Design, Implementation and Testing of an Attraction type Electromagnetic Suspension System

S. Banerjee, D. Prasad and J. Pal

***Abstract*—This paper describe the design principle of a DC attraction type electromagnetic suspension system where a hollow steel cylinder of 658 gm mass is levitated under a fixed I-core (solenoid type) electromagnet with a single degree of freedom. Electromagnet exhibits non-linear force versus distance characteristics and hence this controller has been designed by using linear small perturbation model of the magnet at the desired operating point. In all previously reported papers [1-4] the system design has been done by considering a suitable voltage source as the exciting input to the magnet coil. In the current work, over all system order reduction has been tried by taking a controlled current source as the excitation for the magnet coil. The resulting system is simpler and has second order transfer function. The current source is realized by using a two-switch asymmetrical bridge type switched mode dc to dc converter. The prototype has been successfully tested and levitation demonstrated.**

***Index Terms*—Electromagnetic levitation and suspension, dc-to-dc chopper control, proportional plus derivative compensation, position and current feedback.**

I. INTRODUCTION

Electromagnetic levitatation systems are used in the field of high speed vehicles, frictionless bearings etc. The stable suspension of a metallic body in a magnetic field has been a subject of considerable interest since the 1930's.

As is well known, electromagnetic levitation can be achieved either by the electromagnetic attraction or by repulsion. The present work describes a DC attraction type device, where the current of the electromagnet is controlled by switched mode chopper circuit utilizing outer position control loop and inner current control loop. The system has been designed, fabricated, analyzed and tested on a laboratory scale. In this setup, a steel cylinder of 658 gm mass is made to suspend in air. The block diagram of the proposed magnetic levitation system is shown in Fig.1.

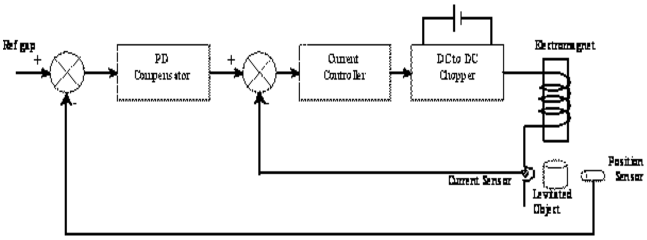

Fig. 1 Block diagram of the proposed scheme

The force between the magnet and the steel mass varies as the inverse of the square of the distance between them and is also proportional to the square of the current. The attraction type levitation is not only very unstable in nature but is nonlinear too. Many researchers have tried to analyze and control the electromagnetic levitation system based on linear approximation of the non-linear model [1-4]. Most of the researchers have taken voltage as the exciting input to the magnet coil and this results in a third order unstable system. In our approach we have assumed a controlled current source as the excitation for the magnet coil, which results in a simpler second order transfer function (still unstable) for the system.

II. SYSTEM MODELLING

The force of attraction between a ferromagnetic mass and the magnet is non-linear. The variables of interest are the distance between the mass and the magnet (x) and current in the electromagnet coil, (i). The force expression is given by equation (1) below:

$$F = \frac{dw}{dx} = \frac{d}{dx}\left\{\frac{1}{2}Li^2\right\} = \frac{i^2}{2}\frac{dL}{dx} \qquad (1)$$

where, w is the co-energy in the air-gap and L is the inductance in the system. The suspended steel mass contributes to the inductance of the electromagnet coil. As the body approaches the magnet, the magnet-coil inductance goes up. As the mass moves farther from the magnet, the inductance decreases, reaching a minimal value when the mass is too far. The inductance variation with distance is shown in Fig.2

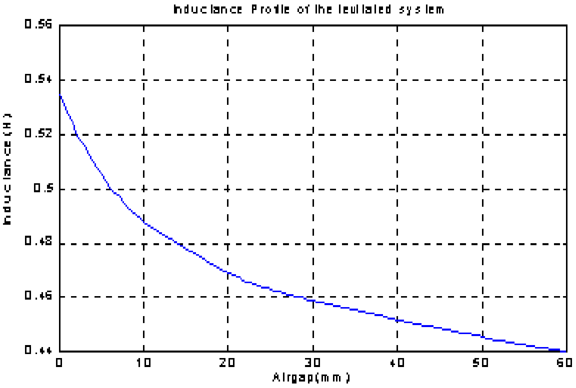

Fig.2 Inductance profile of the levitated system

The dynamics of the idealized system may be described by the following basic equations :

