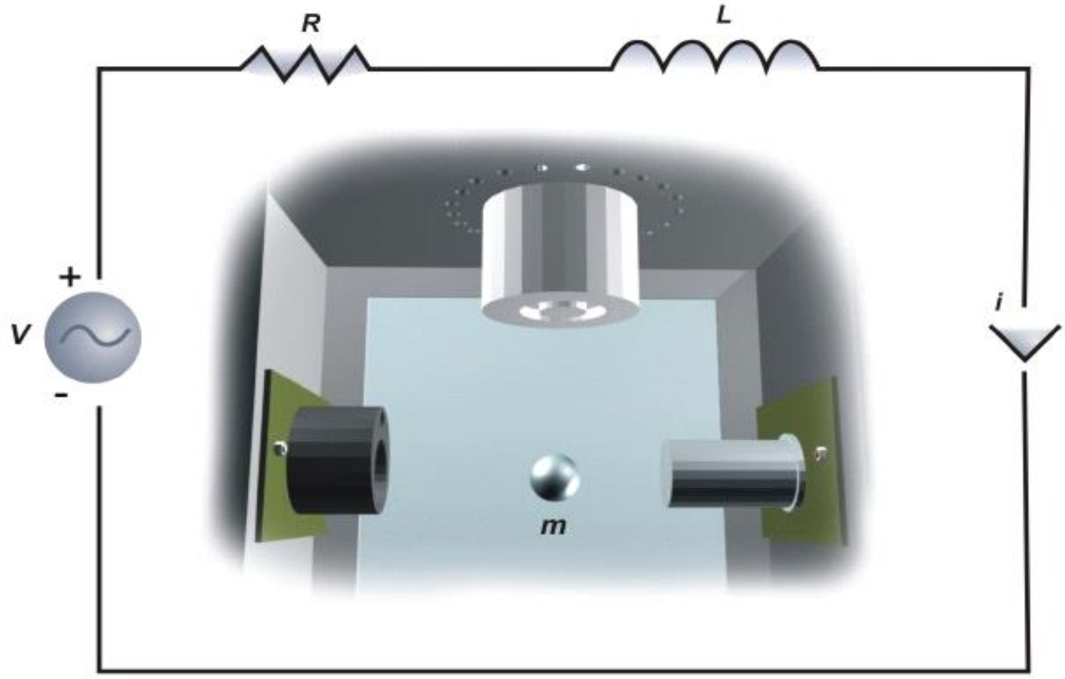

Fig. 4.3 Analogous Circuit Diagram of Maglev System

For the most part, real time models are not linear, that implies in any event one of the conditions (I – current, x–ball position) is a contention of a nonlinear capacity. To present a particularly model as an exchange work (a type of straight plant elements portrayal used in charge designing), it must be linearized.

As per the electrical-mechanical graph introduced in Figure 4.3 the nonlinear model conditions can be determined.

4.2.1 System equations:

The simplest nonlinear model of the magnetic levitation system relating the ball position and the coil current i is the following:

$$m.\ddot{x} = m.g - k\frac{\iota^2}{x^2} \qquad (1.1)$$

Here letter k is constant relying upon loop (electromagnet) boundaries. For introducing the full real time system, a relation between the controlling voltage u and the current of the loop required to set up, dissecting the entire Magnetic levitation hardware. Anyway Magnetic levitation is furnished with an inward loop of control giving an output current relative to the voltage control that is produced:

$$\mathrm{i} = \mathrm{k} \times \mathrm{u} \qquad (1.2)$$

Eqns (1.1) and (1.2) formulates a system which is not linear,

The control signal range is fixed between [-5V ..+5V].

Magnetic levitation is a Single Input Single Output plant – one information one yield (Figure 1.4). Coordinate is the system result and control signal belongs to voltage.

Figure 4.4 Magnetic levitation model for controlled position

Fig. 4.4 I/O Block diagram of Maglev

4.3 Non Linear Model Testing

In any case the user is informed to check the reactions with respect to the Maglev model the iron ball will fall in continuous manner when zero voltage control is given, we will show what will occur with the system output with u = 0. We first do the experiment with different estimations of the control signal by varying the information changing esteem.

Figure 5 shows the output of the Magnetic levitation system when the controlling signal applied is Zero.

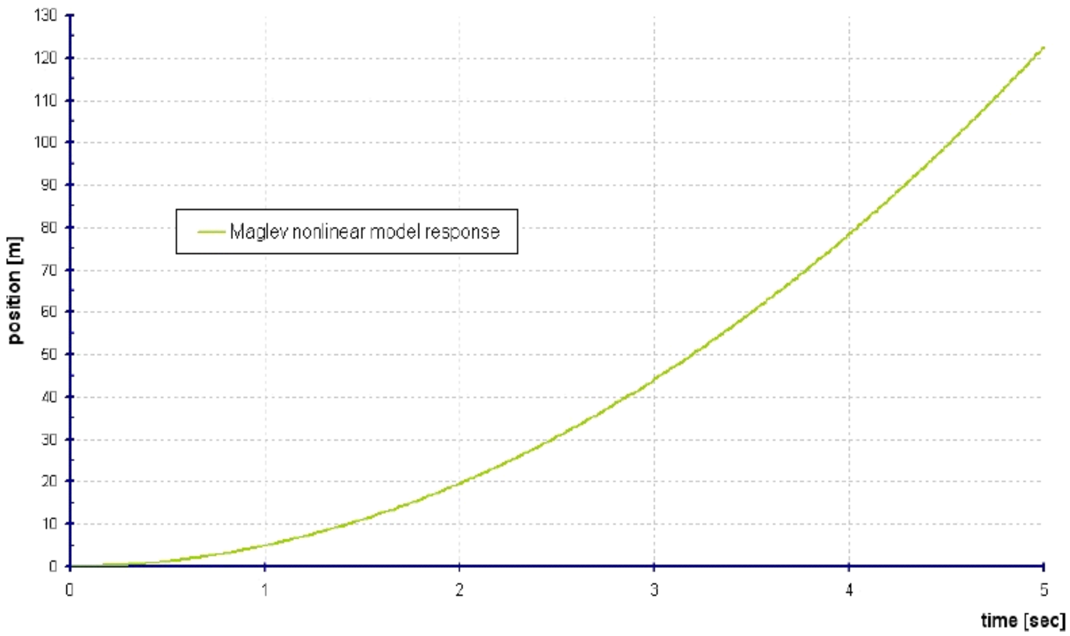

Fig.4.5 Non Linear Model output Position Vs Time

4.4 Linearization

To do examination of the model elements for open loop1 frameworks utilizing methods, for example, Bode plots, Pole-zeros plot, Nyquist plots, RL (for close loop2 frameworks just), the model must be linearized. Such a linearization is done in the balance purpose of x_o = - 1.5 [V] (the coordinate is communicated in volts), i_o = 0.8 [A]

$$\ddot{x} = g - f(x,i) \qquad (3)$$

$$f(x,i) = \frac{k}{m}(\frac{i}{x})^2 \qquad (4)$$

From here we can calculate the equilibrium point from:

$$g = f(x, i) \Rightarrow x_o, i_o. \qquad (5)$$

The conversion into the linear form is as following:

$$x = -(\frac{\delta f(i,x)}{\delta i} |i_o, x_o \Delta i + \frac{\delta f(i,x)}{\delta x} |i_o, x_o \Delta x \qquad (6)$$

$$s^2 \Delta x = -(K_i \Delta i + K_x \Delta x) \qquad (7)$$

$$\frac{\Delta x}{\Delta i} = \frac{-K_i}{s^2 + K_x} \qquad (8)$$

Where,

m=0.02kg, g=9.81m/s2, io=0.8A, xo=0.009m

K_i= 2mg/i0 = -0.4905 and K_x = -2mg/x0 = -43.6

4.5 Linear Model Testing

After performing linearization the above model will produce the output with zero control signal.

