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MOTION CONTROL OF A MAGNETICALLY SUSPENDED OBJECT BY PD CONTROLLER

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Abstract*- This paper emphasizes on the design, construction and control of a single degree-of-freedom magnetic levitation system. The maglev system is stabilized to levitate an object using PD controller. PD controller is designed and fabricated using analog controller. PD controller mainly suspends the mass of the object as well as controls its motion. Despite the simplicity and low cost of the position sensing system, it is able to detect the ball position at a distance of 2-5 mm. The electromagnetic force is varied by changing the flow of current to set the ball at a stable position. The successful operation of this system, made of relatively low cost components, depicts cheap, integrated magnetic levitation systems, which is becoming more feasible for a variety of applications.*

Keywords: PD Controller; Magnetic Levitation, Motion Control, Mechatronics.

1. INTRODUCTION

In the advanced technological world, the advancement in mechatronics field is momentously captured by magnetic levitation systems. Recently, they are becoming popular because of having hands-on significance in many engineering systems such as high-speed passenger trains, frictionless magnetic bearings, levitation of object in wind tunnel models and vibration isolation tables [1-3]. In magnetic levitation system, the magnetic force from the electromagnet keeps the object, which is to be levitated, floated in the air-gap against the gravitational force. The force exerted on the levitated object is a function of the current passing through the coil of the electromagnet and the displacement between the electromagnet and the levitated object. At a certain position of the levitated object, the relation between the coil current and the magnetic force, varies depending on the position of the levitated object [4]. As the substance of the levitated object in our designed model is a ferromagnetic ball, the magnetic force is proportional to the square of the coil current [3,5,6]. Magnetic levitation or maglev system itself is very complex because of the nature of the plant dynamics, the small degree of natural damping in the process, the strict positioning specifications often required by the application and the open-loop unstable system dynamics from the point of view of control engineering. Hence the application of control technologies for use in magnetic levitation systems has become inevitable. For a past couple of decades, a lot of researches have been conducted for the control of magnetic levitation systems. To take care of nonlinearity of the systems, various nonlinear control techniques such as feedback linearization, sliding mode control, and back stepping have been applied [3,4,6,7]. Feedback control is a best way to take care of a magnetic levitation system, though it does not guarantee robustness in the presence of modeling error and disturbances. However in active feedback control system using PID, LQR, H∞, PI control, repetitive controls are extensively used [8,9]. In this research, a different method of controlling the magnetic force is investigated. PD controller is being used for its simplicity and low cost. Moreover, it makes the system more stable with less consumption of energy as compared to the other processes. Considering the object to move in vertical translational direction, i.e. single-degree-of-freedom motion (SDOF), the controller is made enable to control this motion. The steady state condition is realized with this control in which the attractive force produced by the electromagnet balance the weight of the floated mass. Further experimentation reveals the acceptance of the method. The paper is organized as follows: Section 1 introduces the paper; section 2 reveals mathematical modeling of a maglev object. In Section 3, controller is designed. In Section 4, experimental setup is described. Section 5 depicts experimental result and finally, Section 6 concludes the paper.

2. MODELING

2.1 Electromagnetic force dynamics

The ball dynamics model of the Levitation System is described by the following equation

$$m\ddot{x} = mg - f(i, x) \tag{1}$$

where m is the mass of the steel ball, x is the distance between ball and the electromagnet, $f(i, x)$ is the

electromagnetic force that counteracts the weight force ($w=mg$) to bring the ball in the equivalent position.
The electromagnetic force created for the coil current i is given by using the magnetic energy equation (Faraday's inductive law and Ampere's circuit law) in the following form

$$f(i,x) = -\frac{i^2(t)dL(x)}{2dx} \tag{2}$$

where L is the total inductance of the electromagnet. When the ball comes closer to the electromagnet the total inductance increases. Taking this incremental variation of the total inductance into consideration, equation (2) can be transformed as follows

$$f(i,x) = -\frac{i^2 d}{2dx}[L_1 + \frac{L_0 x_0}{x}] \tag{3}$$

where L_1 is the inductance of the coil without the levitated object, L_0 is the additional inductance caused by the presence of the levitated object and x_0 is the air gap at the equilibrium position of the levitated object. The inductance is firmly depends upon the geometry and construction of the electromagnet, and can be experimentally determined.
Now taking the derivative of the inductance with respect to the ball position is given by

