CHAPTER 1

INTRODUCTION

1.1 DEFINITION OF MAGNETIC LEVITATION

Magnetic Levitation (ML) is a technique by which a ferromagnetic object is freely suspended without any mechanical support. To achieve this, a magnetic field is used to balance out the gravitational force on the object to be suspended.

This technique is implemented to avoid friction in moving objects. Moreover, the products of friction are eliminated. As it is free from lubricants it can also operate at high temperatures.

1.2 APPLICATIONS OF MAGNETIC LEVITATION TECHNIQUE

A few interesting applications of this technique found in literature are:

a. Maglev train. (Taniguchi 1992)

b. Silicon wafer transportation in clean room (Jin 1994, Park et al 1998)

c. Energy storage through flywheel (Hawkins et al 2006)

d. Wind tunnel (Daniels 1988, Muscroft et al 2006)

e. Magnetic bearings (Chiba et al 2005)

g. Magnetic levitation furnace (Takahashi 2006).

h. Centrifugal blood pumps (Hijikata 2011)

1.3 METHODS OF MAGNETIC LEVITATION

There are various methods to levitate an object as described by Jayawant (1981). The most common ones are:

a. Superconductive

b. Diamagnetic

c. Eddy current

d. Attraction type magnetic levitation (AML)

1.3.1 Superconductive Levitation

A passive levitation method using magnets and superconductors is based on Miessner’s effect. When a magnet is brought near to a superconducting ring, a current gets induced in the ring producing magnetic field to repel the magnet (as per Lenz’s law). When the magnet moves little up or down, the magnitude of the current changes accordingly and the magnet remains dynamically stable above the superconducting ring. The advantage of this passive levitation is that it does not need any closed loop control. It is inherently stable. It is less complex and needs no electronics and power supplies. But the main drawback is requirement of low temperature, needing continuous supply of a liquefied gas. The system fails if the temperature increases.
1.3.2 Diamagnetic Levitation

Diamagnetism occurs in materials having relative permeability less than one. In this method of levitation, diamagnetic material is levitated by a repulsive force produced by a magnet placed below it. But the repulsive force produced is very weak. Therefore this method is generally used to levitate very light pieces of pyrolytic graphite or bismuth above a moderately strong permanent magnet. As water is predominantly diamagnetic, this technique has been used to levitate water droplets and even live creatures, such as grasshopper and frog.

In case of diamagnetic levitation, as the repulsive force produced is very weak, the magnetic field required is very strong, that can create significant problems if other ferromagnetic materials are nearby. Hence these are employed for toys and demonstration purpose only.

1.3.3 Eddy Current Levitation

A force of repulsion is generated between a coil carrying alternating current and an electrically conducting surface above the coil, so that the alternating magnetic field of the coil induces eddy currents in the conductor as explained by Thomson (2000). This technique has also been used for simultaneous levitation and melting of specimens at 10 kHz for zone refining of metals (Laithwaite 1965). It has become a standard technique for preparation of small quantities of alloys without contamination from crucibles (Takahashi et al 2006).

The main drawback of this method is that high frequency fringe flux may produce unwanted heat in nearby metallic objects. Magnetic cards, hard disk of computers or even USB lying in the vicinity may be damaged or their data may get corrupted.
1.3.4 Attraction Type Magnetic Levitation System

In this type the magnitude of current through a coil of an electromagnet controls the force of attraction on the object placed below it. Sensors are used to detect the separation ‘Y’ between the electromagnet and the levitated object (LO). For a stable operation, the current in the lifting magnet (LM) should be an increasing function of the distance between the magnet and the LO. Therefore a closed loop system is required to vary the current in the lifting coil with change in ‘Y’.

The levitated object has six degrees of freedom and its movement is to be restricted in all the undesired modes. The important advantage of this technique is that, heavy objects can be suspended by the electromagnet at comparatively low currents. The magnetic flux predominantly remains confined to the assigned path and nuisance by the fringe flux is minimal. Due to these advantages the work carried out and presented in this thesis is confined to attraction type electromagnetic levitation system.