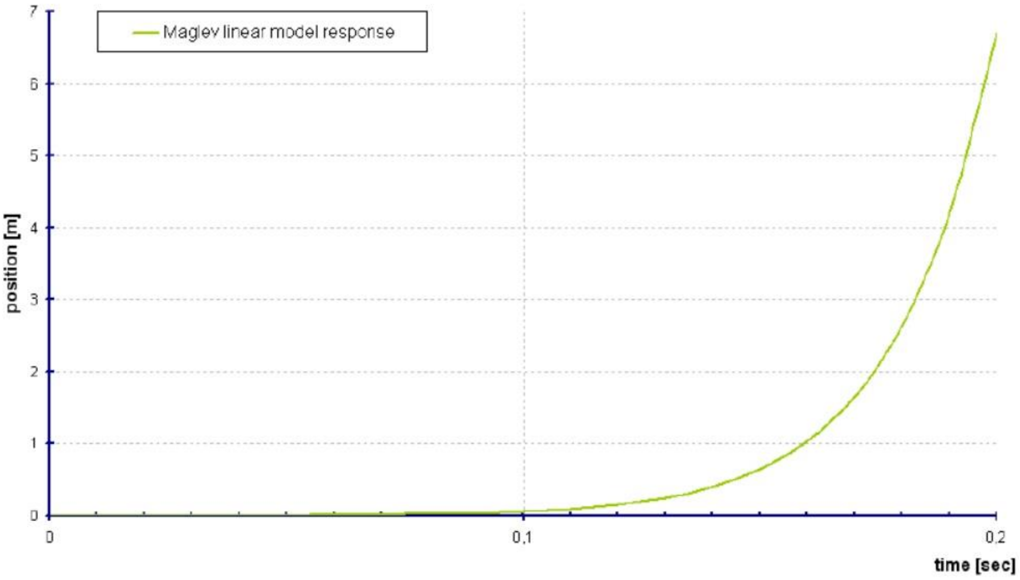

Fig. 4.6 Linear system output graph Position Vs Time

4.6 Simulink Model

The Simulink model of an open loop Magnetic Levitation System is as follows:

