Advance Control Technique for Magnetic Levitation Train

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This thesis is dedicated to my beloved ***Parents***.

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ABSTRACT

The thesis is based on the design of advanced control techniques for Maglev system, the key purpose of this research is to plan an effective control strategy to deal with nonlinear dynamics of Maglev system, that includes the control of air gap, magnetic flux, and momentum. The control strategy that has been investigated is linear model predictive control (MPC) and nonlinear model predictive control (MPC) whereas a comparison with nonlinear techniques such as backstepping and integral backstepping has been made. The linear model predictive control (MPC) and Nonlinear model predictive control (MPC) has been implemented in the MATLAB's MPC toolbox for which the linear MPC is applied after the linearizing the Maglev system whereas nonlinear model predictive control (MPC) uses the nonlinear model of Maglev system. Simulation results for nonlinear model predictive control (MPC) provides a better result in terms of stability, reduced oscillation, and response time whereas as comparison with linear MPC and nonlinear techniques such as integral backstepping. The thesis concludes that nonlinear model predictive control is the most robust and effective control strategy for Maglev system that handles the nonlinearities and complex behavior of system.

Future work can be focused on the adaptive control strategy, real world hardware implementation of Maglev system as to test the performance of controller and computational optimization technique that can reduces the computational power of model predictive control (MPC).

Keywords: Model Predictive Control, Integral Backstepping, Maglev, Stability, Advance Control Techniques.

CHAPTER 1: INTRODUCTION

1.1 Introduction

In Train technology, The Magnetic Levitation (Maglev) is a groundbreaking advancement technology in modern transportation in which the train is levitated in air by supporting superconductor electromagnet force against the gravitational force. The concept of Maglev has brought away to minimize the vibration, mechanical friction losses, maintaining the smooth, quite ride and increase the speed of the train up-to 500km/hr. In this system the train levitates above the guideway up-to 10cm in air by using electromagnetic force. Due to its contactless property and eliminating the mechanical contact the maintenance cost of this system is very cheap and the life span of the overall system, and its parts are very long. On the other hand, the conventional trains totally rely on rail-wheel. [1].

Our focus is to promote more accurate, smoot and very high speed in transportation technology so all the interest comes towards Maglev system. In last few years the Maglev trains are publicly operational in Japan, China, and Korea. Due to the nonlinear properties of Maglev system, excellent control techniques and evaluation are developing. Due to increase in the population day by day there is also increase in the demand of transportation sector and it requires rapid mode of transportation, therefore the Maglev system is the optimal option to meet the requirements for the increasing population in which people can travel from one city to another city in less time than conventional trains. As Maglev is the promising solution for the transportation system, therefore many researchers are working in the improvement of Maglev technology. The Maglev system provides numerous advantages that are mentioned below.

a) Elimination of wheel from train.
b) Construction cost of guideway is reduced due to distributed weight-load.
c) There is less chance of derailment of Maglev.
d) Due to no wheel, there is less noise and vibration in the Maglev.
e) Since there is non-contact system therefore it prevents it from slipping and vibration.

1.2 Main Components of Maglev System

The Maglev system consists of the five major components [3] which are explained below.

1.2.1 Levitation

This technology consisting of the integral of every Maglev system which is used to enable the vehicles to move over air cushion, such method is useful for levitation and magnetic repulsion-based system. Hence the method is further divided into electro dynamic suspension system and permanent magnet electro dynamic system (PM-EDS).

1.2.2 Guidance

To keep the control of the vehicle, the Maglev vehicle needs a proper guidance mechanism, such guidance mechanisms consisting of the magnetic-repulsive forces and magnetic attractive forces. The magnetic repulsive guidance contains the sideway track that contains.

1.2.3 Power Transfer

In Maglev system, the electricity is transferred from the groundside as to power the levitation and propulsion the coil, the speed of Maglev reaches to $300\ km/h$, therefore the use of mechanical contacts is not practical for speed which is greater than $300\ km/h$ and therefore the linear transformer and generators are being required for power delivery system.

1.2.4 Propulsion

Maglev system consists of the contact less thrust system that is used to drive the body of vehicle, the linear motors are used fitting the selection as it produces thrust which does not contain any mechanical conversion.

1.2.5 Maglev Control System

For the safe and efficient operation of Maglev system requires the proper control and monitoring of air gaps, flux and coil excitation. It consists of sensors i.e., speed sensors and position sensors that performs these tasks, generally this system requires a robust and efficient controller as to maintain vehicle's position with respect to guideway therefore it requires to maintain a constant air gap that further maintains the ride comfort [4].

1.3 Problem Statement

The primary challenge in the control of Maglev train system as to achieve and maintain stable levitation, propulsion, and guidance under varying operational conditions.

The specific challenges are:

1.3.1 Stable Levitation

Maintain a consistent air gap between the train and the guideway to ensure smooth, safe operation, stable momentum, and controlled magnetic flux.

1.3.2 Dynamic Response Enhancement

Improve the system's responsiveness to dynamic changes, ensuring quick adaptation to varying loads and external disturbances.

1.3.3 Chattering Elimination

Mitigate high-frequency oscillations (chattering) that can adversely affect ride comfort, positioning accuracy, and energy efficiency.

1.3.4 System Robustness

Ensure global asymptotic stability and robustness to withstand model uncertainties, environmental variations, and disturbances.

To address these challenges, the implementation of a nonlinear control strategy is essential.

1.4 Objectives

Following are the objectives of this research.

a) Maintaining the air gap at needed level.
b) To obtain momentum equal to zero.
c) Tracking of magnetic flux to needed level for maintaining air gap.
d) Eliminating the chattering phenomenon.
e) Ensuring that overall system is stable.

1.5 Proposed Solution

The proposed solution primarily involves discrete mathematical models for designing a nonlinear model predictive control (MPC) system. The designed MPC utilizes an enumeration-based technique with pulse width modulation, where the cost function is computed for numerous input values. The input that yields the lowest cost function value is selected as the optimal input and applied to the plant for a fixed period of the prediction horizon.

The diagram below shows the basic configuration of MPC.

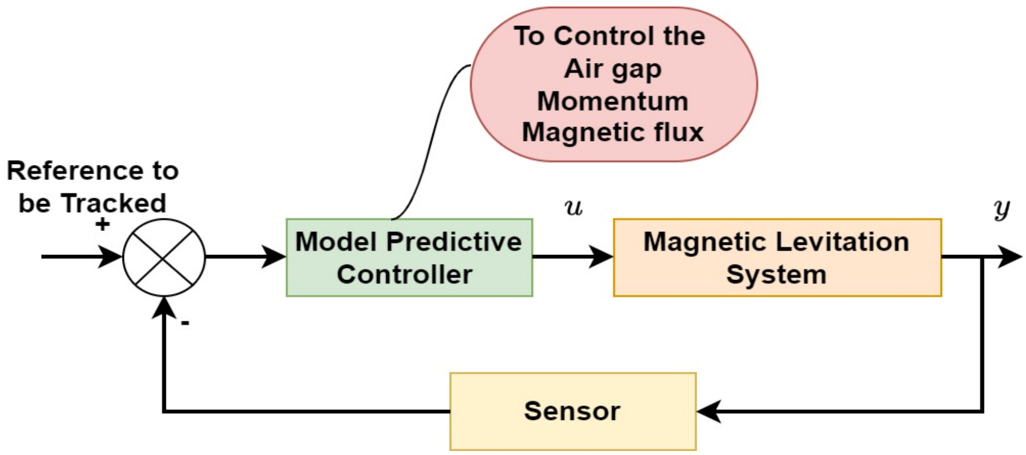

Figure 1.1: Block Configuration of MPC System

In our proposed solution, the MPC is designed on MPC Toolbox whereas the MPC toolbox will be extensively discussed in Chapter 3 and 4.

1.6 Conclusion

This chapter provides an overview of the basics of the Maglev system, discussing its components. It also outlines the problem statement, research objectives, and proposed solutions. The conclusion drawn is that to achieve stable levitation, propulsion, and guidance, a robust controller is necessary. Therefore, it has been decided to design a model predictive controller (MPC) for the Maglev system to achieve better results.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter consisting of Maglev and numerous control schemes that are being used to control the Maglev system. It explains previous advancement and present advancement in Maglev system, control techniques, advanced control techniques and challenges in the Maglev system in extensive manner. Maglev system which implies magnetic, and levitation together is method that uses magnetic levitation as to propel vehicles with magnet as using the wheels, bearing and axles.