In attraction type magnetic levitation system (AMLS) the LM pulls up the LO against gravity. Separation ‘Y’ between the LM and the LO is measured by a sensor. Output of the sensor is suitably processed to vary the current fed to the coil of the electromagnet. A variety of sensors, controllers and current drivers for this purpose have been reported in the literature (Banerjee et al 2007, Yang et al 2007, Bandal 2010, and Hijikata et al 2011). PWM technique is often used to reduce the power loss in the current driver (Hurley 2004).
1.4 CONDITIONS FOR SUCCESSFUL ATTRACTION TYPE LEVITATION

For a successful levitation, the following conditions must be satisfied:

i. Force of attraction by the lifting magnet should be equal to the gravitational force.

ii. Force of attraction by the lifting magnet should be an increasing function of the distance ‘Y’.

iii. Force of attraction by the lifting magnet should be a function of ‘Y’ and its derivative to damp out the oscillations.

It is therefore essential to measure the value of ‘Y’ and to make the current through the coil of the electromagnet, a function of ‘Y’.

1.5 LABORATORY MODEL FOR ATTRACTION TYPE MAGNETIC LEVITATION SYSTEM

A typical attraction type magnetic levitation setup used in the laboratory by the author is as shown in Figure 1.1. ‘E’ shaped transformer laminations were used for making the core of the magnet. Windings on the side limbs were used for lifting the levitated object and winding on the central limb is used for detecting the separation ‘Y’ between the magnet and the levitated object.
1.6 RECENT DEVELOPMENTS IN ATTRACTION TYPE MAGNETIC LEVITATION SYSTEM

To develop the technology, most of the literature has considered only a few degrees of freedom for e.g. motion in the vertical direction only (Lin et al 2010, Lundberg 2004 and Khemissi 2008). Motion in other degrees of freedom is restricted mechanically and not considered for simulation and analysis.

Optical and Hall-effect sensors have been generally used for measurement of ‘Y’ (Hurley 2004, Zomorodian 2007 and Qui 2009). However, magnetic sensors without additional attachments have also been proposed (Kaplan, 1976). Same coil has been used for lifting and sensing the change in ‘Y’ by many researchers (Shameli, 2007, Yetendje, 2010, Lim, 2011).
Though the system under consideration is nonlinear, when the separation ‘Y’ is kept constant, the system can be linearized for small changes in the separation ‘Y’. In such a case, linear transfer function model has been used for modeling and for the design of the controller. Typical cases for such an application are magnetic bearing and magnetically levitated train (maglev) shown in Figure 1.2 and Figure 1.3 respectively.

Figure 1.2 Schematic of a Bearingless motor for constant ‘Y’

Figure 1.3 Schematic of a Maglev for constant ‘Y’
Applications in which the separation ‘Y’ and/or weight of the levitated object has to be changed, parameters of the transfer function will also change. Classical controllers cannot be used and therefore nonlinear controllers have been proposed. Robust controllers for variable structure operation have also been proposed. A typical application in which ‘Y’ changes within wide limits is shown in Figure 1.4. The lifting magnet is required to align the plate containing the silicon wafer to different racks for different processes in a clean room. As the room is very clean, no friction and products of friction are allowed in the room and therefore magnetic levitation technique is used.

![Figure 1.4 Wafer transportation in clean room](image)

Therefore two types of levitation systems, one for constant ‘Y’ applications and another for variable ‘Y’ applications have been developed.

1.6.1 Literature Survey for Constant ‘Y’ Applications

Jayawant et al (1981) in their review paper deals with the physics and engineering aspects of the four principal methods described in section 1.3 above. For advanced ground transportation the developments in this field in Germany, Japan, USA and UK are described. The review also describes some
of the very challenging developments in the application of electromagnetic suspension and levitation techniques to contactless bearings.

A new system of transducerless magnetic suspension (TRAMSS) using controlled DC electromagnets is described by Jayawant et al (1995). This method measures the separation ‘Y’ by measuring the change of inductance of the LM. The method is complex and difficult to implement in practice.