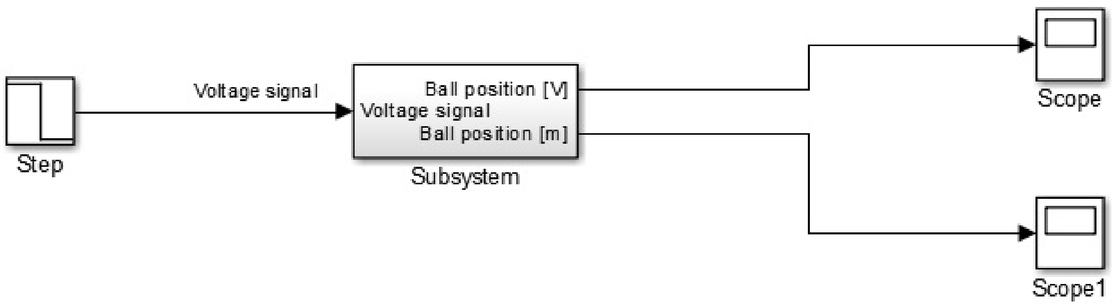

Fig. 4.6 Linear model output graph Position Vs Time

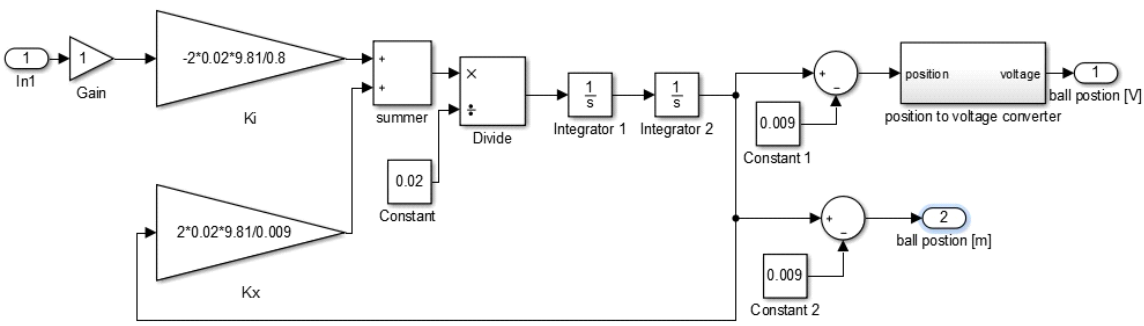

Fig. 4.8 Subsystem

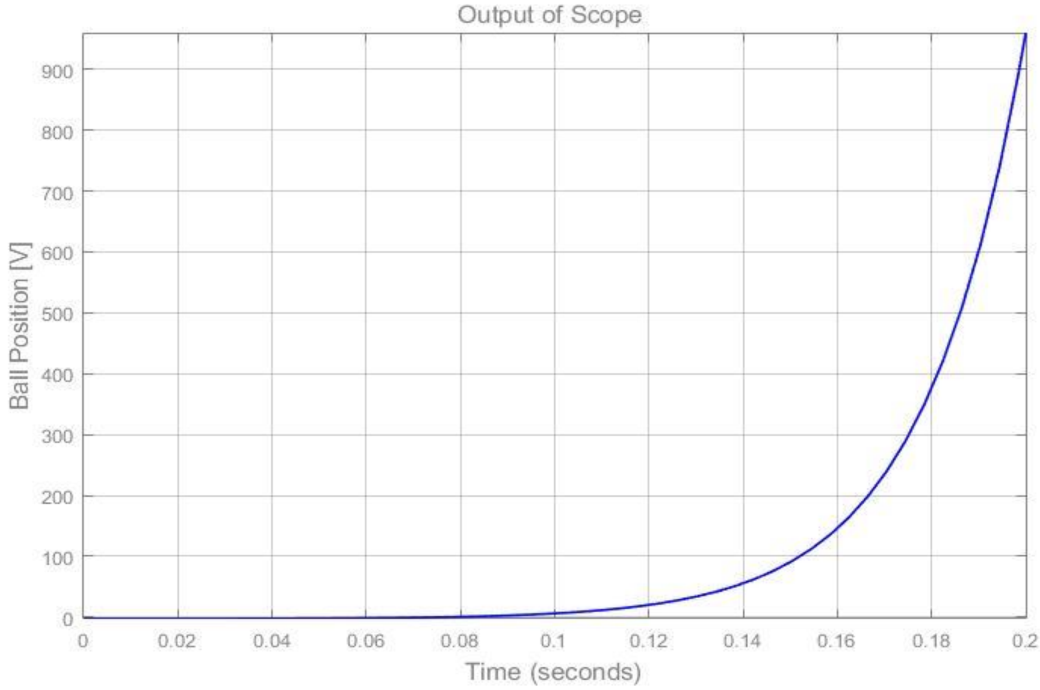

Fig. 4.9 output of scope

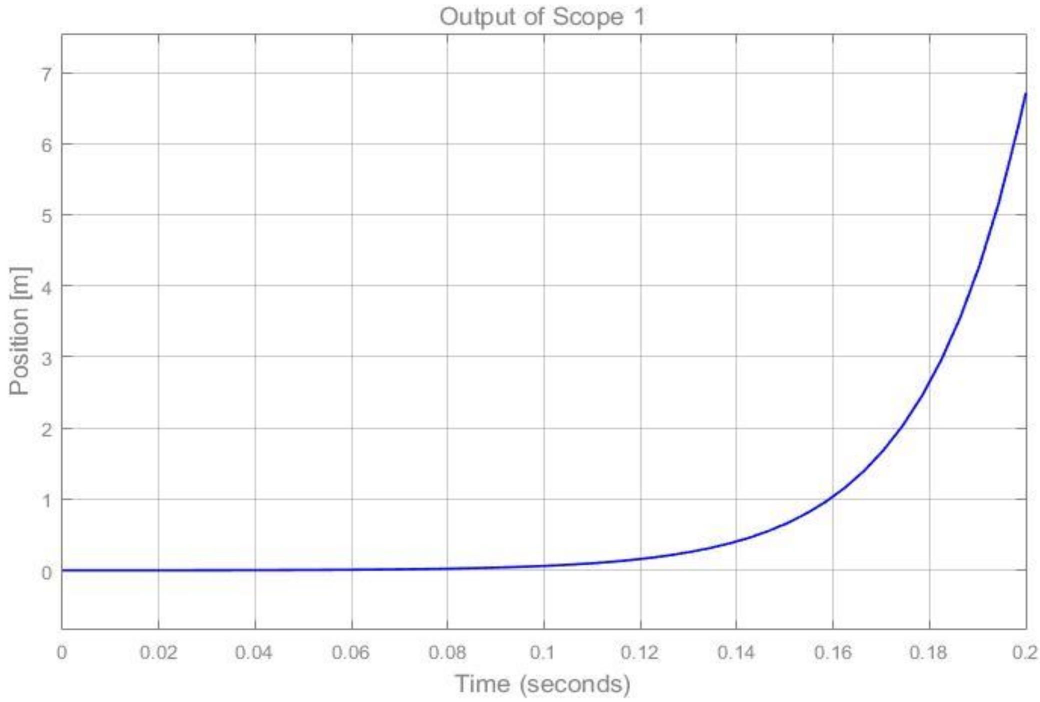

Fig. 4.10 output of scope 1

4.7 Stability analysis of open loop magnetic levitation system:

Using Fig. 4.1 and Fig. 4.2, we analyse and studied the stability of an open loop behaviour of the ball plate balancer system for one dimension, which we choose to be x-axis. Open loop ball plate balancer simulation model is shown in Fig 4.9 and open loop system response is shown in Fig 4.10.

4.7.1 Bode plot

In electrical designing and control framework, a bode plot is a diagram of the recurrence reaction of a framework. It is generally a blend of a Bode size plot, communicating the greatness ordinarily in decibels of the recurrence reaction, and a Bode stage plot, communicating the phase shift. Here w_{pc}, is the phase crossover frequency where phase shift is equal to -180^{o} and w_{gc}, is the gain crossover frequency where the amplitude ratio is 1, or when log modulus is equal to 0.

Stability criteria for bode plot:

To make the feedback system stable, modulus of $G(iw_{pc})$ has to be less than 0db at the phase crossover frequency.

The MATLAB command for the bode plot has to be written as follows

```
h= tf(n);
bode(h);
```

Thus, from the figure 4.3 we found the open loop system is unstable.

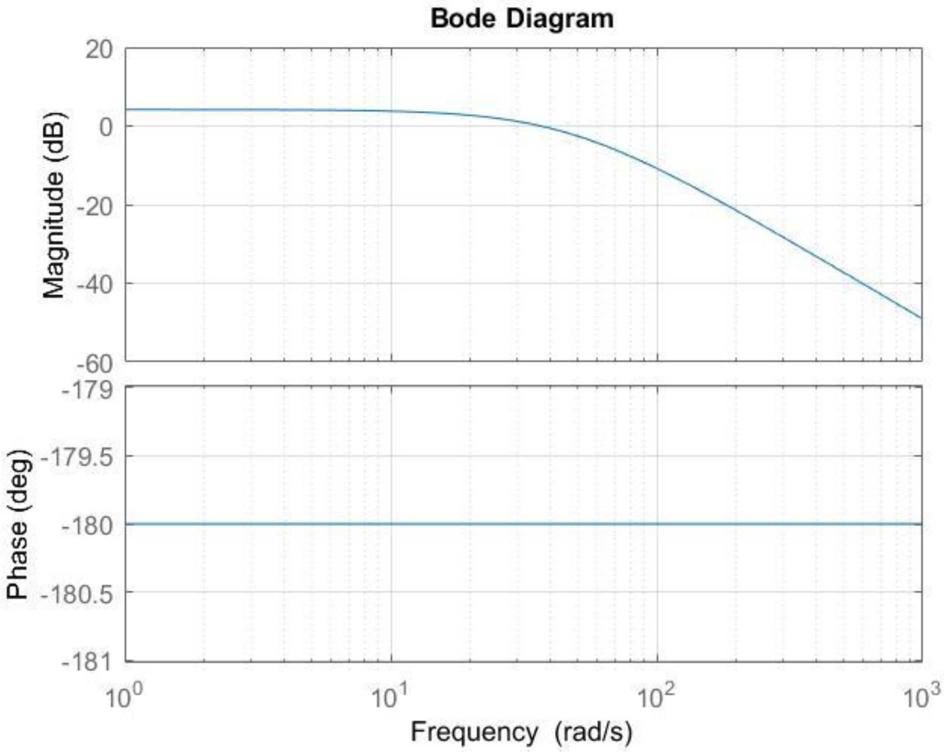

Fig. 4.11 Bode Plot: Phase and gain plot of open loop system

4.7.2 Root locus

The root locus procedure in control framework was first presented in the year 1948 by Evans. In root locus strategy in control framework we will assess the situation of the roots, their locus of development and related data. The MATLAB command will plot the root locus of the system. MATLAB code is shown below as,

```
h=tf(n);
rlocus(h);
```

This information will be used to comment upon the system performance. From the figure 4.12 it is clear that the for the open loop system, root locus shows the poles in right hand side of imaginary axis. Hence, open loop ball plate balancer is unstable system.