S.Banerjee is a research scholar in Electrical Engineering Deptt., IIT, Kharagpur –721302. E-mail: subrata@ee.iitkgp.ernet.in.
D.Prasad and J.Pal are faculty members with Department of Electrical Engineering, IIT, Kharagpur – 721302. E-mails: dinkar@ee.iitkgp.ernet.in and jpal@ee.iitkgp.ernet.in.

$$\mathbf{F} = \mathbf{C}\left(\frac{i}{x}\right)^2 \tag{2}$$

$$V = Ri + L\frac{di}{dt} \tag{3}$$

$$M\frac{d^2x}{dt^2} = Mg - F \tag{4}$$

where, F is the electromagnetic force between magnet and ferromagnetic body, R is the resistance of the coil, L is the inductance of the coil, x is the distance between electromagnet and the object, C is the force constant, g is the gravitational constant, i is the current through coil, v is the voltage across the coil, M is the mass of the cylinder.

The system dynamic equations are non-linear and hence difficult to analyze. So they are linearised about a suitable operating point (i_0, x_0). The linearised model may be found as described below. If the cylinder mass is displaced by an amount Δx from the stable point, the corresponding changes in current, voltage and force are respectively Δi, Δv and Δf. At the equilibrium the position of the mass, the current through the coil and the magnetic force is denoted by x_0, $i_0$and f_0 respectively. Here the magnet current i may be assumed to have two parts: a steady state component (i_0) which generates the vertical attraction force at the equilibrium point (i_0, x_0) and a much smaller component Δi which provides the attraction force for variations around (i_0, x_0). So we can write the force equations as below,

$$F = f_0 + \Delta f = C\frac{(i_0+\Delta i)^2}{(x_0+\Delta x)^2}; \tag{5}$$

$$\text{Again, } M\frac{d^2(x_0+\Delta x)}{dt^2} = Mg - F \tag{6}$$

At equilibrium, the magnetic force on the object equals the gravitational force

$$\text{i.e., } f_0 = C\left(\frac{i_0}{x_0}\right)^2 = Mg; \tag{7}$$

Equations (5)-(7), after binomial expansion and rearranging gives rise to Eqn. 8 below in the Laplace transform domain,

$$\frac{\Delta X(s)}{\Delta I(s)} = \frac{\frac{2Ci_0}{x_0{}^2M}}{\left(s^2 - \frac{2Ci_0^2}{x_0^3M}\right)} \tag{8}$$

The above equation gives the open loop transfer function of the suspended system when the coil is excited by the current source. With voltage as the system input, combining equation (3) and (8) the open loop transfer function becomes,

$$\frac{\Delta X(s)}{\Delta V(s)} = \frac{\frac{2Ci_0}{MLx_0^2}}{\left\{\left(s+\frac{R}{L}\right)\left(s^2 - \frac{2Ci_0^2}{x_0^3M}\right)\right\}} \tag{9}$$

The block diagram of the mathematical model of the levitated system (based on Eqn.9) can be represented in Fig.3

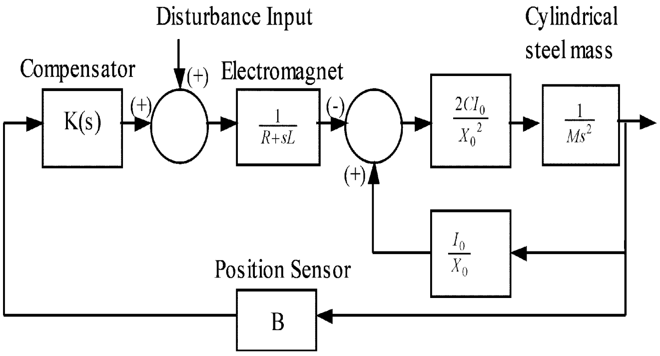

Fig. 3 Block diagram representation of the model

III. PARAMETER DETERMINATION AND CONTROLLER DESIGN.

The parameters in the system equations are determined as follows. The mass of the cylinder (M), the resistance of the coil (R) and the inductance of the levitated system (L) at different air-gap positions are determined. The desired initial distance, x_0 is chosen and the corresponding coil current (pick-up current) for which the cylindrical mass just lifts is determined. This current is i_0. We can now find the constant C by using Eqn. (7).