Jayawant et al (1996) have discussed the design aspects of the digital controller. The LM is driven by external PWM voltage amplifiers and the system does not require observer control which makes the system simple.

Hurley (1997) has mainly concentrated on the coil design of the LM under varying temperature. A linear model is developed and a proportional plus derivative (PD) compensator is designed. Oliveira et al (1999) have designed and implemented a digital suspension system for laboratory purpose.

Yu et al (2002) have discussed the modeling and control of DC magnetic suspension systems. Two new control schemes based on the structural information and energy based information have been proposed. However, the equations obtained are very complicated.

Morita et al (2002) and Lundberg (2004) have described a voltage controlled feedback linearization technique. But this method requires very accurate mathematical model of the analyzed system. Dolga et al (2007) have analyzed and simulated a voltage controlled ML system. The analysis is simple and is easily adaptable for optimization. Yang et al (2002) have implemented modified dynamic surface control technique to improve back stepping. They have used laser sensor to sense the position of a ball weighing 0.54 Kg.
Li (2005) has proposed a DSP based control to stabilize the system. The current control loop comprises of a PI controller and IIR filter. A PD control and FIR filter are employed to stabilize the position of the levitated object. Current transducer and a paired infrared emitter and receiver are used as position sensors. Challa (2007) has described design and implementation of ML of a steel ball and its analog controller. A phase lead compensator control circuit is designed.

Zomorodian (2007) has implemented hardware in loop with real time algorithm based on PID for stability and used light source and photodarlington pair as sensors.

Choi et al (2010) deals with design and dynamic analysis of rectangular surface electromagnets for ML application. On the basis of equivalent magnetic circuit method and 3D finite element analysis (FEA) model, initial and detailed design of an electromagnet is presented. A closed loop PID control algorithm is employed and the dynamic behavior of electromagnets is investigated experimentally.

Yetendje (2010) has designed multi sensor fault tolerant system with two position sensors and one current sensor. Oza et al (2010) has implemented Hall Effect sensor for sensing position of small magnetic disc.

1.6.2 Literature Survey for Variable ‘Y’ and Sliding Mode Control

For applications like wafer transportation in clean room as shown in Figure 1.4, the wafers are transported using magnetic levitation and requires variation in ‘Y’.

Cho et al (1993) have made an experimental comparison between sliding mode controller and classical controller for stabilizing a ML system.
Various linear classical controllers are also synthesized and the performance of the PI plus lead controller is compared with that of sliding mode controller (SMC). Sliding mode controller is found to be superior to linear classical controllers.

Barie et al (1996) have designed linear and nonlinear controllers for MLS. Two state space controllers are designed. One based on feedback linearization is used to control the position of the levitated ball. A nonlinear observer with linear error dynamics is used to estimate the speed. The second controller is a linear state feedback controller whose design is based on linear model found by perturbing the nonlinear system model about an operating point. Linear observer is used to estimate the ball’s velocity.

Lee et al (2000) have proposed a self-tuning controller with unknown mass variations for EMLS. It demonstrates the capability of its control action against mass uncertainty as well as against high frequency oscillations. Hassan et al (2001) have presented a variable structure control design procedure for robust stabilization and disturbance rejection of magnetic levitation system. Several simulation results have been presented.

Kharaajoo et al (2004) have considered position tracking problem of voltage controlled MLS. A SMC is employed to control the system. To show the effectiveness of the controller, its performance is compared with that of feedback linearization method.

Yang (2004) has developed a robust position control of ML system via modified dynamic surface control technique. It is also applied to the system to overcome the difficulties in back stepping.

Muthairi and Zribi (2004) have designed static and dynamic type of SMC. Robustness of the control schemes to changes in the parameters of the
system is also investigated. Dynamic sliding mode is proposed to overcome chattering.


Benevento et al (2005) have considered the problem of disturbance suppression for a MLS in presence of physical uncertainties. A saturated feedback is used to solve the problem, designing an internal model-based regulator in presence of input constraint providing a robust solution with respect to the uncertain parameters.