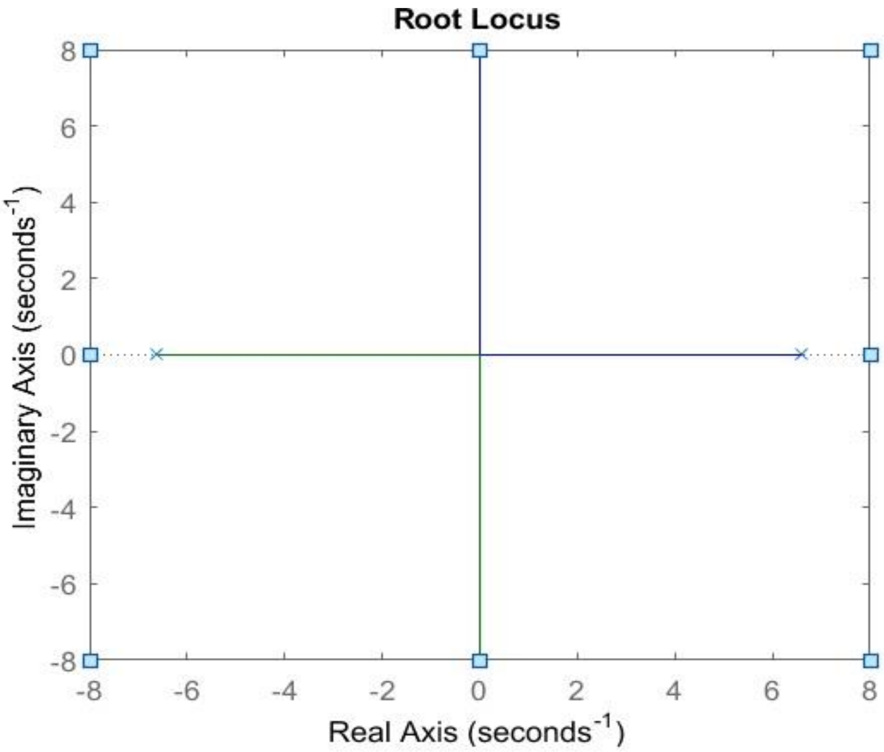

Fig 4.12 Root locus of open loop system

4.7.3 Nyquist plot

In control theory and stability theory, in 1932 at Bell Telephone Laboratories, Swedish-American electrical engineer Harry Nyquist discovered the Nyquist stability criterion for determining the stability of a system in frequency domain. While Nyquist is perhaps the most broad soundness tests, it is as yet confined to direct, time-invariant frameworks. The command for plotting Nyquist plot in MATLAB is shown as below,

h= tf(n);

nyquist (h);

The figure 4.13 shows that the open loop Magnetic Levitation system is unstable.

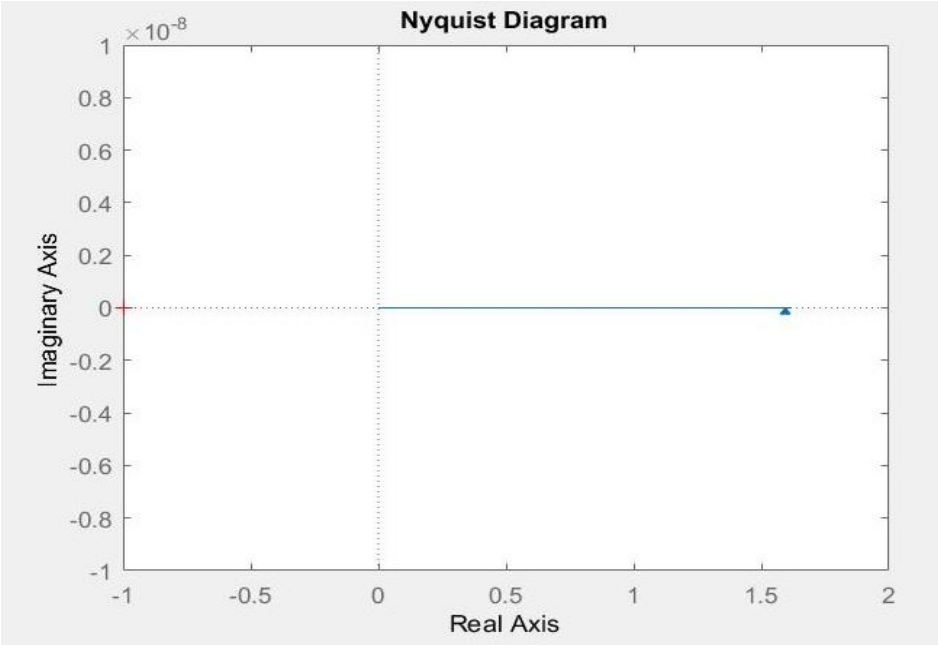

Fig 4.13 Nyquist plot for open loop system

From Fig 4.10, Fig 4.11, Fig 4.12, 5 it is observed that Magnetic levitation control system is an unstable system and the system behaviour such as open loop time response, frequency response, bode plot, root locus and Nyquist plot are shown in above figures conforms the Magnetic levitation system is unstable.

CHAPTER 5: CONTROL DESIGN AND IMPLEMENTATION

The regulator plan acknowledgment is actualized utilizing three control draws near, to be specific PID regulator, LQR regulator. For dynamic of regulator plan, a couple of plan specifications have been wanted.. The time domain requirement for controlling the position of the ball for both the x and y axes on the Magnetic Levitation Ball model are given as,

Specification 1: 4% settling time, ts≤ 3.0 s

Specification 2: percentage overshoot PO ≤ 10%

Specification 3: steady state error, ess≤ 5mm

5.1 PID Controller Design

These days, over 90% of all the controlling loops are PID, with a wide scope of utilizations: measure control, engine drives, magnetic and optical recollections, auto, flight control, instrumentation, and so on. This is basically because of its capacity in settling a wide class of functional control issues just as its underlying effortlessness, no consistent state blunder, permitting the administrators to utilize it absent a lot of trouble. However, there are additionally a few issues, for example, the boundaries of the PID regulator are provided by the experiences of humans and the boundaries can't be changed once recognized. For the mechanical cycle frameworks with nonlinearity, huge deferral, boundary inconstancy, model vulnerability and different variables, it's hard to meet the presentation necessities by utilizing the PID regulator.

The combinative activity of Proportional, Integral and Derivative activity is an affective instrument for controlling process cycles. It is a conventional control loop feedback technique broadly utilized in mechanical control framework. An error esteem is determined by the PID regulator as the contrast between an ideal set point and estimated measure variable. By changing the process control inputs the error is limited by the regulator.

The PID regulator is now and again called Three-term regulator as the figuring includes three separate consistent boundaries which are the Proportional, Integral and Derivative characteristics indicated P, I and D. These characteristics can be deciphered as far as time: P proportional to present error, I on the reconciliation of past mistakes, and the forecast of future mistakes is meant by D, in view of current pace of progress. The cycle is changed dependent on the weighted amount of these three activities through a control component, for example, the situation of a damper, a control valve, or the force provided to a warming component.

The regulator can give control activity intended to explicit cycle prerequisites by tuning the three boundaries in the PID regulator calculation. The responsiveness of the regulator is given by how much the regulator overshoots the set point, its reaction to a mistake and the level of framework oscillations.

The output of the controller in continuous form is denoted by:

$$R(t) = Kp.e(t) + Ki.\int e(t) + Kd.\frac{de(t)}{dt} \quad (5.0)$$

The continual is the proportional gain, is the integral time, is the derivative time, and e is the error between the reference and the process output. We are worried about computerized control, and for little testing periods T(s), the condition might be approximated by a particular estimation. Supplanting the subsidiary term by a retrogressive contrast and the vital by a whole utilizing rectangular incorporation, an estimate is Record n alludes to the time moment.