2.2 Advancement in Maglev System

Maglev technology is the possible key for the traffic and ecological tests which has key advantages of Maglev technology that is obvious short trip times which is due to high speed and high acceleration, there are several Maglev technology for the transportation system that has been constructed and it is operation in the world i.e. Shangai high speed Maglev in China which is running from Shanghai Pudong International Airport to Longyang station, which is interchange station and therefore it connects the Shanghai subway line 2 [5] and [6]. There are some other lines that is operated from low speed to medium speed i.e. Linimo in Aichi Prefecture, Japan, low to medium speed Incheon Airport Maglev which runs from Incheon Airport in South Korea [7] and [8]. Based on the potential of the market, the Maglev transportation system is gradually integrated into urban rail transit systems. The construction and operation for Maglev transportation shows the Maglev transportation which is promising public transportation that plays great role in the transport systems [9]. Maglev technology is the solution for the future in transportation system and it has major advantage for the short trip due to high speed, it has level safety. The Maglev transportation system is further divided into electro-magnetic suspension (EMS) and electro-dynamic suspension (EDS). These two branches for which variety of vehicle are manufactured accordance with country use and vehicle purpose. The Maglev has three functions that includes the levitation, propulsion, and guidance. The major variation in these two groups is the positioning of magnets. In EMS system the location of magnets is within moving vehicles which levitate 1 or 2 cm above guideway. In EDS system the magnets are in train and train uses a force to get the desired levitation which is 1 to 10 cm above track [10]. Today there is much advancement in the Maglev technology that has mainly consisting of following technologies:

2.2.1 High Speed Rail Technology

High speed rail technology is most promising application for Maglev technology, it has enhanced speeds since they have very small friction with the track, in the year of 2023 the countries such as Japan, China and Germany have made great progress in the Maglev systems, the Maglev system provides the promising to revolutionize long distance that travel by offering speed which exceed for those of outdated trains.

2.2.2 Urban Transportation

Maglev technology is used for urban transportation systems that offers solutions in congestion and pollution for highly populated areas, the short distance can cover within few minutes by using a Maglev technology. Big cities such as Dubai and Tel Aviv have started realizing Maglev-based urban transportation system and then it indicates the rising interest and likelihood of system.

2.2.3 Freight Transport

Besides the transportation of passengers, the Maglev can be used in freight and industrial sectors. The Maglev-based cargo transport can be pointedly used in the improvement of efficiency and speed moving good that reduces the transportation cost and CO_2 emissions. The industrial processes also involve movement of manufacturing items and assembly using Maglev technology [11].

2.3 Control Strategies in Maglev System

There are enormous control strategies that have been suggested for the control of electromagnetic levitation systems. These control methods consisting of the linear control, nonlinear control, and advanced control.

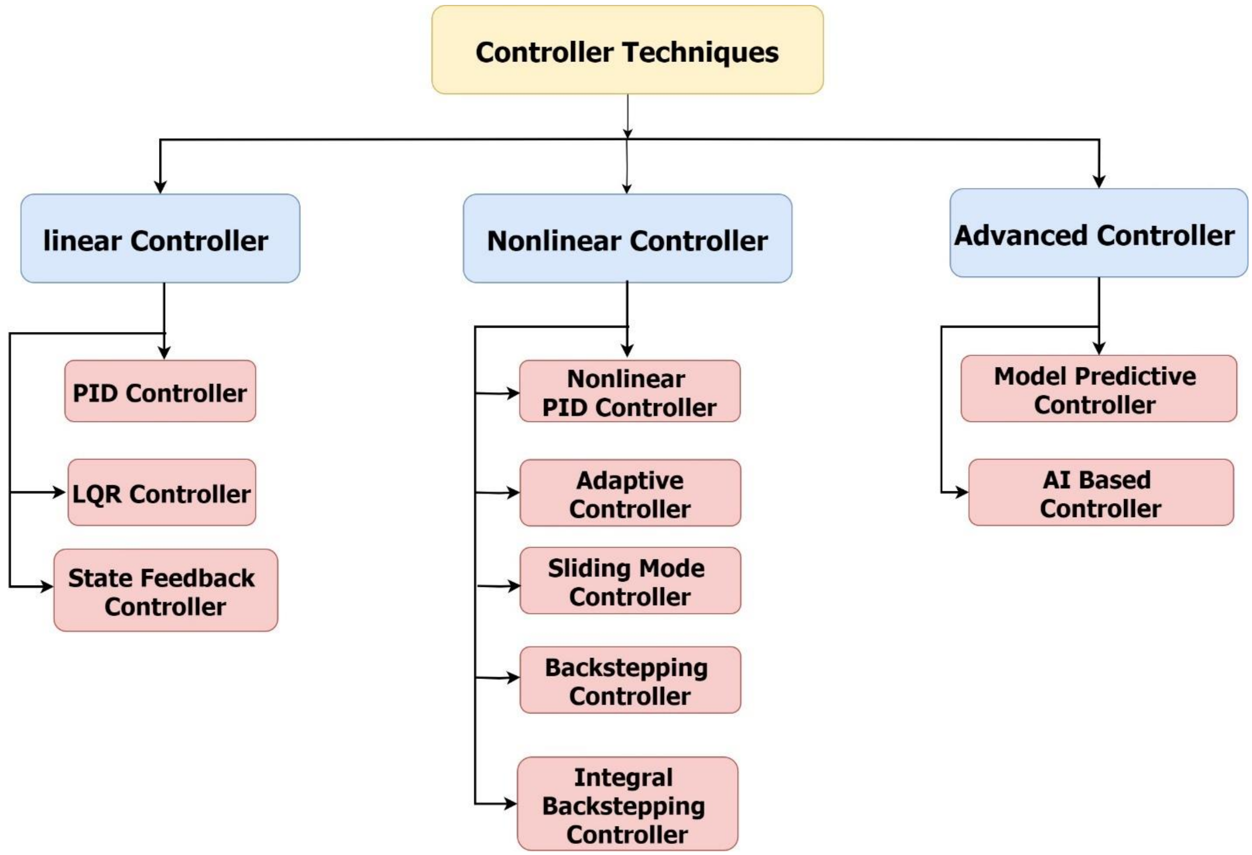

Figure 2.1: Controller Techniques.

2.4 Classical Linear Control

The classical linear control technique is founded on the linearized Maglev train system. The techniques consisting of single point levitation model and uses an theory of levitation electromagnet and guideway in steady position [12]. The most used classical control techniques are proportional integral differentia (PID) control [13], state feedback control [14] and linear quadratic regulator (LQR) control [15]. In case for air gap that is not in equilibrium state, then stability of control-based system for used linear control method decreases, therefore this problem can be solved by using a feedback linearization method for nonlinear system which is proposed in [16].

2.4.1 PID Controller Design for Maglev System

PID controller is widely used for numerous systems in industrial application, the typical PID equation is described as

$$G(s) = K_D s + \frac{1}{s} K_I + K_P \tag{1}$$

Where K_D is derivative gain, K_p is proportional gain, K_I is integral gain and s consisting of complex number in Laplace transform. The values of co-efficient drastically effects the performance of overall system, beside there are many methods that has been proposed to find these gains which are Ziegler-Nichol method, Ziegler Nichol frequency method, internal model control method, optimal control method and Cohen-Coon method [17].

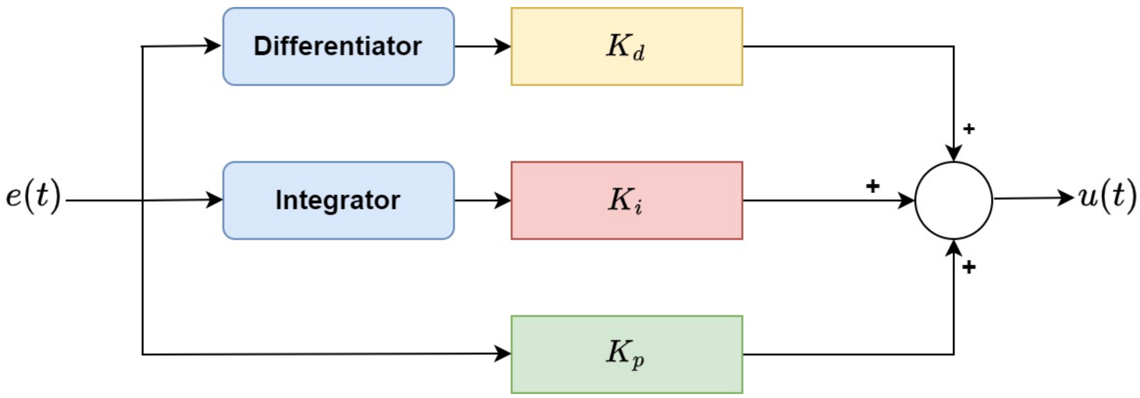

Figure 2.2: Schematic of the PID Controller.

2.4.2 Feedback Control

The basic state feedback controller is intended for state space model, which is used for the part of feedback linearization, in this controller the control signals are being resolute by multiplication of state variables with the controller gain matrix [14]. The state space equations are given as

$$\dot{x}\,(t) = Ax(t) + Bu(t) \tag{2}$$

$$y(t) = Cx(t) \tag{3}$$

The matrices such as A, B in input equation is input matrix of state and C in output equations are in output matrix of state, whereas $x(t)$ and $y(t)$ is the inputs and outputs of the system. The control signal is calculated by combination of n state variables i.e.

$$u(t) = \; -[k_1x(t) + k_2x(t) + k_3x(t) \ldots\ldots + k_nx(t) \tag{4}$$

$$u(t) = -Kx(t) \tag{5}$$

K is controller gain, the state feedback control has been designed in [12], the controller consisting of specific variables that is related to guideway and electromagnet has been proposed. There are various state feedback controllers that has been proposed in [18], [19] and [20] which aims to control the Maglev system.