Bandyopadhyay et al (2006) have designed a SMC for higher order system via reduced order model. It is expressed in terms of aggregation matrix to design sliding mode control.

Shameli et al (2007) have designed a nonlinear controller to achieve precise motion control of a LO with submicron positioning accuracy. Laser sensors are used for sensing position of a small permanent magnet and force model is used to propose a control technique for position control. Lyapunov method is used to obtain stability. Khamesee et al (2002 and 2003) performed a comparative study of a model-reference adaptive controller and a conventional PID controller for 3D position control of a magnetically levitated microrobot. The experiments showed that the adaptive control technique has a better performance in rejecting the modeling uncertainties and variations in the payload with positioning accuracy of 0.1 mm over a 30 mm traveling range.

Khamessi (2008) has proposed and simulated a disturbance observer based sliding mode position controller for magnetic suspension ball system.
Bharathwaj et al (2008) designed linear and non linear controllers for MLS. The linear controller based on Jacobi linearization design deteriorated the tracking performance with the increasing deviation from nominal operating point. This linear model was then controlled by feedback linearization control. This controller was found to be sensitive to parameter variation and hence a sliding mode controller was designed to make the system robust.

1.6.3 Literature Survey for Techniques Employing AC for the Lifting Coil

This technique is based on the use of AC for the lifting magnet. The LM forms the inductive part of a series resonant circuit. The resonance frequency is kept slightly lower than the excitation frequency. If the LO moves towards the magnet, ‘Y’ decreases, inductance of the LM increases and it gets more untuned. This decreases the coil current and thereby reduces the lifting force to increase ‘Y’ restoring the position of the levitated object. Reverse happens when the ‘Y’ tends to increase. The system is therefore stable under steady-state and no separate sensor is required to measure ‘Y’.

Due to absence of friction, the LO begins to oscillate with increasing amplitude due to unmodelled negative damping. Several methods have been suggested by Kaplan (1967) and others to damp these oscillations without touching the LO.

Kaplan (1974) has controlled the oscillations in tuned circuit by introducing electronic circuit. Slow varying quantities like inductance, amplitude and phase of the current etc are determined for rapid calculation of transients in the tuned levitators. The drawback of the circuit was for obtaining the envelop signal the rectifier and low pass operation increased the
delay as well increased the number of components. Kaplan (1976) has achieved dynamic stability of a tuned levitator by implementing mechanical stabilization method. Further a chaos controller based on time delay auto synchronization system (TDAS) to prevent dynamic instability in tuned circuit levitators have also been proposed by Kaplan (1999).

Acht (1997) has developed various ways to measure inductance of coil for a MLS. The methods include measurement of oscillation frequency of LC oscillator by using phase locked loop, counting pulses between two zero crossings and checking Q-factor. A high frequency component is added to voltage over the coil and high frequency current is measured to obtain inductance. The merits and demerits of the developed system are also discussed. Choi et al (1999) have proposed amplitude modulation and demodulation method with a positive position feedback controller to damp the oscillations of a self sensing ML using LC (inductive capacitive) resonant circuit.

Hanson et al (2004) have described measurement of the back-emf generated by electromagnetic actuators using a simple model based on empirical measurements of electrical impedance. Self sensed displacement is used as a feedback to maintain constant amplitude vibratory excitation from an electromagnetic shaker. Using the designed actuator a simple rheo-meter is constructed for a biomedical application.

Lim et al (2011) have proposed computer simulation and experimental investigations instead of directly using the coil current to extract ‘Y’. Two identical demodulation filters, one coil inductance simulator and one PI convergence controller have been used. The design of the circuit implementing the algorithm of the self-sensing parameter estimator is described.
Gluck et al (2011) have introduced a novel method for the estimation of ‘Y’, based on a least squares identification strategy. Based on this model, an estimation algorithm for the inductance of the MLS is introduced. The estimation errors are compensated by means of a suitable estimation strategy. Furthermore, it is outlined that the chosen structure of the estimation scheme allows for a very efficient implementation in real-time hardware. The design of a cascaded position controller has been proposed.