Characteristics:

- It adds both pole and zero.
- It improves both transient and steady state response.
- It decreases offset error and oscillations and increases stability.

For the better tuning of PD Ziegler Nichols's method is used. For the output PD controller, the coefficient value tuned as to be Kp= 9.07, Ki=32.4 rad/s and Kd= 0.753 rad/. This Fig 2.1 is representing the simulation model of closed loop system for Magnetic Levitation System. Ball Magnetic levitation system is modelled using mathematical modelling the control design is implemented in MATLAB/SIMULINK. The input is unit step with value 1 unit is provided to the adder then to get the output of system transfer function. Summer in below diagram send the error signal to the PID controller in order to get the controlled and improves response.

5.2 Simulink Model

The Simulink model of a closed loop Magnetic Levitation System is as follows:

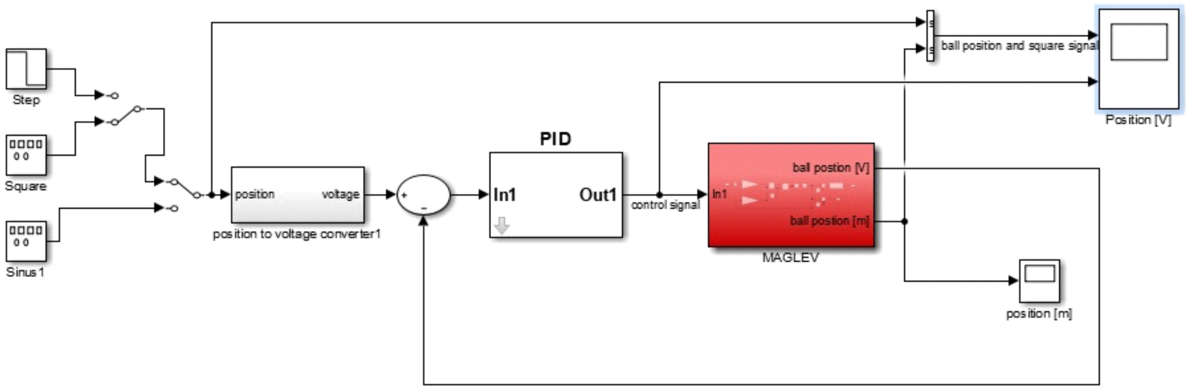

Fig.5.1 Magnetic Levitation Model with PID

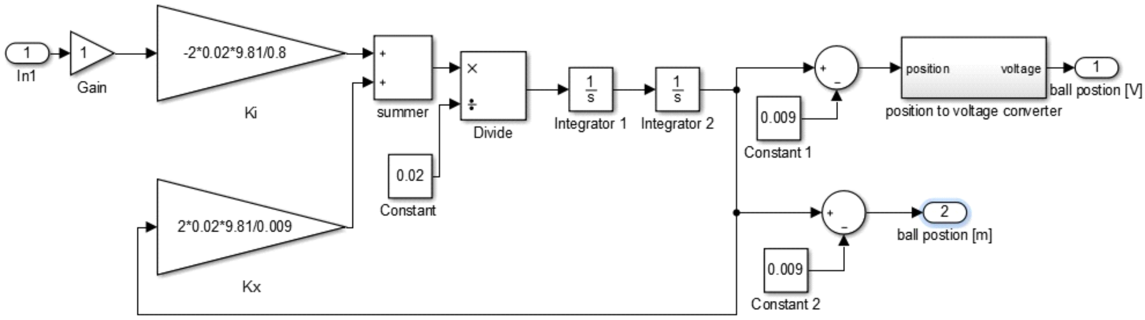

Fig.5.2 Maglev – Magnetic Levitation transfer Function Model

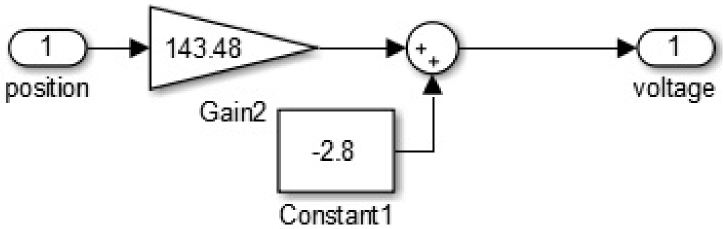

Fig.5.3 Subsystem 2- Position to Voltage converter

5.3 LQR Controller Design

The Magnetic levitation framework non-linear model equation which relates the i current in coin and the x as position of the ball are as following:

$$m.\ddot{x} = m.g - k\frac{i^2}{x^2} \tag{5.1}$$

Let us describe 'g' is the quickening because of gravitational pull, ball's mass is represented as m and k is a consistent whose worth relies upon the boundaries of curl. The Maglev is operational with an inner control circle which gives the related current converted into the control voltage. Consequently, the relation between the control signal voltage u that is created for control reason and the loop current i is represented by:

$$i = K_1 \times u \qquad (5.2)$$

Where K_1 is the magnitude of control voltage to coil current. The equation of non-linear framework has to be made in linear fashion around the balance point x_0, $i_0$for examination and regulator configuration purposes. Consequently, the linearized model exchange capacity of Maglev framework, is given beneath:

$$\frac{\Delta x}{\Delta u} = \frac{-3518.85}{s^2 - 2180} \qquad (5.3)$$

The instrument yield (in volts) is given by *x* and controlling signal voltage is given by *u*. Maglev is a solitary information single yield (Single Input Single Output) plant where the signal control voltage u and x ball position is the plant result or output. The state space frameworks in controllable accepted structure can easily be acquired from (5.3) and are given by:

$$A=\begin{bmatrix} 0 & 1 \\ 2180 & 0 \end{bmatrix} \qquad (5.4)$$

$$B=\begin{bmatrix} 0 \\ -3518.85 \end{bmatrix} \qquad (5.5)$$

$$C=\begin{bmatrix} 1 & 0 \end{bmatrix} \qquad (5.6)$$

$$D=[\,0\,] \qquad (5.7)$$

Now we can express, the equations of state space using (5.4), (5.5), (5.6) and (5.7) as:

$$\dot{x}_1 = x_2 \qquad (5.8)$$

$$\dot{x}_2 = 2180x_1 - 3518.85u \qquad (5.9)$$

$$y = x_1 \qquad (5.10)$$

Where x_1 is the condition of ball position$x$, x_2 is the state of loop current i, the control input is given as u and the output of Magnetic Levitation expressed for ball position$x$. The optimal control configuration infers a control law or signs which cause the dynamical framework to accomplish an objective or pursue the direction and furthermore extremize an exhibition file simultaneously. The plant Magnetic Levitation system dynamics is considered in the form of state variable form which is shown in (5.8), (5.9) and (5.10), performance index in general can be represented in terms of the final cost function S(X(t_f), t_f), states X(t) and controls u(t) is addressed as:

$$J = \left(S\left(X\left(t_f\right), t_f\right)\right) + \int_{t_o}^{t_\infty} V(X(t), u(t), t)dt \tag{5.11}$$

$$S\left(X\left(t_f\right), t_f\right) = \frac{1}{2}(X^T\left(t_f\right)F\left(t_f\right)X\left(t_f\right)) \tag{5.12}$$

$$V(X(t), u(t), t) = \frac{1}{2}\{\left(X^T(t)QX(t) + u^T(t)Ru(t)\right)\} \tag{5.13}$$