2.4.3 LQR Control Technique

PID controller technique is efficient and simple for Maglev technology, but its parameters determination is the challenging issue. The problem faced by the parameter determination is solved by LQR. In which all state variables are assumed to be used for feedback. The LQR design process consists of a specific set of states that are going to be manipulated. The LQR is designed to aim to optimize the performance of control system and achieve the objectives for desired controller technique. The famous equation in LQR i.e. Riccati equation is given as

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{6}$$

Q & R are weighting matrices for state variable whereas P can be explained by using Riccati equation method. The feedback of LQR can be found by $K = R^{-1}B^T P$. The LQR system is designed for the Maglev system and results are compared with the PID controller and Fuzzy logic controller in [14]. Many of the LQR controllers are also proposed in [21], [22], [23] that is based on the disturbance observer-based control (DOBC) and incremental controller gain system.

2.5 Classical Nonlinear Control

Maglev system consisting of nonlinear system does not compatible with the linear controller and faces the issue of the robustness and practicality since the model is being linearized. Therefore, for the past few years the researchers worked on nonlinear controller techniques which is consisting of backstepping, integral backstepping, sliding mode control and adaptive control.

2.5.1 Nonlinear PID Controller

The nonlinear consisting of PID for which the performance of the control is relying on the system's state and tuned parameters for the PID controller. In [24], the conventional PID controller is used for the Maglev system, another PID controller is designed in [25] which is based on characteristics model specific with Maglev, it has been deduced that conventional controller is also easy to tune. To improve the performance of PID controller for nonlinear Maglev system the exponential function is introduced in [26]. The control signal for the PID nonlinear controller is given as

$$u = K_D x_2^a + K_p x_1^b \tag{7}$$

Where $x_2 = \dot{x_1}$ and $x_1 = x - x_{eq}$ and $u = i - i_{eq}$, where x is the air gap, $x_{eq}$and $i_{eq}$are the airgaps at equilibrium points.

2.5.2 Adaptive Control

Adaptive control is a talented technology to enhance the implementation of control systems consisting of numerous factors that includes degradation and modelling uncertainty. The adaptive control is divided into two categories that includes the direct and indirect control [27]. The direct controller is represented with mathematical equation given as

$$u = k_r(t)r + \ k_x(t) \tag{8}$$

Here k_r and k_x are gain of controllers and r is the reference state. The gains can be adjusted by the adaptive law, the focus of adaptive law is to cancel the uncertainty that is not required. The indirect controller is represented with the mathematical equation that is represented as

$$u = k_x\big(p(t)\big)x + k_r\big(p(t)\big)r \tag{9}$$

Here $p(t)$ are parameters of system which is computed online with control gains.

2.5.3 Sliding Mode Control (SMC)

SMC consists of nonlinear control that has fast response, robust and simple in implementation on MATLAB, D-Space and physically. The nonlinear system is given as

$$\dot{x} = f(x, u, t) \tag{10}$$

The sliding mode surface is defined consisting of $s(x)$ which is partitioned into two distinct regions i.e. $s(x) > 0$ and $s(x) < 0$. The representation diagram of state motion process is given as

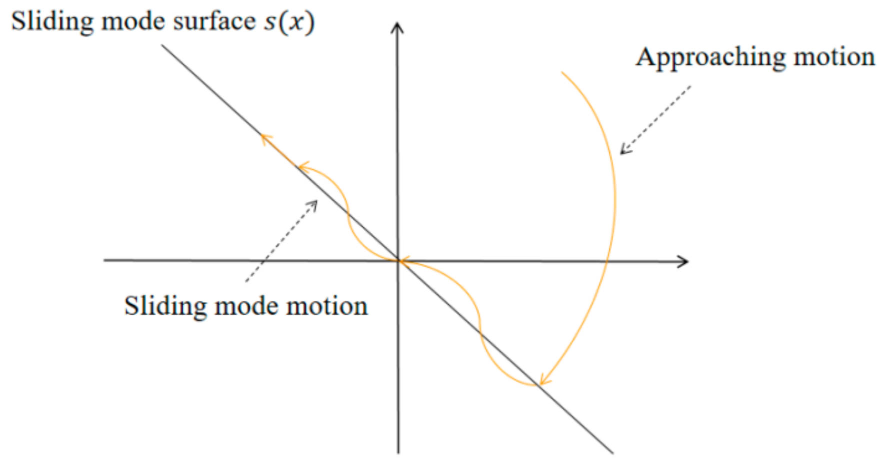

Figure 2.3: State Motion Process [27].

It can be observed that the state point undergoes a phase in which approaching the sliding surface and the other phase is moving along the sliding surface [27].

2.5.4 Backstepping Control

The backstepping control consists of a recursive design, it has link with the Lyapunov function and feedback controller. This system shows the global asymptotic stability for the feedback systems [28]. The backstepping control technique for Maglev system is presented in [29], the presented control technique is focused on tracking of air gap in accordance with provided reference. As to evaluate unknown parameters for control system, in [30] a multi-input and multi-output (MIMO) system has been derived by using an adaptive backstepping controller.

2.5.5 Integral Backstepping Control

Integral backstepping is like the traditional backstepping controller but includes the integral of the error which is concerning the reference value and the state value. This technique was applied in [31], where a continuous mathematical model of the Maglev system was used to design an integral backstepping controller. The control objectives were to track the air gap, maintain the needed magnetic flux to sustain the air gap, and reduce reduces the momentum to zero. The results were compared with those of a synergetic controller and a PI controller, showing that the integral backstepping and synergetic controllers provided better performance than the PI controller-based design approach.

2.6 Advanced Controller

In modern control techniques, artificial intelligence-based methods have been introduced. Advanced control techniques such as artificial intelligence control, neural network control, fuzzy control, and model predictive control (MPC) have demonstrated better results compared to classical linear and nonlinear controllers [32]. Artificial intelligence controllers represent nonlinear functions with a high level of accuracy through the process of training on data.

2.6.1 Artificial Intelligent Control Technique for Maglev System

Artificial intelligence control methods are introduced due to their self-adaptation, self-optimization, and self-learning characteristics. The weighting in artificial intelligence control can be adjusted to replicate nonlinear functions with enhanced accuracy. These methods have the capability to represent complex systems and unknown models [33].

2.6.2 Model Predictive Control (MPC)

MPC is although a classical control technique but there are numerous variants of MPC that exist in the literature that have fast response and enhanced robustness. The MPC toolbox is currently used as an advanced control technique consisting of the functions, Simulink block and reference blocks that provides the optimization solvers and can be used in custom solver. The MPC toolbox consists of MPC design, explicit MPC design, adaptive MPC design and nonlinear MPC design [34]. The modern MPC control can deal with the constrained case in which optimization problem can be solved for real time for each sampling interval.

2.7 Conclusion

The chapter presents a literature review of Maglev systems, focusing on advancements in Maglev technology that demonstrate its use in high-speed rail, urban transportation, and freight transport. Various control strategies discussed in the literature include both classical linear and nonlinear control techniques as well as advanced control methods. These techniques encompass a range of control schemes. The review concludes that advanced control techniques, such as artificial intelligence and model predictive control (MPC), have proven to be robust and capable of handling the complexities inherent in Maglev models.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The model predictive control (MPC) toolbox consists of the function which is industrialized for analysis and design of model predictive control (MPC) systems, the MPC was developed in the 1970s and the use has increased in 2000s. Today the industry uses optimal control method whereas MPC is used for each type of problem, the major strength of MPC is given as:

- The number of controlled variables & manipulated variables.
- Time delays.
- Varying control goals and failure in equipment
- Constraints imposed on controlled variables.

The MPC is also referred as dynamic matrix control (DMC) and it has closeness with linear quadratic regulator. In MPC optimization is solved for every time step and in real time. Hence it is much easier to implement the MPC on hardware.

3.2 State Space Model

Consider the model as shown in figure 3, the model consisting of the discrete time model which is used in the MPC toolbox.

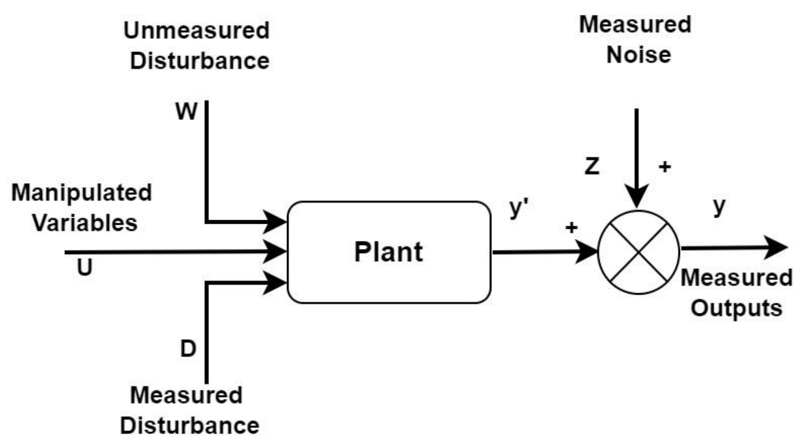

Figure 3.1: Model of the System.