$$\frac{dL(x)}{dx} = -\frac{L_0 x_0}{x^2} \tag{4}$$

Putting this value in Eq. (2), we get

$$f(i,x) = -\frac{i^2}{2}(-\frac{L_0 x_0}{x^2}) = \frac{L_0 x_0}{2}\frac{i^2}{x^2}$$

$$f(i,x) = k\frac{i^2}{x^2} \tag{5}$$

Where $k = \frac{L_0 x_0}{2}$ is the attractive force coefficient for electromagnet, i is the coil current and x is the mean distance between electromagnet and suspended object. To design a linear control system the non-linear electromagnetic force $f(i,x)$ is linearized about an equilibrium position of the levitated object, say x_0

$$f(i,x) = k\frac{{i_0}^2}{{x_0}^2} + (\frac{2ki_0}{{x_0}^2})i - (\frac{2k{i_0}^2}{{x_0}^3}) + \ldots$$

$$f(i,x) = f_0 + f_1 + \ldots \tag{6}$$

Where, $i = i_0 + \delta i$
$x = x_0 + \delta x$

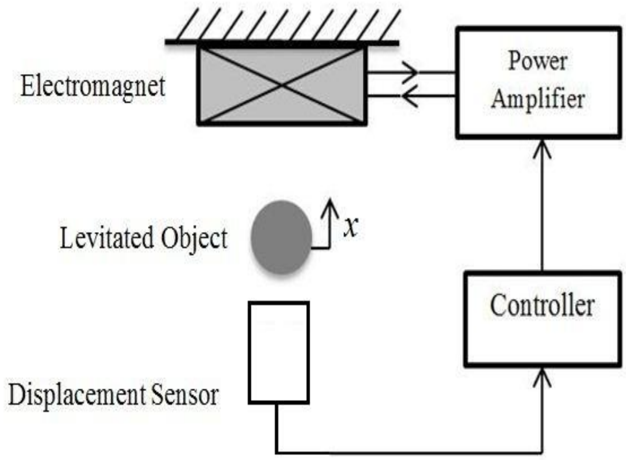

Fig1: Basic model of an active magnetic levitation System

where i_0 and δi respectively represent the equilibrium and incremental values of current, x_0 and δx represent the equilibrium and incremental values of position. In our further analysis, i and x represent the change of current and position from the equilibrium respectively.

2.2 Motion dynamics

A basic control model is designed based on linearized equation of motion with the assumptions that the displacement of the suspended mass (steel ball) is negligibly small, the nonlinear terms are neglected and the suspended mass m is moving only in the vertical translational direction as shown in the Fig. 1. The equation of motion is given by

$$m\ddot{x} = k_s x + k_i i + w \tag{7}$$

where k_s is the gap force coefficient, k_i is the current force coefficient, w disturbance acting on the suspended mass, i is the control current. The coefficients k_s and k_i are positive. Denoting each Laplace-transform variable by its capital and assuming the initial values to be zero for simplicity, the transfer function representation of equation (7) becomes

$$X(s) = \frac{1}{ms^2 - k}(k_1 I(s) + W(s))$$

$$X(s) = \frac{1}{s^2 - a_0}(b_0 I(s) + d_0 W(s)) \tag{8}$$

where, $a_0 = \frac{k_s}{m}, b_0 = \frac{k_i}{m}, d_0 = \frac{1}{m}$

In current control magnetic levitation system, PD control can be represented as

$$I(s) = -(P_d + P_v s)X(s) \tag{9}$$

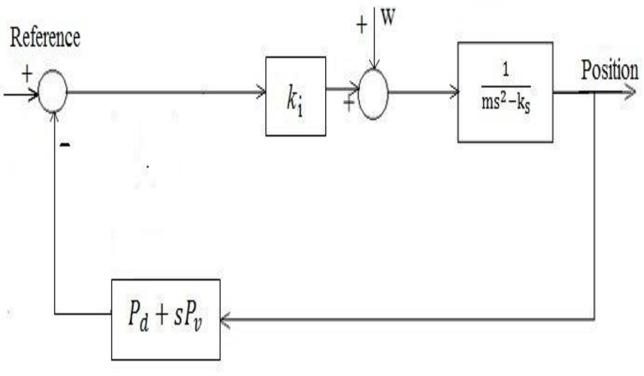

Fig.2: Block diagram of a maglev system with PD controller

$$X(s) = -\frac{I(s)}{(P_d + P_v s)} \tag{10}$$

$$\frac{X(s)}{I(s)} = -\frac{1}{(P_d + P_v s)} \tag{11}$$

From this linearized system, $X(s)$ and $I(s)$ represent the change from the equilibrium values of position and current respectively. Hence the negative sign implies that with an increase in $X(s)$ there will be a decrease in $I(s)$, and vice versa.