The transfer function in Eqn. (8) shows that the system is open loop unstable and it cannot be stabilized by simply adjusting the amplifier gain. To make the overall system stable, a zero is added to the open loop transfer function. For implementing this a Proportional plus Derivative (PD) controller is designed with a provision to vary the proportional and derivative gains separately. This has been indicated in the schematic control block diagram of Fig.1. The block diagram shows an inner current control loop and an outer position control loop. The output of the position control loop sets the reference current value for the inner current control loop. The response time of position loop is expected to be much slower than the inner current loop. To simplify the position controller design the inner current loop is taken as a unity gain block. Essentially it means that the reference current command of the position controller output is almost immediately complied by the inner current control loop. The overall loop transfer function for the position control loop then becomes :

$$G(s)H(s) = \frac{\left\{KB(s+z_c)\frac{2Ci_0}{x_0{}^2M}\right\}}{\left(s^2 - \frac{2Ci_0{}^2}{x_0{}^3M}\right)} \tag{10}$$

where z_c is the PD compensator zero, B is the sensor gain and K is the over all gain of the system. After obtaining the exact parameters for the model, a simulation is carried out to get the accurate zero location and to find the gain of the system. For an equilibrium position (x_0) around *40 mm*, the pick-up current (i_0) is 4.4 A; so from equation (7) the force constant C is 5.3306×10^{-4} (N-m^2/A^2); Then from equation (8) the transfer function of the plant is given by,

$$\frac{\Delta X(s)}{\Delta I(s)} = \frac{4.46}{(s-22.15)(s+22.15)}; \qquad (11)$$

The root-locus plot of the uncompensated system shown in Fig.3 depicts that the system is open loop unstable and it is impossible to get closed loop stability by simply adjusting the gain of the system. To pull the root-locus into the left-hand plane, a compensator zero is needed in the left-hand plane after the pole of the system. After obtaining the zero location the compensated open loop transfer function becomes,

$$G_c(s)H_c(s) = \frac{K(s+120)17840}{(s+22.15)(s-22.15)} \qquad (12)$$

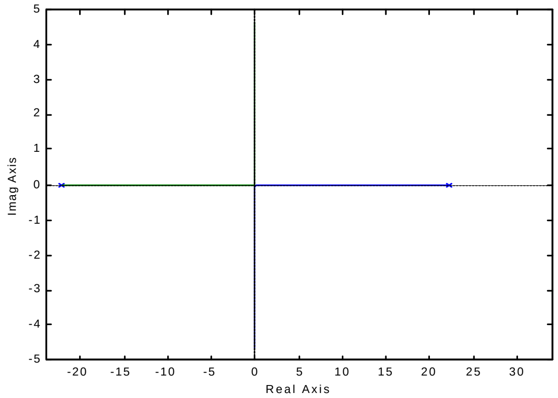

Fig. 4 Root-locus of the original plant

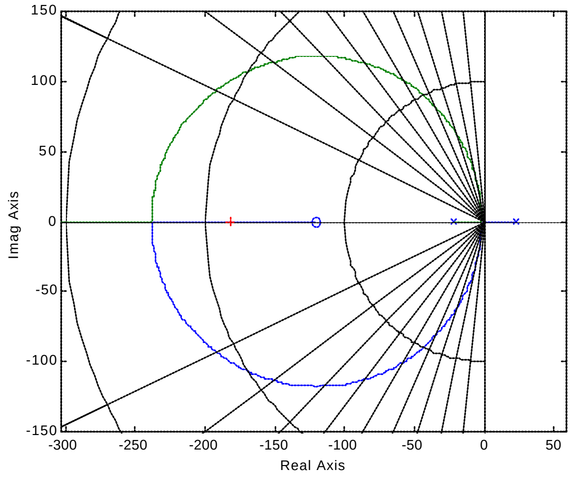

Fig. 5 Root-locus of the compensated plant

TABLE I

Parameters	Values
Mass of the cylinder	.658 kg
Height of the cylinder	7.5 cm
Diameter of the cylinder	7.5 cm
No of turns of the coil	1065
Resistance of the coil	7.1 ohm
Inductance of the coil	.440 H
Sensor gain	4000 v/m