State model is presented as:

$$x(k+1) = \Phi x(k) + \Gamma_u\, u(k) + \Gamma_d\, d(k) + \Gamma_w w(k) \tag{1}$$

$$y(k) = \bar{y}(k) + z(k) \tag{2}$$

$$= Cx(k) + D_u u(k) + D_d d(k) + D_w w(k) + z(k) \tag{3}$$

Here x is the n state variables, n_u is manipulated variables whereas n_d represents the changing inputs, w represents unmeasured disturbances, y is vector of n_y plant outputs. z is noise which is being measured whereas Φ, Γ_u, etc are the matrices consisting of appropriate size. The matrices Γ and D is given as

$$\Gamma = [\Gamma_u\ \Gamma_d\ \Gamma_w] \tag{4}$$

$$D = [D_u\ D_d\ D_w] \tag{5}$$

There are certain applications for which all outputs are being measured, whereas n_{ym} is considered to measured and n_{yu} is unmeasured variables in y, whereas $n_{ym} + n_{yu} = n_y$. Matrix toolbox basically assumes y vector with C & D matrices are arranged with measured outputs which is followed with the unmeasured outputs.

3.3 Mathematical Modelling of Maglev System

Maglev system is dependent on the electrical and mechanical components, Now counts the iron ball that is present in magnetic field that is produced in magnet, the equation for such system has been given in [35] are described as

$$\dot{\lambda} + Ri = u \tag{6}$$

$$m\ddot{\phi} = F_{m-}\, mg \tag{7}$$

The equation (6) is derived from the Kicrhoff's voltage law whereas equation (7) is derived using Newton second law, the flux produced by field that is depends upon θ is described as

$$\lambda = i \times L(\phi) \tag{8}$$

Here ϕ is air gap, which is center for iron ball and magnetic coil, g is gravitational constant, R is the resistance and F_m is magnetic force which is given as

$$F_m = 0.5 \times \frac{\partial\, L(\phi)}{\partial \phi} \times i^2 \tag{9}$$

The inductance L of the coil is given using following.

$$L = \frac{k}{1-\phi} \tag{10}$$

L has some limitation from $-\infty < \phi < 1$, the K is positive integer which depends on number of turns of coil which is used to control the air gap to 1. The equation for the current becomes.

$$i = \frac{(1-\phi)\lambda}{k} \tag{11}$$

The equation (6) becomes.

$$\dot{\lambda} + \frac{R(1-\phi)\lambda}{k} = u \tag{12}$$

The magnetic varies directly with rate of change in inductance of coil that concerns the air gap and the value of F_m is given as

$$m\ddot{\phi} = 0.5 \times \frac{\partial\, L(\phi)}{\partial\phi} i^2 - mg \tag{13}$$

The momentum is given as:

$$\rho = m\dot{\phi} \tag{14}$$

Taking time derivative of the equation, we have

$$\dot{\rho} = m\ddot{\phi} \tag{15}$$

Therefore, the equation (13), becomes.

$$\dot{\rho} = 0.5 \times \frac{\partial\, L(\phi)}{\partial\phi} i^2 - mg \tag{16}$$

Partial derivative of inductance L as respect with magnetic flux is mentioned as:

$$\frac{\partial L(\phi)}{\partial\phi} = \frac{k}{(1-\phi)^2} \tag{17}$$

$\dot{\rho}$ can be obtained using equation is given as

$$\dot{\rho} = \frac{\lambda^2}{2k} - mg \tag{18}$$

By using equations (12), (15) and (18), the mathematical model is given as

$$\dot{\lambda} + \frac{R(1-\phi)\lambda}{k} = u \tag{19}$$

$$\dot{\phi} = \frac{\rho}{m} \tag{20}$$

$$\dot{\rho} = \frac{\lambda^2}{2k} - mg \tag{21}$$

The state variables are used to define these variables are given as

- The air gap ϕ by x_1
- The momentum ρ is x_2
- The magnetic flux λ by x_3

The state variables x_1, x_2 and x_3 are given as

$$\dot{x_1} = \frac{x_2}{m} \tag{22}$$

$$\dot{x_2} = \frac{\dot{x_3}}{2k} - mg \tag{23}$$

$$\dot{x}_3 = -\frac{R(1-x_1)x_3}{k} + u \tag{24}$$

3.4 Nonlinear Model Predictive Control

The control approach for model predictive control (MPC) has been introduced in the early 2000s, whereas the control strategy gets the more attention within few years, it has fast microprocessor with enhanced computational capabilities whereas it has also advantage of optimal control strategy, therefore it can be used in the many applications such as power electronics, vehicular technology, industrial heavy machines, etc. MPC can be easily applied to the multi-input and multi-output (MIMO) plants, the MPC consists of three major components i.e.

3.4.1 Mathematical Modelling

From the name MPC implies the model-based control technique that uses the model of the plant, which is used, the mathematical model of the MPC is discrete time model. The system is generally in the following generic form.

$$x(k+1) = f\big(x(k), u(k)\big) \tag{25}$$

$$y\,(k) = g\big(x(k)\big) \tag{26}$$

$x(k) \epsilon\, R^n$ consisting of state vector and time step kT_s, $u(k) \epsilon R^m$ consisting of input vector for which time step kT_s, the functions f and g consisting of the state renew and output function which is linear & nonlinear and T_s consisting of sampling interval. Starting from current state $x(k)$, there is finite number N for which control action is being planned i.e. $\{u(k), u(k+1), \dots u(k+N-1)\}$. Therefore, state at step $k+2$ is:

$$x(k+2) = f\,(x(k+1), u(k+1) \tag{27}$$

For N number of time step $k+N$ is mentioned as:

$$x(k+N) = f\big(x(k+N-1), u(k+N-1)\big) \tag{28}$$

The plant is used for the operation of physical limits without any violations. Constraints can be imposed to state variables & manipulated variables i.e., control input, these variables have lower and upper bound. The constraints are physical set of the system that can be defined as

$$\mathcal{M} = \big\{x(l)\big|a_{x,l} \leq x(l) \leq a_{x,p}, l = k, \dots . k+N\big\} \tag{29}$$

$$\mathcal{H} = \big\{u(l)a_{u,l} \leq u(l) \leq a_{u,p}\; l = k, \dots . k+N-1\big\} \tag{30}$$

The vector $a_{x,l}, a_{x,p} \in R^m$ consisting of the state lower and upper constraints and $a_{u,l}, a_{u,p} \in R^m$ consisting of input constraints.

3.4.2 Optimal Control Problem

As to define the optimal control objectives the control objectives must be clearly defined, the control objectives for the Maglev system is described as

- Maintaining of the air gap in accordance with reference being generated.
- The convergence of momentum to zero.
- Ensuring overall stability and robustness of system.

The control problem i.e. objective function is mentioned as:

$$J = \sum_{k=0}^{N_p} \left(||x(k) - x_{ref}(k)||Q + ||\Delta u(k)||R \right) \tag{31}$$

The objective function based on our state variables in which x_1 = air gap, x_2 = momentum and x_3 = magnetic flux. The main purpose of objective function finds the minimum control sequence which results in the optimal performance of plant.

3.4.3 Receding Horizon Policy

When the optimal sequence $U^*(k)$ is obtained, then only first element of that sequence is given to the plant whereas rest of the elements will be discarded. The horizon is shifted to the next time instant $k + 1$ and optimal problem is again solved.

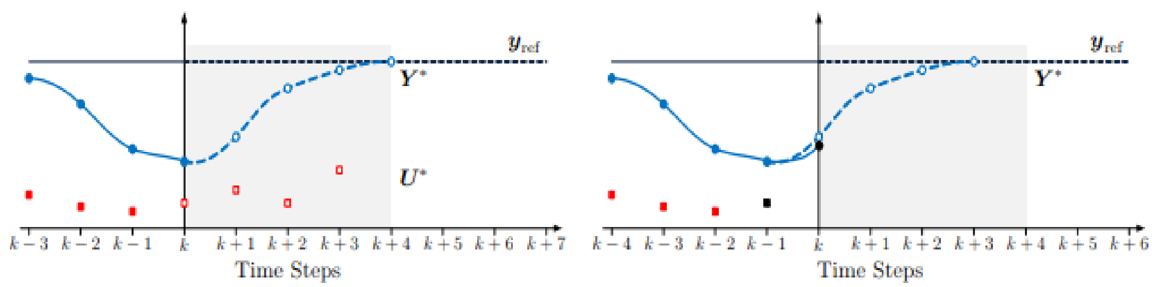

Figure 3.2: 1st Iteration for Optimal Sequence and Shift Horizon.

