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# Development of a Solar Magnetic Suspension System Using PD Controller

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## Abstract

*This paper presents the development of an active magnetic levitation system using electromagnet and position sensor. The developed system is capable to levitate a 15 gm steel ball associated with vertical translation i.e. single-degree-of-freedom motion (SDOF). PD controller has been implemented for the system. The ball can levitate 1 mm to 3mm in the vertical direction. The developed active feedback control system of the PD controller mainly suspends the mass of the object as well as control its motion. It consumes very low power and can be operated by both solar power and electric power. An eddy current sensor is used for its simplicity and low cost. The controller circuit has been designed in such a way that it would be able to precisely control the electromagnetic field to stabilize the position of the levitated object. Some experimental results are presented of the developed system.*

Keywords: Magnetic Levitation, Vertical Translation, Feedback Control, Magnetic Suspension, Electromagnet.

## 1. Introduction

Magnetic levitation, maglev, or magnetic suspension is a method by which an object is suspended with no support other than magnetic fields. Magnetic force is used to counteract the effects of the gravitational acceleration and any other acceleration. It is one of the best recent technologies. It has no physical contact between the motion object and stable part of the system. So there is no friction and wear in such type of technique [1 – 3].

The researches on magnetic levitation and control have become a widespread and significant attention recently due to their broad and potential applications in many advanced fields including semiconductor manufacturing precision measurement, space vehicle and many other applications [3 – 8]. For steady state levitation, it is equally important to minimize several kinds of force such as force due to acceleration (disturbance), damping force, gravity force, magnetic force and feedback control force. An active feedback control system has been an unquestionable choice for magnetic levitation system.

Feedback control is the best way to take care of a magnetic levitation system but it does not guaranteed robustness in the presence of modeling error and disturbances. However, in active feedback control system using PID, LQR, $H\infty$, PI control, repetitive control, pole placement are extensively used [8, 9]. The advanced technology of semiconductor devices and high density recording precise magnetic levitation systems has increasingly been demanded. Most of the active feedback control systems used high performance sensors, such as servo-type accelerometers. Large amount of control current is consumed to drive the actuators for those high performance sensors [9 – 12]. The system is very expensive for that reason. This is one of the most obstacles to expand the field of application of an active control system.

To overcome this, an active feedback control magnetic levitation system has been developed using PD controller powered by solar energy [6, 12]. PD controller has been used for its simplicity. Considering the object to move in vertical translation i.e. single-degree-of-freedom motion (SDOF), the controller has been made enable for this motion. An eddy current sensor is used for displacement feedback. The control current is very low for this system using eddy current sensor. Solar power has been used to drive the actuator in the steady- state. The steady state condition has been realized in this control, in which the repulsive or attractive force produced by the electromagnet balance the weight of the suspended mass.

Therefore, the objective of this paper is to introduce an active feedback controlled magnetic levitation system using solar power.

## 2. Basic Magnetic Suspension System

It has been a viable choice of active magnetic suspension system for many industrial machines and devices as a noncontact, lubrication free support [19, 20]. It would become an essential machine element from high speed rotating machines to the development of precision vibration isolation system. By using electromagnet and/or permanent magnet magnetic suspension can be achieved. Electromagnet or permanent magnet in the magnetic suspension system causes flux to circulate in a magnetic circuit and magnetic fields can be generated by moving charges or current. The attractive force of an electromagnet, F can be expressed approximately as

$$F = \mathbf{K}\frac{I^2}{\partial^2} \tag{1}$$

Where K: attractive force coefficient for electromagnet, I: coil current and $\delta$ : mean gap between electromagnet and the suspended object. Each variable is given by the sum of a fixed component, which determines its operating point and a variable component. Such

$$I = I_0 + i \tag{2}$$

$$\delta = D_0 - x \tag{3}$$

Where $I_0$: bias current, i: coil current in the electromagnet, $D_0$: nominal gap and x: displacement of the suspended object.