In (5.11), t_o and t_f Transfer function are beginning and last focuses separately. Here a non-negative, real, and definite matrix F in (5.12). In (5.13), Q and R are weighting networks with the end goal that Q = QT ≥ 0 and R = RT > 0. One of the calculations for c$x$hoosing loads frameworks for ideal LQR is available in. Be that as it may, the determination of matrices Q and R in the paper is carried by experimentation premise.

$$Q=\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \tag{5.14}$$

Let us assume R = 1 and Q as resented in (5.14), the initial procedure for optimization to form H Hamiltonian function which is given as:

$$H\left(X(t), u(t), J_X^{*^T}, t\right) = V(X(t), u(t), t) + J_X^{*^T}(X(t), t)\{AX(t) + Bu(t)\} \tag{5.15}$$

For optimizing of *H* w.r.t. *u(t)*, the most important condition is (*∂H/∂u)*=0 which finally gives

$$u^*(t) = -\{R^{-1}B^T J_X^{*^T}(X(t), t)\} \tag{5.16}$$

Using the control (5.16) in Hamiltonian function (5.15), optimized Hamiltonian (5.17) is obtained.

$$H^*\left(X(t), u^*(t), J_X^{*T}, t\right) = \frac{1}{2}\left\{\left(\left(X^T(t)QX(t)\right) - \left(J_X^{*T} R^{-1} B^T J_X^*\right)\right)\right\} + \{J_X^{*T} AX(t)\} \quad (5.17)$$

The H-J-B equation is represented as

$$J_t^* + H^*\left(X(t), u^*(t), J_X^{*T}, t\right) = 0 \quad (5.18)$$

with boundary condition:

$$J_X^*\left(X^*(t_f), t_f\right) = \frac{1}{2}\left(X^{*T}(t_f)F(t_f)X^*(t_f)\right) \quad (5.19)$$

where F(t_f) is expressed as:

$$F(t_f) = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad (5.20)$$

Here, the J(11) is performance index which is a two degree function of the state, so the result can be stated as:

$$J^*(X(t), t) = \frac{1}{2}\left(X^T(t)P(t)X(t)\right) \quad (5.21)$$

P(t) is a coefficient of Riccati matrix which has to be solved and which satisfies

$P(t) = P(t)^T > 0$ for every value of *t*.

$$J_t = \frac{\partial J}{\partial t} = \frac{1}{2}\left(X^T(t)\dot{P}(t)X(t)\right) \quad (5.22)$$

$$J_t = \frac{\partial J}{\partial t} = P(t)X(t) \quad (5.23)$$

Therefore, from (5.19), (5.20) and (5.21); the value of P(t)

Found at t = t_f is

$$P(t_f) = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad (5.24)$$

Utilizing accepted arrangement of execution record (5.21) with (5.22) and (5.23) in the H-J-B condition (5.18), following condition is acquired called the (MDRE) Matrix Differential Riccati Equation.

$$P(\dot{t}) = -\,[P(t)A] - [A^T P(t)] - [Q] + [P(t)BR^{-1}B^T P(t)] \quad (5.25)$$

Then using (5.23) in (5.16), the optimized input signal control in related term of voltage is found as

$$u^*(t) = -\{R^{-1}B^T P(t)\} \quad (5.26)$$

The fundamental body diagram of closed coil optimal LQR regulator with Magnetic levitation framework is reperesent in Figure 4 in which K = {R^{-1} BT P(t)} and it comes out to be

$$K = [-1.7959 \ -0.0319] \quad (5.27)$$

```
clear all;
clc;
display('------------Linear Quadratic Regulator-----------------')
A=[0 1;2180 0];
B=[0;-3581.85];
C=[1 0];
D=[0];
[b,a]=ss2tf(A,B,C,D);
sys1=tf(b,a)

W=1
if W==1
   Q=[1 0;0 0];
else
   Q=transpose(C)*C
end

R=[1];

Y=input('if want to enter value of N manually enter 1 else 2 = ')
if Y==1
   N=input('enter value of N = ')
else
   %%
   N=0
end
[K,S,e]=lqr(A,B,Q,R,N)
sys=ss(A,B,C,D)

n=length(K);
AA=A - B * K
for i=1:n
   BB(:,i)=B * K(i);
end
display(BB)
```

```
CC=C
DD=D
for i=1:n
    sys(:,i)=ss(AA,BB(:,i),CC,DD);
end
subplot(111)
step(sys(:,1))
```

CHAPTER 6: RESULTS OF SIMULATION PERFORMED

6.1 PID simulation result

Snap on the *Start* re-enactment button, or on the Beginning thing in the Reproduction menu, to run the shut circle framework utilizing PID regulator and the degrees should peruse as demonstrated in Figure 5.1, Figure 5.2. In each scope, the ball position (red trace) and should track the corresponding square signal (purple trace) which is a desired position signal. Also, examine the control signal (purple plot).