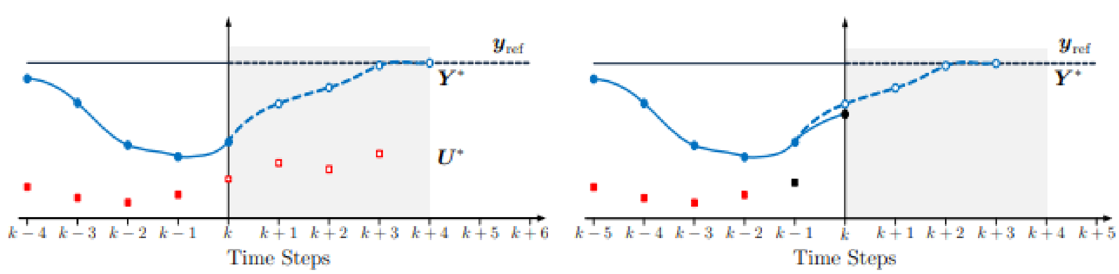

Figure 3.3: 2nd Iteration for Optimal Sequence and Shift Horizon

As to measure the MPC procedure, consider the case as shown in the figure 4 and 5, the optimum problem is solved for at k to determine the $U^*(k)$. In figure 4, the optimal control input is calculated for four step horizons with red indicated empty dots whereas the output of the plant is indicated with blue empty circles. The applied inputs are red solid dots whereas blue solid dots indicate the output variables, finally the past outputs are indicated with the solid line whereas future values are represented by the dashed one. In this case, on the first element of the sequence is applied to the plant which is mentioned as a black solid square at time step $k-1$ in figure 4. The resulting output variable $y^*(k)$ is not same as predicted one and this mismatch arises due to mismatch between the model and plant. In figure 5, it has been seen the discrete time is updated at which $k=k+1$ and the optimization problem is again solved for the shifted horizon, therefore by repetition of procedure for next time steps, output can be tracked to reference values.

3.5 Model Predictive Control Toolbox

MPC toolbox package is introduced for the practicing engineer, it assists for the communication concepts of MPC to an engineer in the inductor course whereas it can be used for the research purpose as well. The MPC toolbox requires the following requirement for the system.

- MATLAB needs to be installed on the PC.
- In the case of simulation of nonlinear system, the SIMULINK needs to be installed.
- System Identification Toolbox needs to be used to create model in MPC *mod* format, then system identification toolbox function uses polyform.

The MPC Toolbox analysis & simulation algorithms are numerically intensive whereas it requires 1 MB of memory that depends on input and outputs, the available memory of computer can limit size for the system that is handled by the MPC toolbox.

3.6 Parameters Used in MPC Toolbox for Design

The MPC parameters are needed regardless of whether the nonlinear MPC or linear MPC is being designed. The design parameters require the tunning for the improvement in results. This section is mainly about the key parameters of MPC that explains the computational complexity for MPC optimization problem.

3.6.1 Sample Time

The sample time is the main concept in the MPC consisting of two parts prediction sample time and control sample time, during MPC design the sample time and control sample time are used to equal or even treated as one parameter and therefore it is much important for distinguishing the effect of performance on them.

3.6.2 Prediction T_s

The prediction T_s consisting of the sample time of internal prediction model, it mainly defines how each prediction step last. The prediction step determines the upper bound of achievable control bandwidth. The upper bound of prediction T_s is being determined using dynamics of plant and response time.

3.6.3 Control T_s

The control T_s is used for the determination of sample time of MPC controller, MPC optimization problem is solved at run time and the control sample time is typically equal to prediction sample time. Faster control T_s improves the performance and robustness of the system. When the control T_s becomes smaller the rejection for unknown disturbances that includes the internal MPC model and actual plant improves. Furthermore, the controller is used to respond faster to changes in the environment. As the control sample time decreases the computational efforts increase and MPC optimization problem is solved faster. Therefore, the optimal choice always consists of a balance of performance and computational effort.

3.6.4 Prediction Horizon

The prediction horizon consisting of the future control intervals for MPC controller that is used for the optimization, the duration for each control is mainly determined by using sample time, choosing the prediction horizon depends on characteristics of plant dynamics. Mainly the system has slower dynamics that require longer prediction in which MPC controller can be used to predict manipulated variables that affect cost and outputs of interests. The prediction horizon and T_s are linked with each other.

3.6.5 Control Horizon

The control horizon consisting of the manipulated variables moves to be optimized for control interval k and it is taking values between 1 and prediction horizon p, the multivariable determines the values for MPC solution for each step of control horizon and for each manipulated variables which is provided in the problem.

3.6.6 Manipulated Variable Blocking

It is an alternative way for simpler control horizon concept, and it has various benefits, as contrast to use scalar value to specify control horizon, the manipulated variables block breaks the prediction horizon into series of blocking intervals by specifying control horizon. The sum of block size must match the prediction horizon ρ, this can allow to specify the number of manipulated variables moves duration as well for each movie as shown below in figure.

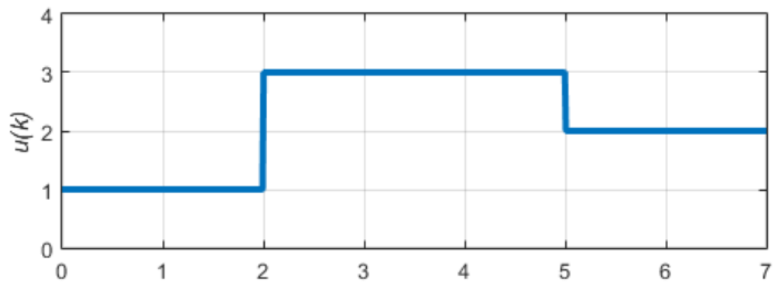

Figure 3.4: Manipulated Variable Blocking.

3.6.7 Constraints

MPC solves the constrained optimization for each time step, if there are large number of constraints, the large time is taken by solver to solve the problem since the system becomes complex. MPC toolbox defines the hard and soft constraints that ultimately helps for setting up the well-defined optimization problem. The system must satisfy the hard constraints whereas the soft constraints can be discarded when there is a need. If the constraints are bounded, then they are known as hard constraints. The plant generally consists of mixed input and output constraints.

3.6.8 Parameters for Run Time

MPC consists of certain design parameters for MPC problem that varies with run time. For example, for tunning the weights of cost function, the online and offline modifications can be done, similarly the control and prediction horizon can be also adjusted, constraints also change over the fixed period of horizon, whereas there are certain situations that is used for adjusting the parameters at run time that increases the complexity of system as well.

3.7 Using Appropriate Solver

The MPC technique is a numerical technique that is mainly dependent on the configuration of solver. If the MPC parameters are set, a better solver can be used that leads to faster solutions rather than poor solutions.

3.7.1 Optimization Solver

MPC requires a high-quality solver that is used for carrying the real time optimization with common performance requirements which mainly involves the execution time, accuracy, memory footprint and robustness. The selection of appropriate solver gives us better execution time. For the real time performance of MPC application the following choices can be beneficial.

a) Active set algorithm.
b) Interior point algorithm
c) Dense problem
d) Sparse problems

3.7.2 Analytical Jacobians for Nonlinear MPC

The nonlinear MPC has constraints and plan dynamics to be nonlinear, similarly the cost function is also non-quadratic function consisting of decision variables, the nonlinear MPC can be solved in MPC toolbox that uses the optimization toolbox and *fmincon* function. For each time instant of MPC, the method solves optimization subproblem that uses a quadratic model of objective subject as to linearize the constraints. If the SQPP solver is selected then Jacobian for plant constraints and cost function analytically is not selected, the Jacobian is computed with numerical perturbations. For nonlinear MPC there is no way for predicting the number of iterations used by solvers for finding an optimal solution, hence in real case scenario the iterations change dramatically as control interval changes which is dependent on the solver algorithm.

3.8 Conclusion

The chapter consists of the proposed methodology for which the model predictive control (MPC) design is discussed, the MPC can be linear and nonlinear, for the linear MPC, the nonlinear model is to be linearized whereas for nonlinear MPC, nonlinear model can be used. The enumeration based MPC consisting of three major components i.e. mathematical model, optimal control problem and receding horizon policy, all these components are being designed in the MPC whereas in MPC the cost function needs to be formulated for the fixed period of horizon. Finally, the MPC control toolbox consisting of various parameters has been discussed, for designing either linear or nonlinear MPC in MPC toolbox of MATLAB there are several parameters that needs to be set which can be sample time, prediction horizon, control horizon, manipulated variable blocking, constraints and choosing a correct solver for the simulation.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The chapter is based on the results of simulation that is performed on the MATLAB/Simulink, the MPC for the Maglev system is being designed on the MATLAB toolbox for linear, nonlinear system and comparison of the designed controller with previous controller design i.e. backstepping and integral backstepping. The detail for the MPC toolbox has been mentioned in the chapter 3, MPC toolbox is a toolbox that is provided by the Simulink and it's a complete package to design a linear or nonlinear MPC by adjusting the sampling time, control horizon, prediction horizon, constraints, and initial states values.