From Eq. (8), (9) and (10)

$$-\frac{I(s)}{(P_d + P_v s)} = \frac{1}{(s^2 - a_0)}(b_0 I(s) + d_0 W(s))$$

$$\frac{I(s)}{W(s)} = \frac{-d_0(P_d + P_v s)}{(s^2 + P_d b_0 + P_v s b_0 - a_0)} \tag{12}$$

Again putting the value of, $I(s)$ from Eq. (11) in Eq. (9)

$$X(s) = \frac{1}{s^2 - a_0}[b_0\{-(P_d + P_v s)X(s)\} + d_0 W(s)]$$

$$\frac{X(s)}{W(s)} = \frac{d_0}{s^2 + P_d b_0 + sP_v b_0 - a_0} \tag{13}$$

3. CONTROLLER DESIGN

Magnetic Levitation system can be controlled by various ways. In this paper, PD controller is used to produce active feedback control system.

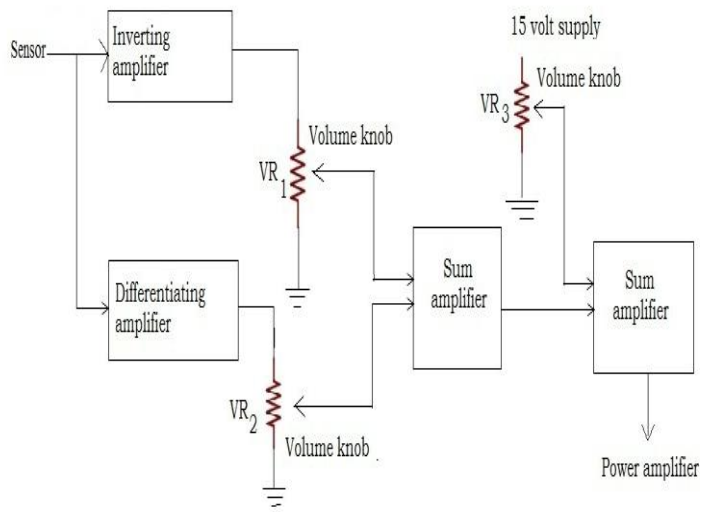

Fig.3: Block diagram of PD controller for maglev system.

PD controller can be implemented by any of the followings, such as DSP, PLC, microcontroller and analog circuit. Here the controller is designed based on analog circuit with 'Op-Amp' as shown in Fig.3. The feedback from the sensor is inverted to boost up the voltage, V_{CE} when the object comes close to the sensor. The output is then passed through a proportional circuit to lift the object and a derivative circuit to dampen the vibration. After that the output from these two circuits is summed in another circuit and combined with an offset power supply. To amplify the output voltage two bi-polar junction transistors (BJT, BD135) are used to increase the base current of BJT (BC458). So the collector gain of transistor (BC458) is increased and the power input to electromagnet is also amplified.

4. Experimental setup

A basic model of single-degree-of-freedom motion magnetic levitation system using PD controller is shown in Fig 4. The setup consists of a wooden structure which has three stands. One rectangular and two circular plates are set one over another. The middle plate clamps the sensor and the upper plate holds the electromagnet. The height and diameter of the total setup is 23 mm and 11.5 mm. Each stand is round shaped and of 2 mm diameter. Both the top and middle plates are fixed. The sensor is clamped such that its position can be varied by two identical hexagonal nuts when needed. A controller board is attached to the base plate. Wood is being used for low cost and simplicity