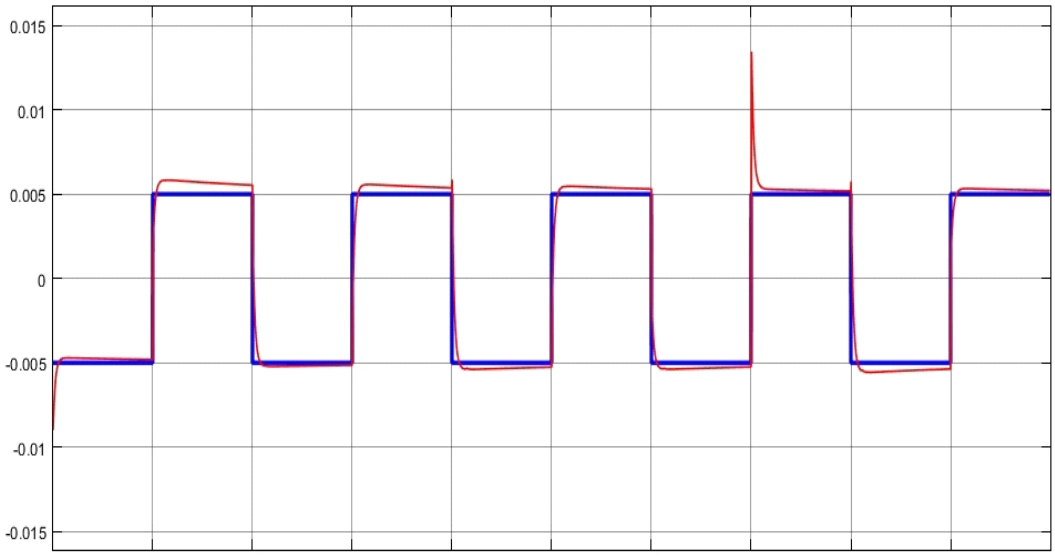

Fig 6.1 Simulated Ball position and desired Position for Kp=112 Ki=5 Kd=0.5

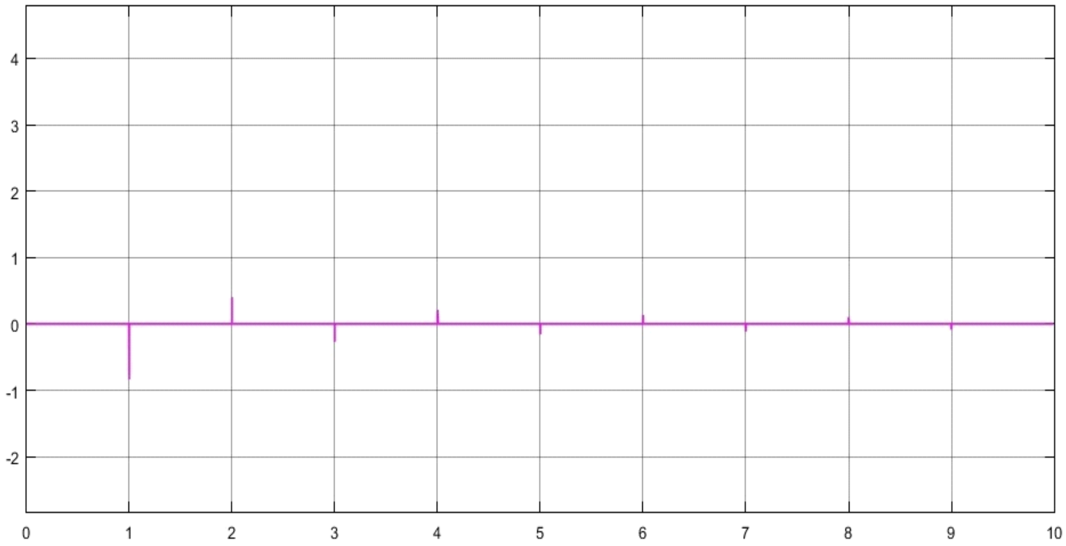

Fig 6.2 Simulated Control signal using PID controller for Kp=112 Ki=5 Kd=0.5

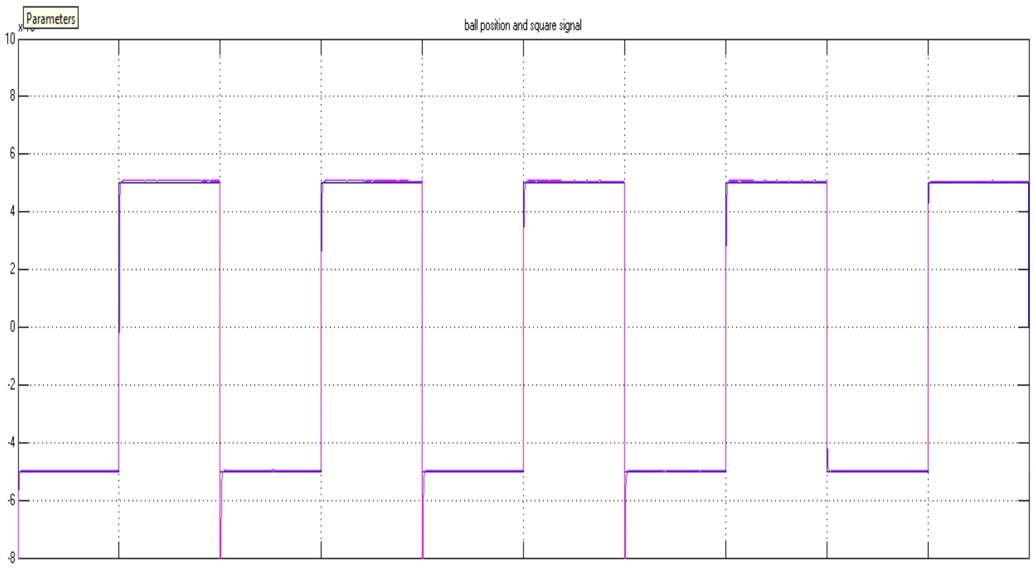

Fig 6.3 Simulated Ball position and desired Position For Kp=9.07 Ki=32.4 Kd=0.0753

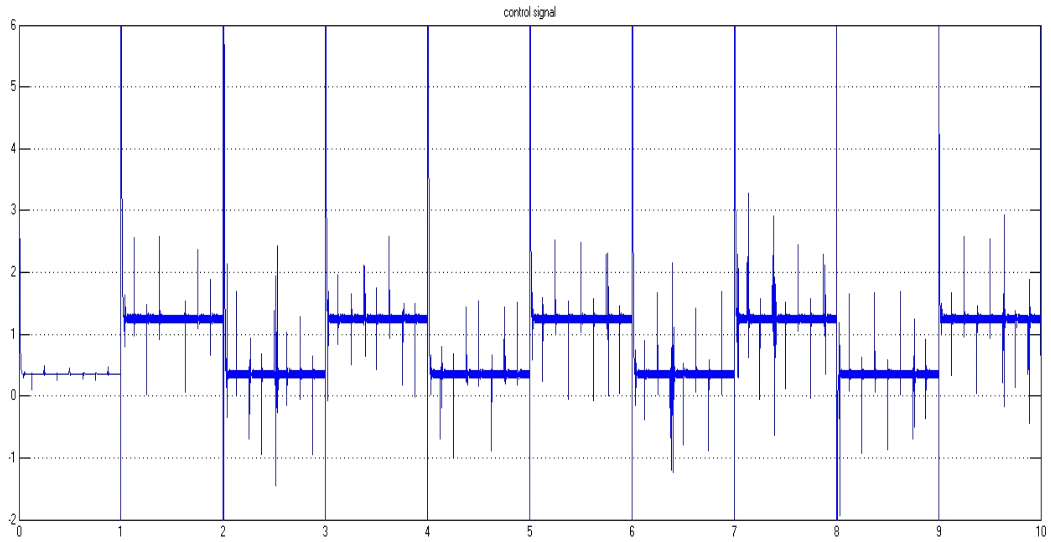

Fig. 6.4 Simulated Control signal using PID controller for Kp=9.07 Ki=32.4 Kd=0.0753