4.2 Design of MPC for Maglev System

The MPC has been designed for the Maglev system for which the MPC toolbox is used in the Simulink, the design parameters for both controllers have been adjusted to achieve the control objectives. The control objectives for both linear and nonlinear MPC is described as:

a) Air gap is tracked between metallic ball and solenoid.
b) Magnetic flux is tracked to maintain air gap.
c) The momentum of a system must be zero.
d) Assuring the stability and robustness of the overall system.

The design parameters for both controllers are given as

Table 4.1:Parameters.

Parameters	Linear MPC	Non-Linear MPC
Prediction Horizon	3	4
Control Horizon	2	3
Max Step Size	0.1	0.1
Sample Time	0.1000	0.1000
Start-Stop Time(sec)	$0-10$	$0-10$
Weight of u (Input)	1	1×10^{-3}
Weight of x_1(Output)	0.0176	0.4700
Weight of x_2(Output)	0.0104	0.7200

Weight of x_3(Output)	0.0368	0.2100
ECR Weight	1×10^5	1×10^5
Scale Factor u (Input)	1	1
Scale Factor x_1(Output)	2.38×10^{-8}	1×10^{-4}
Scale Factor x_2(Output)	4×10^{-8}	1×10^{-3}
Scale Factor x_3(Output)	1×10^{-6}	1×10^{-3}

The simulation for linear and nonlinear MPC is performed for 20 seconds.

4.3 Linear MPC for Maglev System

For designing the linear model of plant, the transfer function is converted into state space model, since the system was nonlinear therefore it was linearized into the system matrices (A, B, C, D), the MPC function is used to create the MPC controller and function is provided with the sample time, control horizon and prediction horizon. After setting the constraints and weights of the controller, the MPC controller was simulated on Simulink. The block model for the MPC controller is given as:

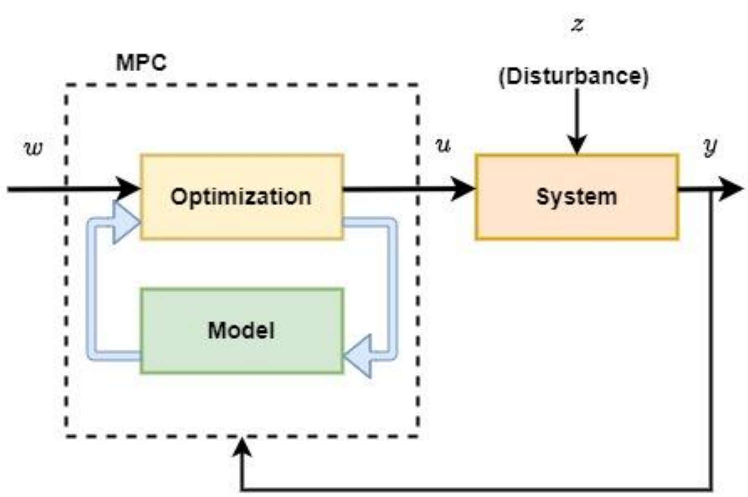

Figure 4.1: Block Model for MPC

Further the prediction horizon, control horizon and weights can be adjusted to a better performance of controller.

The air gap state x_1 for linear MPC controller is given as

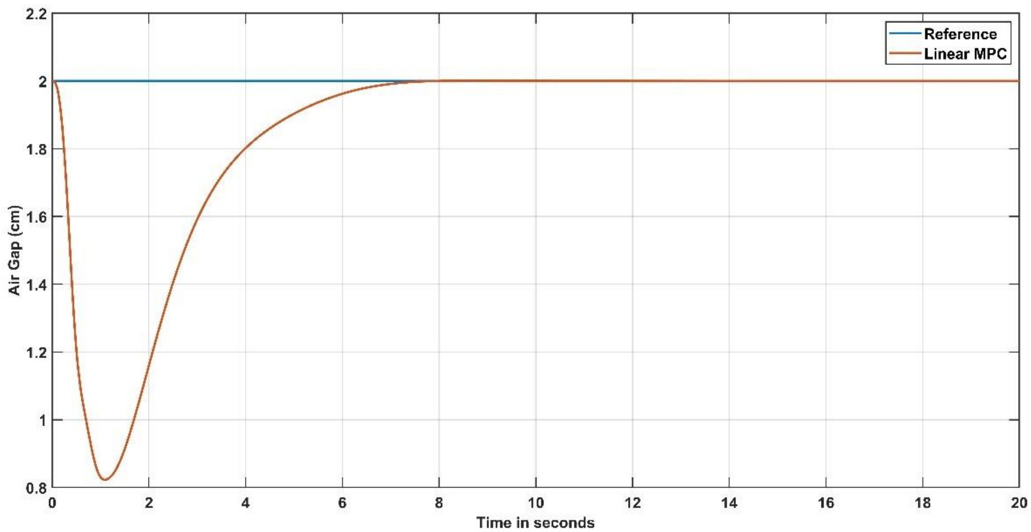

Figure 4.2: Tracking of Air Gap for Linear MPC.

The plot of air gap x_1 in figure 4.2 shows that initially there is some undershoot in the results whereas after few seconds it converges to its steady state value. The tracking reference is 2cm, which shows that metallic ball is levitated at 2 cm in the air. There is undershoot of 0.75 cm. This shows that linear MPC controller tracking to its desired reference value, but it has some undershot and requires a high settling time. The plot of momentum x_2 of a ball is given in figure 4.3. The figure4.3 shows that the momentum convergence to its reference value for a settling time of almost 7.5s whereas it has a zero steady state error, it has initial overshoot of 0.5. The plot of magnetic flux x_3 is given as:

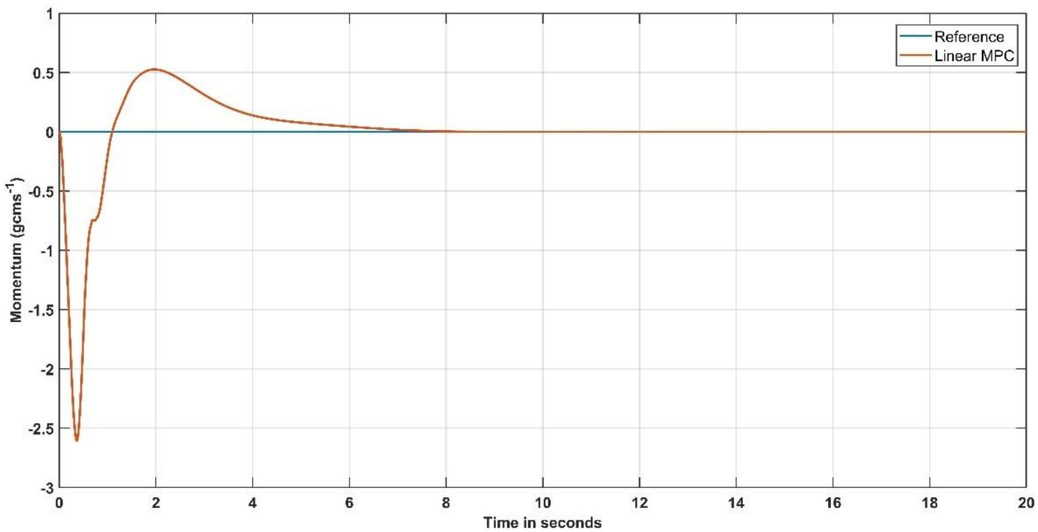

Figure 4.3: Tracking of Momentum for Linear MPC

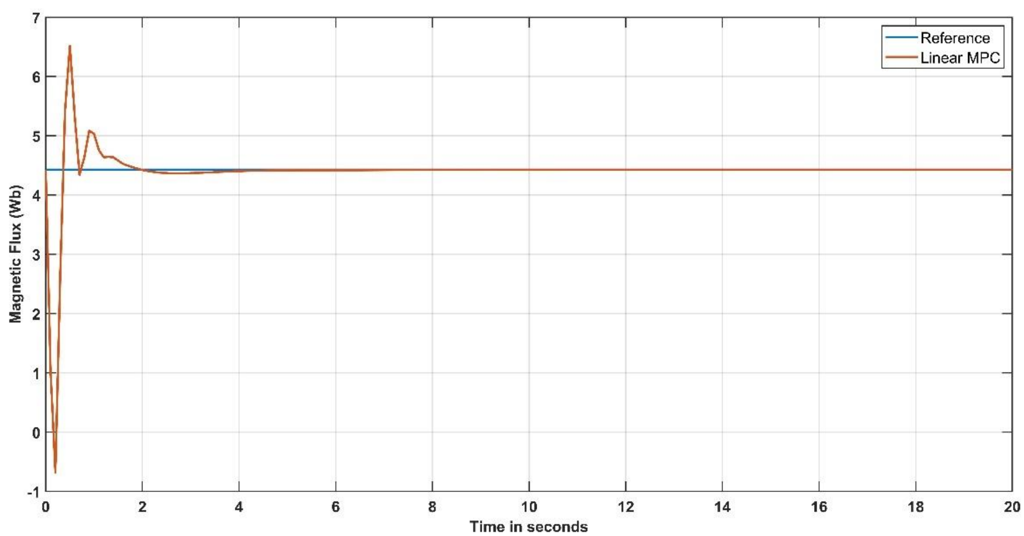

Figure 4.4: Tracking of Magnetic Flux for Linear MPC.