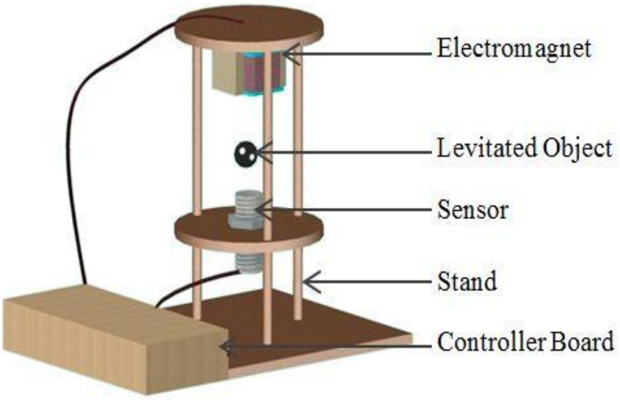

Fig.4: Schematic diagram of the developed system

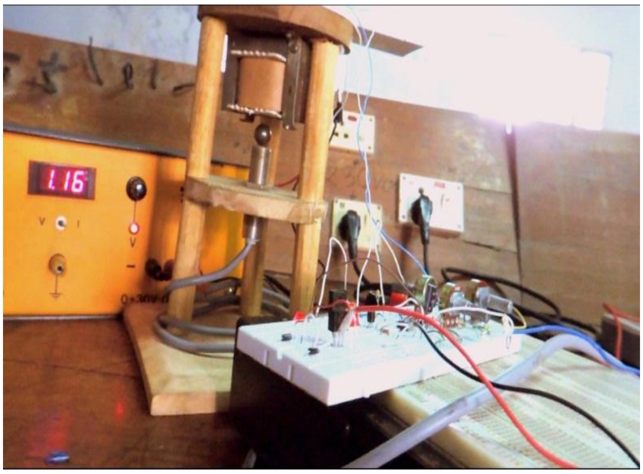

Fig.5: Photograph of the Maglev system

The basic components of the maglev system include a sensor, an actuator (the electro-magnet), and a controller. The sensor is an inductive displacement sensor with an oscillator which generates AC, induction coil that generates changing magnetic field, and a current sensor. The sensor produces a voltage, v_s that is proportional to the position of the levitated object x (Fig.1), with a gain, say β, which is linear around the operating point, $v_s = x\beta$ The electromagnet has a winding of 330 turns of 0.644 mm copper wire in 7.6 mm diameter silicon core. It is able to sustain up to 5 Ampere current. The magnetic force developed is given by $F= Ni$.
Where N is the number of turns and i is the current flow through the winding. Desired force is produced by controlling the current. A steel ball of 1.4 cm diameter and 13.6 gm mass is used as a levitated object. The photograph of the magnetic levitation system is presented in Fig. 5.

5. Experimental results

A stable maglev system is developed using a PD controller. At the same time, the system is suitably controlled by a PD controller. From the experiment, it is observed that the power consumption of the system is approximately 20-22 watt.