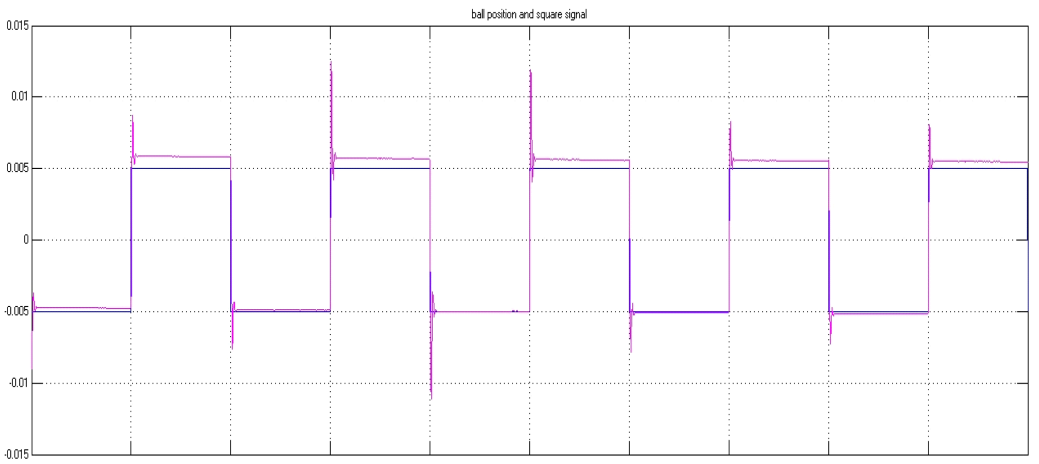

Fig. 6.5 Simulated Ball position and desired Position for kp=10 ki=1.3 kd=0.04

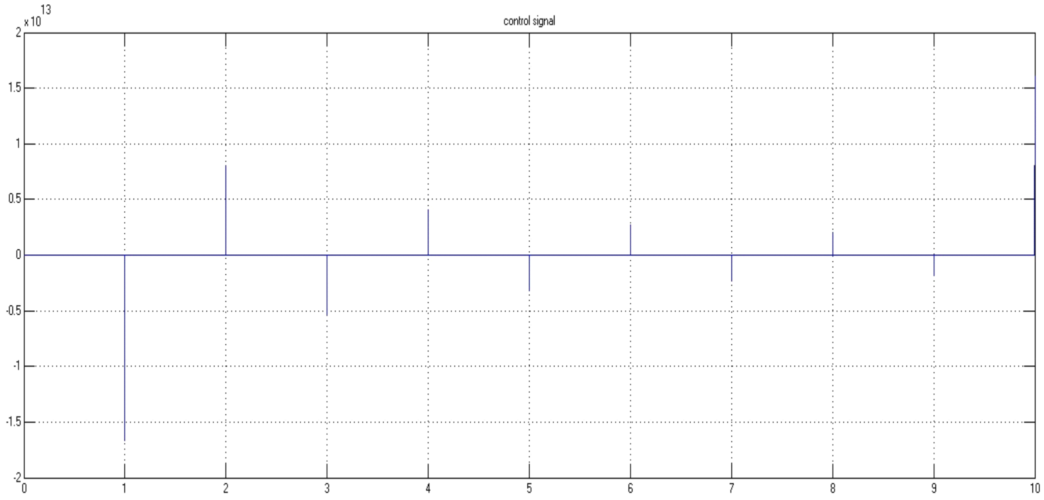

Fig 6.6 Simulated Control signal using PID controller for Kp=10 Ki=1.3 Kd=0.04

6.2 LQR simulation result

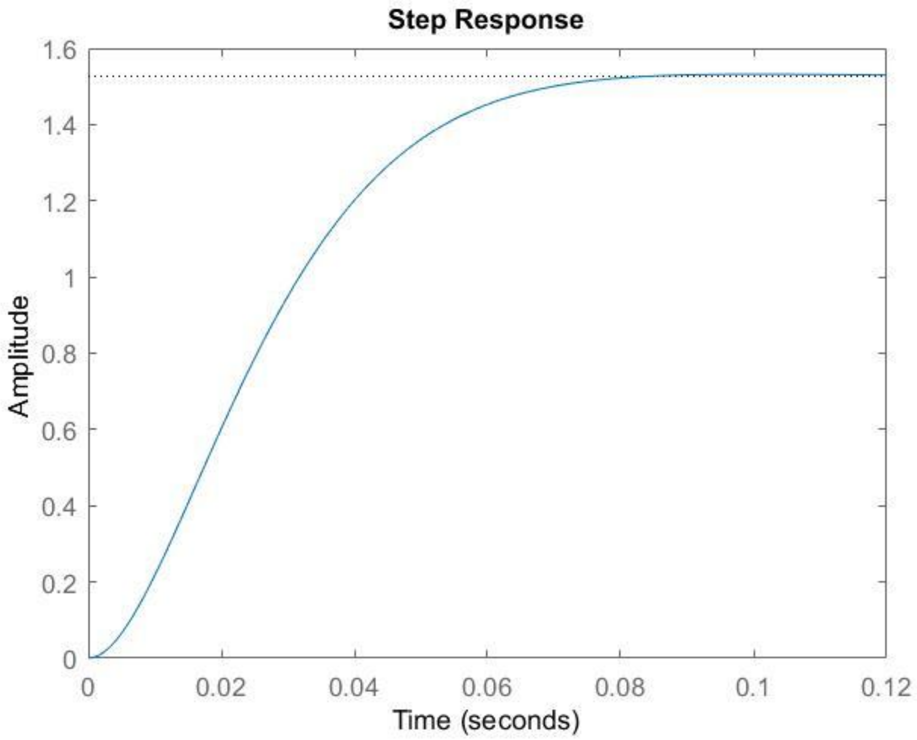

Fig. 6.7 LQR step response for magnetic levitation

CHAPTER: 7 CONCLUSION AND FUTURE WORK

In this thesis, the physical model for a ball plate balancer system is modelled mathematically successfully and the transfer function is deduced. The ball plate balancer system is comprised of three main subsystems which are servomotor model, angle conversion gain, and ball on the plate dynamics each subsystem is represented in individual block and mathematical equation is obtained. Both servomotor and ball plate dynamic have the second order transfer function**.** The two degree of freedom ball plate balancer was taken and studied in a one dimensional assuming our system to be symmetric for both the axis. Different controllers have been designed and simulated in order to meet the desired specifications. Based on the deduced transfer function open loop system. The design of controller is based on mathematical modelling and state space model. The designed controllers have been implemented in MATLAB/SIMULINK. From the simulated response it can be seen that the controller has been successfully designed and implanted and each of these controllers are capable of stabilizing the system later or sooner. The output response of each controller is shown in comparison graphs illustrated in Fig.6.7 that shows that the robust LQR controller approaches the desirable performance in least time as compared with other two controllers. With the fundamental features, it can be noticed that the intelligent controllers, is not providing a good transient output, but still it can used as an alternative for the classical PD controller.

The work of the thesis can be furthered by analysing the closed loop performance of the ball and plate system using fuzzy logic, neural networks, sliding mode controller followed by fabrication of entire system into a hardware prototype. The future work can be established on comparing between the hardware and software results.

REFERENCES

[1.] Huann-Keng Chiang, Wen-Te Tseng, Servo State Feedback Controller with Feedback Linearization for Magnetic Levitation Ball System IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS) 2013.

[2.] Kumar Anurag, Design of LQR-PID Controller for linearized Magnetic levitation system International Conference on Inventive Systems and Control (ICISC 2018).

[3.] Arjun C. Unni, A.S. Junghare, Vivek Mohan, Weerakorn Ongsakul, PID, fuzzy and LQR controllers for magnetic levitation system, International Conference on Cogeneration, Small Power Plants and District Energy (ICUE 2016).

[4.] Ritesh Raj, S.K. Swain, S.K. Mishra, "Optimal Control for Magnetic Levitation System using H-J-B Equation based LQR," 2nd 2018 IEEE International Conference on Energy, Power & Environment (ICEPE 2018).

[5.] Wen-wen cai, Li-xin Jia, Yan-bin Zhang,, Nan Ni, "Design and Simulation of Intelligent PID Controller Based on Particle Swarm Optimization," ICEEE, IEEE, 2010.

[6.] MATLAB Simulation by Stephen J. Chapman.

[7.] Wong, T. H. "Design of a magnetic levitation system-an undergraduate project," IEEE Tran. on Education, vol E-29, no. 4, November 1986.

[8.] Franklin, Powell & R.D Harbor, Feedback Control of Dynamic Systems, 3rd Ed. Addison-Wesley 1994.

[9.] K.H Ang, G Chong, Y Li PID control system analysis, Design and technology IEEE trans on Control system technology 2007.