### 2.1 Zero Power Controlled Magnetic Suspension System

In order to reduce power consumption and continuous power supply, a position sensor is employed in the suspension system to avoid providing bias current. The position sensor is used for the purpose of providing bias flux [21]. This control realizes the steady states in which the electromagnet coil current converges to zero and the attractive force produced by the position sensor balances the weight of the suspended object. Attractive force of the electromagnet, F can be written as

$$F = k\frac{(I_0 + i)^2}{(D_0 - x)^2} \tag{4}$$

Where the bias current, $I_0$ is modified to equivalent current in the steady-state condition provided by the fixed current and nominal gap, $D_0$ is modified to the nominal air gap in the steady-state condition. For zero-power control system, the control current of the electromagnet is converged to zero to satisfy the following equilibrium condition:

$$F_e = mg \tag{5}$$

And the equation of motion of the suspension system can be written as

$$m\ddot{x} = F - mg \tag{6}$$

From eqs. (5) and (6)

$$m\ddot{x} = k_i i + k_s(x + p_2 x^2 + p_3 x^3 + ....) \tag{7}$$

This is the fundamental equation for describing the motion of the suspended object.

### 2.2 Model

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 and is moving only in the vertical translational direction as shown in Fig. 1. The equation of motion is given by

$$m\ddot{x} = k_s x + k_i i + w \tag{8}$$

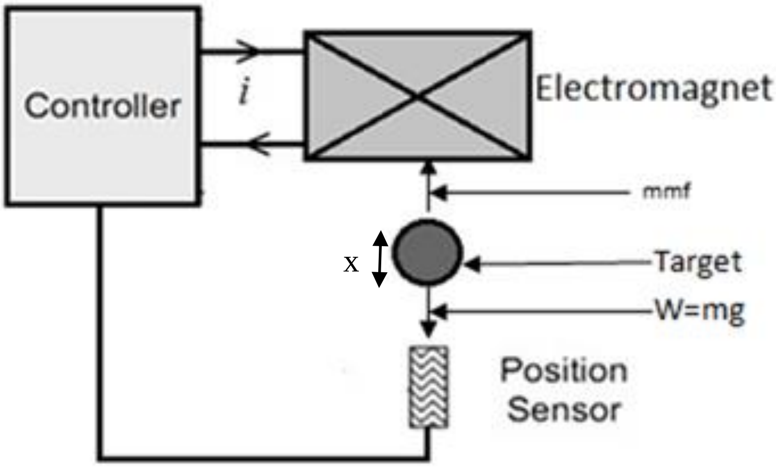


**Fig. 1.** Basic model of a magnetic levitation system

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 Eq.(8) becomes

$$X(s) = \frac{1}{ms^2 - k}(k_1 I(s) + W(s)) \tag{9}$$

$$X(s) = \frac{1}{s^2 - a_0}(b_0 I(s) + d_0 W(s)) \tag{10}$$

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

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

$$X(s) = -\frac{I(s)}{(P_d + P_v s)} \tag{12}$$

$$\frac{X(s)}{I(s)} = -\frac{1}{(P_d + P_v s)} \tag{13}$$

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.(10) and Eq.(11)

$$\frac{I(s)}{W(s)} = \frac{-d_0(P_d + P_v s)}{(s^2 + P_d b_0 + P_v s b_0 - a_0)} \tag{14}$$

Again putting the value of, *I(s)* from Eq.(7) in Eq.(4)

$$\frac{X(s)}{W(s)} = \frac{d_0}{s^2 + P_d b_0 + s P_v b_0 - a_0} \tag{15}$$

To estimate the stiffness for direct disturbance, the direct disturbance, W(s), on the isolation table is considered to be stepwise, that is

$$W(s) = \frac{F_0}{s} \quad (F_0\text{: constant}) \tag{16}$$

The block diagram of the maglev system using PD controller is represented in Fig. 2