From the literature review it is observed that all the authors have used same coil for lifting and sensing the position of the levitated object. Optical or Hall Effect sensors are implemented with classical, adaptive or robust controllers. In self sensing inductive capacitive tuned magnetic levitation system complicated methods have been implemented to damp out the oscillations of the levitated object.

1.7 PROBLEM DEFINITION AND OBJECTIVES

1.7.1 Problem Definition

It is proposed to improve the attraction type magnetic levitation system (AMLS) because this is the most widely used technique. Models and designs have been carried out with reference to E type transformer lamination stack for the LM and I type stack for LO. Details about LM and LO have been presented in Appendix 1. Various techniques proposed in the literature are tried on this model and necessary improvements are suggested and verified through simulation and also by experimentation.
1.7.2 Methodology

Schematic of the proposed magnetic levitation system is shown in Figure 1.5. The system developed has E shape transformer laminations stacked to form the electromagnet. Coils on the left and the right limbs form the lifting coil (LC) and the coil on the central limb forms the sensing coil (SC). Arrangement of the windings is such that change of current in the lifting coil does not induce any voltage in the sensing coil. In contrast to the work done by others, where the sensing and the lifting coils are the same, this method gives greater immunity from noise while measuring the distance ‘Y’.

Figure 1.5 Schematic of the Magnetic Levitation System

The levitated object LO is from the similar laminations of ‘I’ shape. Magnitude of current through the lifting coil LC controls the force of attraction of the levitated object.
The position sensing circuit determines the value of ‘Y’ by measuring the inductance of the coil SC and gives a signal to the controller. The controller gives an appropriate signal to the driver that sends a suitable current to LC to realize the suspension.

Various limitations of the position sensors have been shown in the literature (Mukhopadhya 2005). Hence two novel sensors have been developed to make the system free from any attachment on the levitated object. One is based on phase measurement (synchronous demodulation technique) and the other based on change in impedance of the sensing coil with change of ‘Y’. As both these sensors are integrating type, the noise in the measurement of ‘Y’ is reduced. Near linear relation between displacement of the levitated object and voltage output of the sensor has been realized by both the techniques.

In synchronous demodulation method, a 50 Hz voltage signal is applied to the coil SC, phase difference between the voltage and current in the coil SC due to change in ‘Y’ is determined.

In the second method, a capacitor is connected across the SC winding and its value is so chosen that the circuit resonates at a frequency slightly lower than the exciting frequency for ‘Y’= 0.01meters. As the exciting frequency is 50 Hz, the coil voltage $V_{\text{coil}}$ increases with ‘Y’ due to decrease of inductance and the circuit coming closer to resonance. The voltage $V_{\text{coil}}$ is rectified and passed through a low pass filter to obtain the voltage $V_1$. Near linear relationship between voltage $V_1$ and ‘Y’ was observed for the chosen parameters.

For magnetic bearing type applications, a constant value of ‘Y’ can be chosen. The system can be linearized for small changes in ‘Y’. Particle
swarm optimization (PSO) method (Kennedy et al 1995) for determining the optimal proportional, derivative and integral (PID) controller parameters to obtain the best performance index is implemented. PID with PSO is found to be easy to implement, has stable convergence and good computational efficiency.

For applications like silicon wafer transportation system, a wide variation in ‘Y’ is needed. Linear control techniques are unsuitable and therefore a robust sliding mode controller has been developed. Robustness of the controller for varying values of ‘Y’ and change in mass of the ‘LO’ are studied. For change in position ‘Y’ actual current in the coil LC and the required current as per sliding mode equations are obtained theoretically and experimentally.

In yet another type of circuit, suitable for constant ‘Y’, the coil LC excited by AC supply forms an inductive part of a series inductive- capacitive tuned circuit. It can be designed to satisfy all the conditions of levitation except damping. This circuit does not require any separate position sensor. This system is dynamically unstable as the lifting coil current is not a function of the derivative of ‘Y’. The object oscillates at its natural frequency in all the other modes. A novel circuit with Z-source inverter is developed and used with tuned circuit to bring back the object to its desired position and nearly damp out the oscillations.