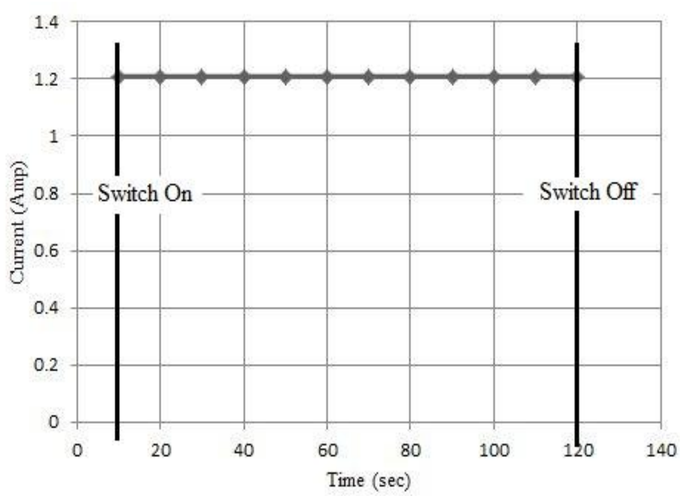

Fig.6: Current vs. time

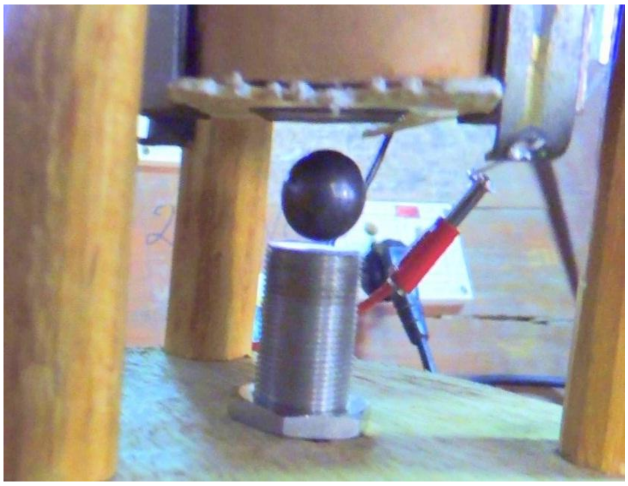

Fig.7: Realization of maglev system

Fig.8: Typical experimental data

It is considerably low regarding the stability of the system. Fig.6 shows the consumed current by the system versus time. It is seen from the figure that the system is stable using PD controller.
The levitation is shown in Fig.7 where the object is levitated at a stable position. Figure.8 represents a typical

experimental data of voltage and current gain. Further accuracy of the system can be easily obtained by using precise equipment.

5.1 Sensitivity of the system

The sensitiveness of the system is how the system reacts while functioning under rough condition. The system shows a high notch of sensitiveness with the variation of the distances of the floating object. The output voltages remain in a consistent trend over the various set of data collected while operation is enduring. Figure 9 represent that the curve shows almost linear behavior from 2.5 mm to 5 mm. So the minimum gap between the sensor and the ball should be maintained within the above value. Therefore the reaction of the system when some ferromagnetic material is brought closer to the sensing element is clearly evident by the curve.

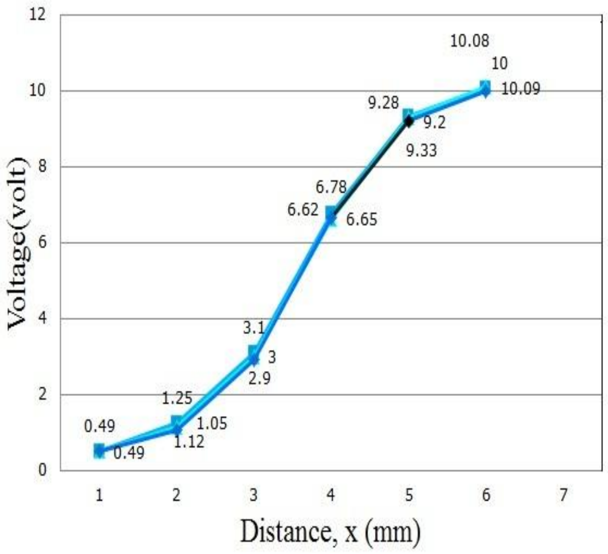

Fig. 9: Voltage vs. Distance curve

6. CONCLUSION

The maglev system is designed and fabricated. The levitation is successfully established. The single degree-of-freedom motion of the levitated object is controlled manually by tuning the controller gain. The position of the ball can be made stable and varied by regulating the current flow. But with a little energy consumption the stability of the levitated object is confirmed. The successful accomplishment of this venture reveals the feasibility of magnetic levitation for miscellaneous applications. At the same time, supporting loads (levitation), magnetic actuators can apply precision force, dampen vibration and move objects at precise distances all with no contact between surfaces and without friction. In punitive surroundings (corrosive, vacuum, etc.) where conventional mechanical or hydraulic actuators may not survive, this type of actuation can be used readily. It can also operate in extreme clean environments without the threat of generating pollutants from its use. Magnetic actuation can be made a sensible and cost effective solution to numerous engineering problems by using the persistent drift of smaller and cheaper semiconductor devices incorporated with low-cost and low-complexity. Further the maglev system can be developed by adapting microcontroller to the control circuit. The use of microcontroller can make the system more precise and economic. It can also enhance the performance of the control system. The power consumption of the control system can be reduced by using permanent magnet. This system can be made more economical by implementing solar power.

7. REFERENCES

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8. NOMENCLATURE

Symbol	Meaning	Unit
i	Control current	(Amp)
L	Inductance	(H)
m	Mass	(gm)
x	Control distance	(mm)