IV. HARDWARE DESCRIPTION

In order to control the coil current effectively and to decrease the size of the amplifier, a switched-mode dc-to-dc chopper is used instead of a conventional linear amplifier. MOSFETs are used as controlled switching devices. The chopper circuit shown in Fig.6 consists of two MOSFETS (IRFP450) and two fast recovery diodes (MUR1560).

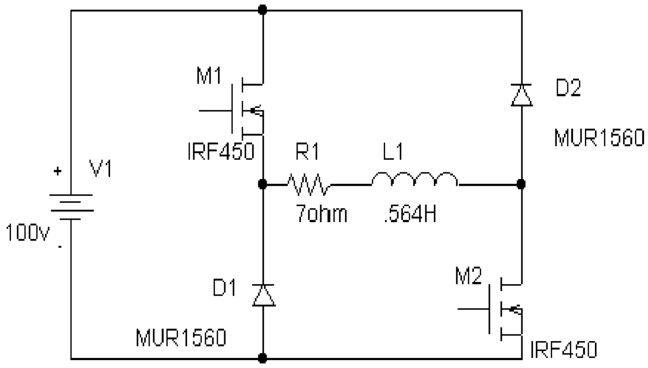

Fig. 6 Switched mode dc to dc chopper circuit

Actual air-gap between the electromagnet and the object is sensed through a linear capacitive type proximity sensor. The proximity sensor output (scale: 1mm= 4 volts) is compared with reference voltage signal indicating the desired gap length at which the stabilization is being aimed. This position error is processed through a PD controller, PD controller as shown in Fig. 7 is realized using simple op-amp circuits. The output of PD controller is taken as reference current signal. The actual current of the coil is sensed by a Hall effect current sensor of LEM make. Current error is processed through a PI controller. Current controller output is used to control the chopper output voltage. The duty ratio of the MOSFET switches vary as the cylinder moves up and down within the electromagnetic field. When the cylinder moves upwards (beyond ref. gap) the duty ratio of the MOSFET gate pulse is decreased, consequently the magnet current decreases and causes the object to go down and vice-versa. To facilitate proper duty ratio control of the MOSFET switches a triangular wave of 6 Khz is produced. The triangular waveform is compared with the PI controller output of the current loop. The comparator generates the desired PWM waveform to be used for driving the MOSFET switches after required isolation and amplification. The gate pulse of one of the MOSFETs and the coil-current waveform under levitated position (with around 40 mm gap) is shown in Fig. 8