1.7.3 Objectives

An outline of the research objectives proposed in this thesis is given below:

1. Development of mathematical model of the system in Laplace domain and state space form
2. Development of better position sensing techniques

3. Development of optimized PID controller and sliding mode controller

4. Development of DC voltage controlled current source (VCCS) and DC voltage controlled voltage source (VCVS)

5. Development of system using AC for the lifting coil

1.8 ORGANIZATION OF THE THESIS

Chapter 1 briefly introduces the phenomena of magnetic levitation, its practical utility and various techniques used to achieve this along with their merits and limitations. The literature was surveyed to study the various techniques available and their relative merits and demerits along with their scope of application.

Chapter 2 deals with development of linear and nonlinear mathematical models of the proposed system. Nonlinear variation of the inductance of the lifting magnet is studied by simulating it with the help of MAGNET software. The results of simulation are verified experimentally. Nonlinear mathematical relations are developed between inductance and ‘Y’. The relation between force and distance ‘Y’ is also modeled. State space form of model is also developed as this form is easy to use for the design of nonlinear systems.

Chapter 3 deals with development of self sensing techniques. First method based on synchronous demodulation technique is developed for obtaining the phase variation between the voltage and current of the SC coil as a function of change in inductance and hence the change in position of the
A near linear relationship between voltage and distance ‘Y’ of the object is established to detect position of the object. Second method is based on resonance technique. Voltage across the SC is obtained as a function of position of the object. Near linear relationship between voltage and Y is observed for the chosen parameters.

Chapter 4 analyzes PID controller with its merits and demerits for the developed system. For constant ‘Y’ particle swarm optimization (PSO) technique for determining the optimal PID controller parameters to obtain the best performance index is implemented. PID with PSO is found to be easy to implement, has stable convergence and good computational efficiency. The chapter also covers the impact of robust controller on the behavior of nonlinear, unstable magnetic levitation system. Hysteresis current control has been developed to control the force produced by the magnet depending on the position of the object. The effect of variation in the mass of the object on the performance of the system is also analyzed. It is observed that for a controller like sliding mode control wide change in mass does not much affect the performance of the system and hence can be called robust for variation in mass of the LO. The model is simulated using MATLAB. Hardware prototype has been developed and implemented digitally.

In Chapter 5, design of simple voltage controlled current source and voltage controlled voltage source are presented. The parameters of the circuits were optimized using PSPICE before fabrication. It is observed that VCCS can be used for system with constant Y and VCVS for variable Y.

Chapter 6 deals with an alternative way to excite the lifting coil by AC current. To maintain the force as an increasing function of ‘Y’, the circuit is series tuned at a frequency less than the excitation frequency at the desired ‘Y’. Corresponding to increase in ‘Y’, the inductance of the magnet decreases
and the circuit approaches resonance. Though the method is simple, natural frequency oscillations of the levitated object continues indefinitely and may also increase due to unmodelled nonlinearities. The oscillations must be damped.

The system with a Z-source inverter circuit using shoot through condition to increase the excitation of the inverter is designed. The system is simulated in MATLAB. Experimental results obtained show that the system works well.

In Chapter 7, advantages and scope of application of magnetic levitation system have been highlighted. Conclusion of the work carried out is presented. Two new types of sensors developed have been described. These sensors are free from any physical attachment to the levitated object. These are less prone to noise and are therefore more reliable. E shape core for magnet is needed for these types of sensors. Voltage controlled current source and voltage controlled voltage source have been developed. The former is suitable for fixed air gap whereas the later is suitable for variable air gap. Linear controller has been developed for fixed air gap and a sliding mode controller for variable air gap. Robustness of the sliding mode controller for variable mass of the levitated object has been proved. Magnetic levitation with AC excitation is discussed and results for a novel circuit developed and implemented are presented. Scope for future work that can be carried out has also been highlighted.