The plot in figure 4.4 shows the convergence of magnetic flux to its reference values at 5s, whereas it has overshoot of $6.67\ Wb$, the MPC controller tries to converge the state to its reference values, but it has slightly high settling time. Linear MPC faces several disadvantages in which assumption of linearity in the model, therefore the model relies on the accuracy of used linear model and there are many discrepancies in the actual model and assumed linear model. Similarly, the complexity of model increases if there are numerous constraints. The linear model is also sensitive to disturbances which are not modelled in the system.

4.4 Nonlinear MPC for Maglev System

Due to issues such as undershoot, settling time, rise time and peak time in linear MPC, the nonlinear MPC has been designed in the MPC toolbox, moreover nonlinear MPC is very close to the actual model since all the nonlinearities in the system has been catered. Designing of nonlinear MPC requires the several steps that includes the following:

4.4.1 Modelling of Nonlinear System

The nonlinear system must be defined in the toolbox, this can be done making a separate function file consisting of the nonlinear system.

4.4.2 Construction of Nonlinear MPC Controller

The nonlinear MPC object can be created by assigning the number of states, outputs and inputs, prediction horizon and control horizon.

4.4.3 Defining of Model Functions

The output and sate function has been described for the system; the function consists of the optimization function.

4.4.4 Assign Constraints & Weights

Finally, the weights and constraints have been assigned to the MPC toolbox, the weights are being given to the cost function of a controller.

4.4.5 Implementation of Nonlinear MPC Simulation

Further the nonlinear MPC can be simulated to obtain the results, the nonlinear results can be made better by adjusting the prediction horizon, control horizon, weights, and constraints.

The plot of state x_1 air gap is given below:

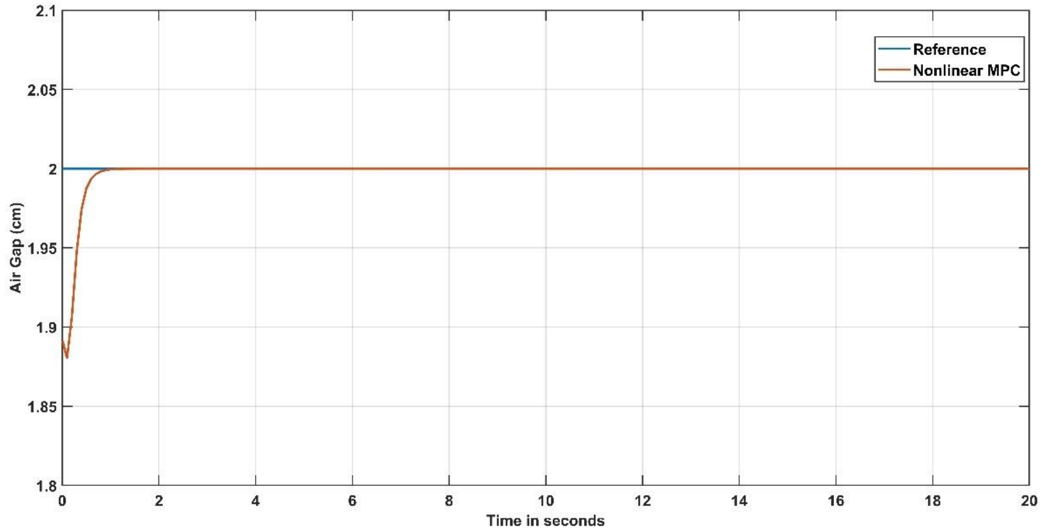

Figure 4.5: Tracking of Air Gap for Nonlinear MPC.

Figure 4.5 shows the significantly setting time reduces to 0.7seconds, whereas there is no overshoot and slightly undershoot in the figure 4.5, the nonlinear MPC shows the fast convergence to reference, whereas the steady state error is zero. The plot of state x_2 momentum is given as :

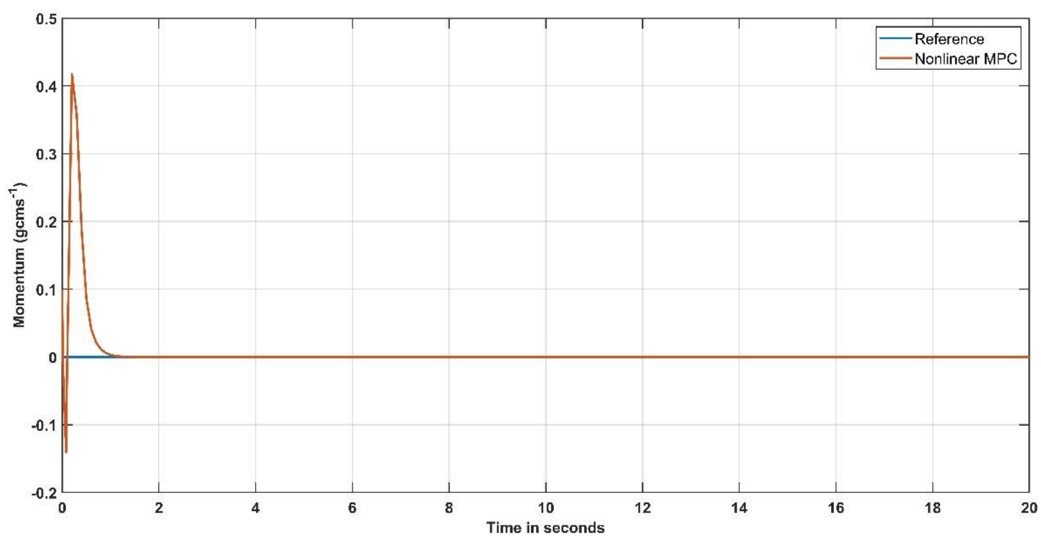

Figure 4.6: Tracking of Momentum for Nonlinear MPC.

Figure 4.6 shows the settling time is reduced as compared with the linear MPC, similarly there is no overshoot and undershoot, the nonlinear MPC is perfectly tracking to its reference values with zero steady state error.

The plot of state x_3 for magnetic flux is given in figure 4.7.

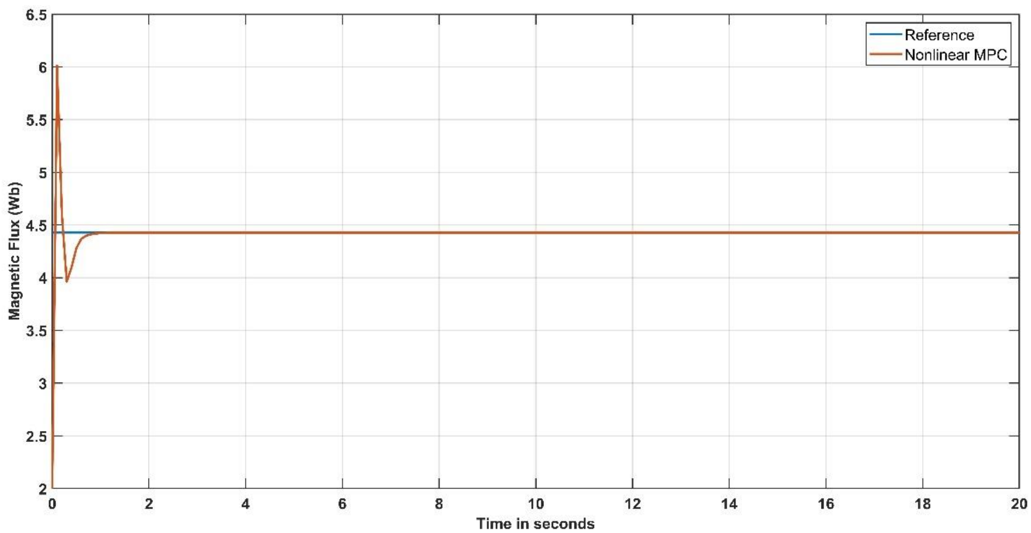

Figure 4.7: Tracking f Magnetic Flux for Nonlinear MPC.

The figure 4.7 shows the slightly overshot and undershot as comparison to the nonlinear MPC, whereas it reaches its steady state value in a very less time. The settling time is 0.6969seconds. Nonlinear MPC generally gives us better results as compared to linear MPC since the nonlinear dynamics plays a much significant role, the system has accurate representation of nonlinear dynamics whereas there in linear MPC is captured with some linear assumptions, the nonlinear MPC predicts the behavior of plant more accurately, similarly the nonlinear MPC can be able to handle nonlinear constraints more efficiently. The objectives function in nonlinear system is well defined that takes a error of each state and provides an optimal control input to the system.

Nonlinear MPC in this system proves to be more efficient and robust due to its better prediction capabilities for the future states whereas linear MPC has less accurate model which leads to failure in the control action since the system is highly nonlinear.