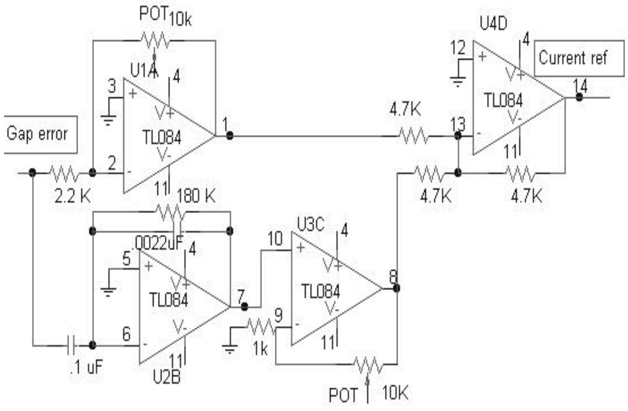

Fig. 7 PD Compensator details

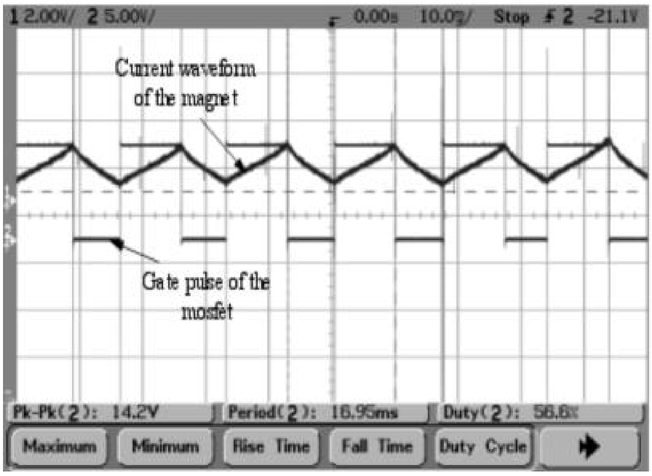

Fig. 8 Gate pulse of Mosfet and coil current during levitated position

V. RESULTS AND DISCUSSIONS

The hollow steel cylinder has been successfully suspended under the I-core electromagnet. The movement of the cylinder is restricted in vertical direction by putting a rod through the cylinder. The photograph of the setup is shown in Fig.8 during levitated condition with around 40 mm distance between magnet face and cylinder. To test the efficacy of the feedback system, small disturbances were mechanically applied to the levitated cylinder. The feedback system was able to overcome the disturbances and maintain correct airgap (for up to 45 mm gap distance). To check the response characteristics of the current loop it was first tested separately (with position controller output not connected). A dc voltage superimposed with sine wave was applied as the reference current signal and the actual coil current was sensed. The actual current follows the demand current in the frequency range of zero to around 100 Hz, for an input DC voltage supply of 100 volts and with a 20 ohm external resistor connected in series with the magnet. The demand current for the current loop test was given from a signal generator (dc superimposed with sine wave of up to 100 Hz). The current controller (Proportional plus Integral control) is intended to be faster than the actual inertial time constant of the cylindrical mass.

The dynamic response of the compensated system is simulated using Matlab. Table II shows variation of time and frequency domain parameters ($\xi = 0.6$) with different levitated gap-lengths between magnet and the cylinder. It is observed that there is an improvement of peak overshoot and steady state error at higher gap position. Stability margin is also increased as we go from lower gap to higher gap position. But at the same time the required coil current for lifting the mass is increased. In Table II below the following nomenclatures have been used:

k_p - Gain of position controller, k_d - Gain of derivative controller, m_p - Peak overshoot, c_{ss} - Steady state output, GM- Gain margin, PM- Phase margin

TABLE II

Air-gap (mm)	Open loop Poles of plant	Gains of controllers	Time Response specifications	Frequency Response specifications
10	44.29 -44.29	k_p =.408 k_d =.0034	m_p =1.35240 c_{ss} = 1.11692	Gm=19.64 dB Pm=55.65 deg
20	31.32 -31.32	k_p =.612 k_d =.0051	m_p =1.29306 c_{ss} =1.04885	Gm=26.19 dB Pm=57.67 deg
30	25.57 -25.57	k_p =.828 k_d =.0069	m_p =1.27703 c_{ss} =1.03005	Gm=29.84 dB Pm=58.22 deg
40	22.15 -22.15	k_p =1.14 k_d =.0095	m_p =1.27027 c_{ss} =1.02087	Gm=32.35 dB Pm=58.32 deg