4.5 Comparison of Results with Previous Studies

The results are being compared with nonlinear controller that is given in [31] the integral backstepping control has been proposed [31] whereas the results are being compared. The figure 4.9 for comparison with state x_2 shows that integral backstepping with linear and nonlinear MPC, it has been observed the results nonlinear MPC is better in terms of steady state error, settling time and rise time. Moreover, the objective function is calculated for each possible combination of control input whereas the minimize value of objective function gives us optimal control input which is given to plant.

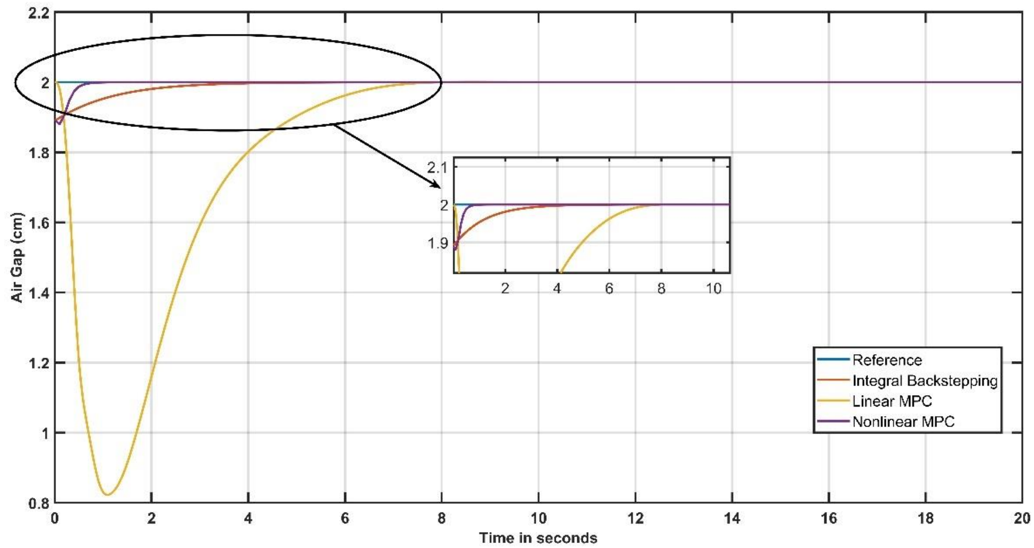

Figure 4.8: Comparative Analysis of Air Gap for IBS, Linear MPC with Nonlinear MPC.

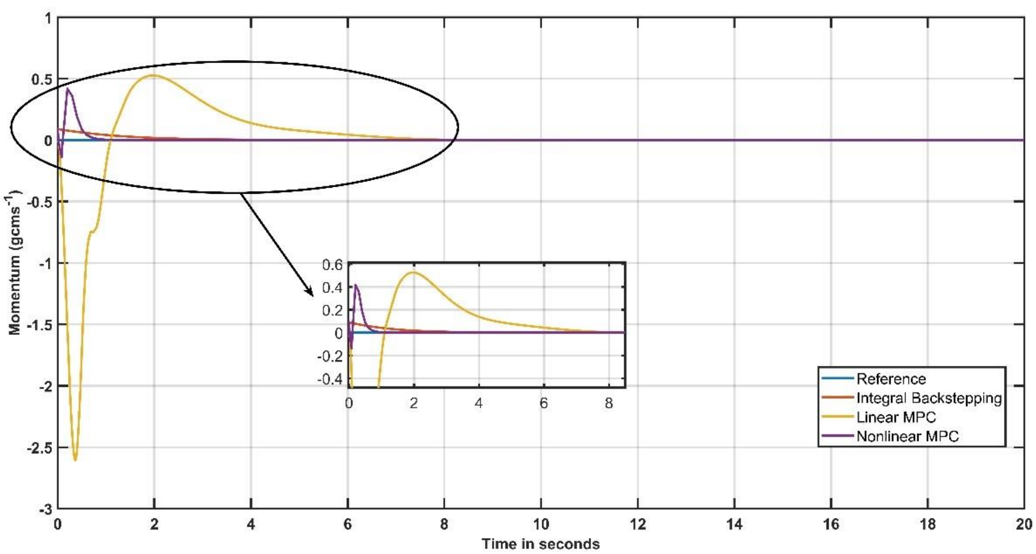

Figure 4.9: Comparative Analysis of Momentum for IBS, Linear MPC with Nonlinear MPC.

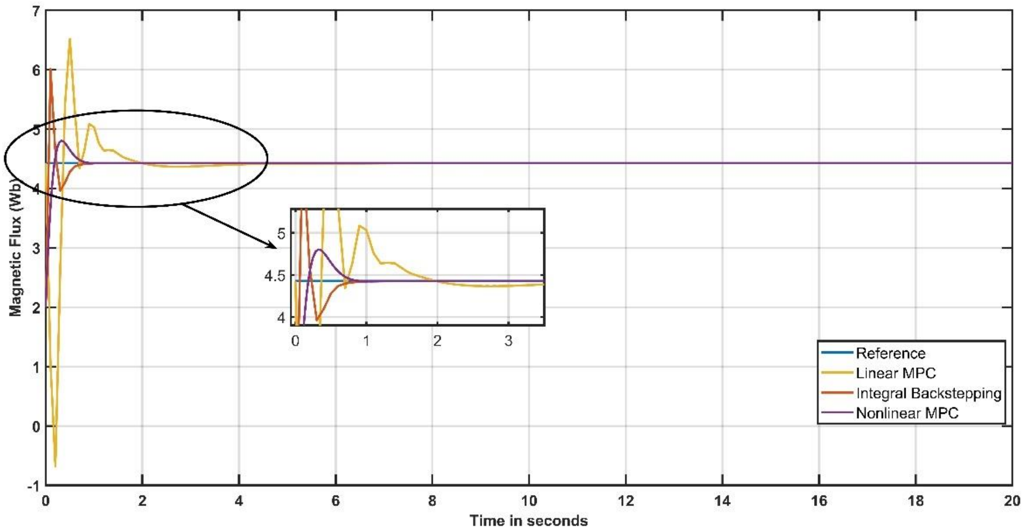

Figure 4.10: Comparative Analysis of Magnetic Flux for IBS, Linear MPC with Nonlinear MPC

Figure 4.8, 4.9 and 4.10 shows the comparative analysis for three techniques i.e. integral backstepping, backstepping and linear MPC with the nonlinear MPC, it can be seen the nonlinear MPC tracks the system more accurately as compared with nonlinear controller whereas it can handle constraints, predictive control and adaptability to nonlinearities. Nonlinear MPC also offers flexible tunning with selecting the optimal constraints and cost function whereas backstepping and integral backstepping mainly relies on the Lyapunov function as for ensuring the stability. Table 1 gives comparative analysis for the proposed nonlinear MPC with backstepping, integral backstepping and linear MPC.

4.6 Conclusion

The chapter is based on the results and discussion section for which the linear and nonlinear MPC controller has been designed for the Maglev system in MPC toolbox in Simulink, the results are much better for nonlinear MPC since it encounters the nonlinear dynamics of the system as compared to linear system which is an approximation for linearizing the model. Finally, the results are being compared with the integral backstepping and backstepping controller which uses a continuous time model and relies on the Lyapunov function for ensuring its stability whereas the nonlinear MPC uses the cost function and predicts the future behavior of plant and then provides the optimal control input for each time instant.

CHAPTER 5: CONCLUSION

5.1 Conclusion

The Thesis is based on the advanced control strategy for the Maglev system, the major objectives is to compare study and implement the advance control technique such as model predictive control (MPC) and then comparing it with nonlinear control techniques such as backstepping and integral backstepping. The main conclusion drawn from this thesis is as follows:

a) The linear MPC provided satisfactory results for Maglev system, but it is unable to deal with the nonlinear dynamics of system. It has oscillation in response and the slow tracking behavior was noticed during the transients.

b) Nonlinear MPC has completely different results from linear system, it has faster convergence, low oscillations, and better overall stability for the system. The nonlinear MPC uses the constraints that are the best application for the controller.

c) The integral backstepping also has decent performance for control of Maglev whereas it has issues with the flexibility and tunning offered by MPC system. Integral backstepping is robust but it is not as robust and precise as with nonlinear MPC.

d) Non-linear MPC is optimal solution for tracking the reference, increasing system stability, and reducing the oscillation of system, whereas linear MPC, backstepping controller and integral backstepping control performed well but still they faces issues for handling the nonlinear behavior of Maglev system.

5.2 Future Work or Recommendation

Some of the future work can be suggested that can be exploring of the adaptive control technique in the nonlinear MPC as to enhance the stability of system and dealing with time changing dynamics and uncertainties. Similarly, the nonlinear MPC needs the complex optimization problem for dealing in real world system that increased computational cost therefore the research must be focused to find the efficient ways to reduce the computational time without effecting the performance of controller.

The implementation of control strategies that have been designed in this thesis can be the next step for the validation of results in real world environments. Therefore, it needs to deal with the actuator, communication delays and noise. There are some other advanced control techniques such as fuzzy logic and neural networks that can be implemented for this system and its performance can be checked. These techniques are hybrid techniques that can enable the system to learn from real time and improve the control design.

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LIST OF PUBLICATIONS

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