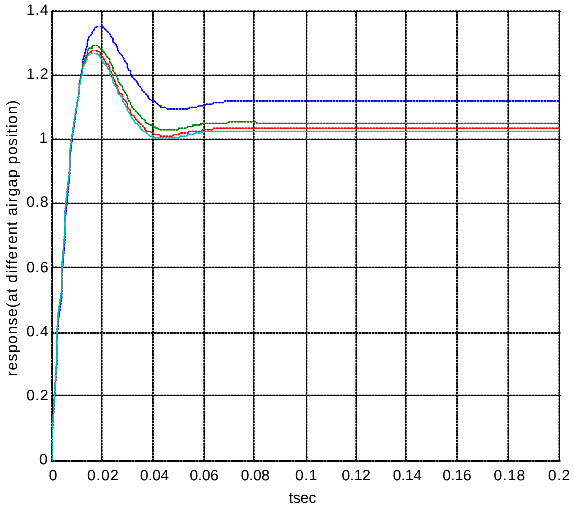

Fig.7 Time response plots of different levitated positions

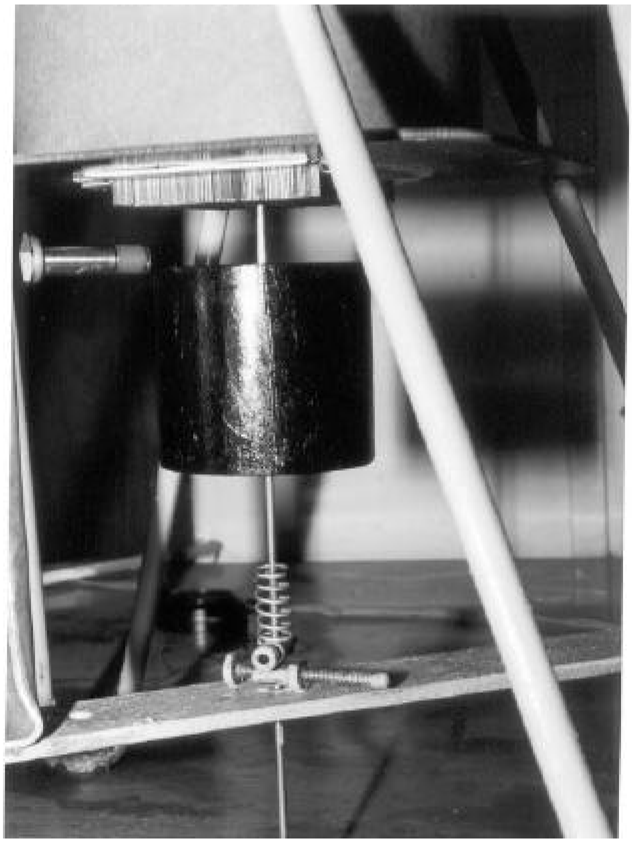

Fig.8 Photograph of the levitated system

VI. CONCLUSION

A laboratory scale DC attraction type suspension system is described. The system model is developed and simulated and control circuit hardware is realized. The unique feature of the present scheme is the use of the inner current control loop taking its input command directly from the position controller output. This simplifies the overall system design. Switched mode dc to dc converter circuit used in this work is more efficient over linear power amplifiers used in most of the reported papers. Because of the increased energy efficiency the proposed system can be used for heavier payloads. The switched mode supply circuit however produces unwanted switching noise that becomes a nuisance for the PD type controller and calls for a better layout of the power-board. Future experiments are going on inverted model where electromagnet itself acts as the levitated object under the ferromagnetic guideway.

REFERENCES

[1] Wong T.H., “Design of a Magnetic Levitation Control System, An Undergraduate Project”, IEEE Trans on Edu., Vol. E-29(4), Nov.,1986,pp196-200.

[2] P.K.Sinha, “Control, Measurement and Design aspects of low-speed magnetically suspended vehicles”, Measurement and Control, Vol. 11,Nov.1978, pp 427-435.

[3] V.A.Oliveria, Eduardo F. Costa and J.B. Vargas,”Digital Implementation of a Magnetic Suspension System for Laboratory Experiments”, IEEE Transactions on Edu., vol 42 No.4 Nov.,1999

[4] M. Sengupta, A. Sengupta, D.Banerjee, P. Banerjee, R. Majumdar, S. Majumdar, S. Mukherjee, S. Pramanik, R. Sarkar, M. Rehaman “Design Implementation and Testing of an Attraction Type Magnetic Levitation System”, International Conference on EAIT, pages 17-20 ,2001, IIT Kharagpur.

[5] Ogata K., Modern Control Engineering, Prentice Hall of India Pvt. Ltd.,New Delhi, Third Edition, 2000.

[6] Mohan, N., T. M. Undeland and W. P. Robbins, Power Electronics: Converters, Applications and Design, Wiley, New York, 1989.