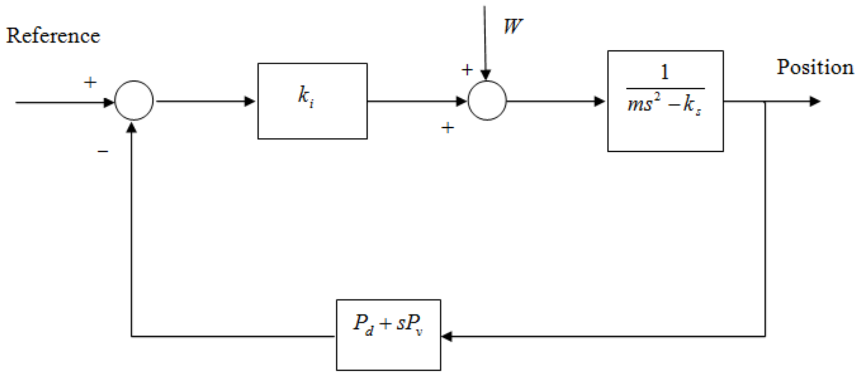


**Fig. 2.** Block diagram of a magnetic levitation system with PD controller

From eqs. (14) & (16)

$$\lim_{t \to \infty} i(t) = \lim_{s \to 0} I(s) = 0 \tag{17}$$

The negative sign in the right sight indicates that the new equilibrium position is in the direction opposite to the applied force. It means that the system realizes negative stiffness. If that stiffness of any suspension is denoted by k. The stiffness of the zero power controlled magnetic suspension is, therefore negative and given by

$$K = -k_s \tag{18}$$

## 3. Experimental Setup

The developed model of single-degree-of-freedom motion magnetic levitation system using PD controller is shown in Fig. 3. The setup consists of a Stainless steel 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 30 cm and 10 cm. A controller board is attached to the base plate. The basic components of the maglev system include a sensor, an actuator (the electro-magnet), and a controller.

## 4. System Realization

A stable maglev system is developed using a PD controller. At the same time, the system is suitably controlled by the controller. From the experiment, it is observed that the power consumption of the system is approximately 20-22 watt. It is considerably low regarding the stability of the system. Fig. 5 shows the consumed current by the system versus time. It is seen from Fig. 4 that the system is stable using PD controller.

**Fig. 3**. Photograph of the developed Maglev system

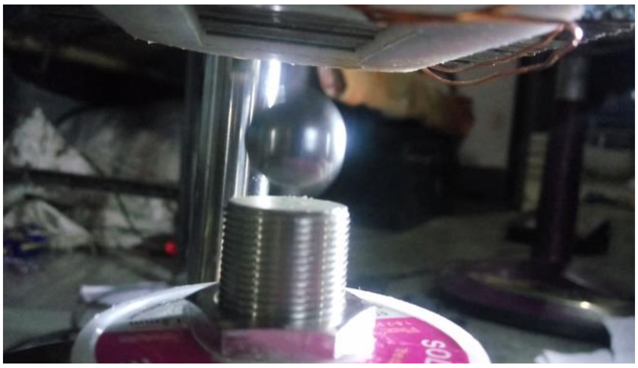

**Fig. 4.** Realization of maglev system.

## 5. Experimental Result

Different experimental works are conducted to examine the attributes of the developed system. The existing setup can control the motion in the vertical direction only. The vibration of the object is further reduced by

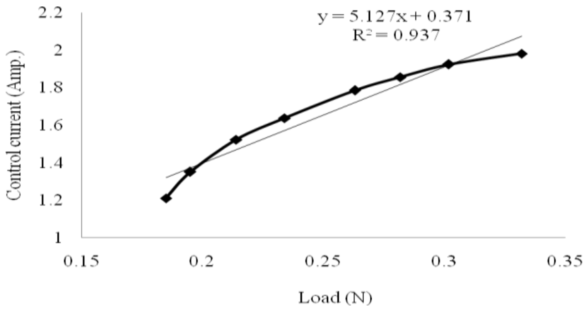


**Fig. 5.** Variation of control current at different loads.

aligning the object perfectly with the sensor and the electromagnet. Fig. 5 depicts the increase in control current with the increase in load because more current have to pass through the electromagnet coil to keep higher loaded object in levitated position.

## 6. Conclusions

A basic magnetic levitation system has been developed using solar power source i.e., renewable energy. It requires very little amount of power to operate the system. To reduce reflection, the steel ball was colored white and made its surface rough. The developed system was statically and dynamically stable. The steel ball can be levitated only in vertical direction. At stable position, the air gap of the steel ball from the electromagnet and the position sensor was 1 mm to 3 mm. Furthermore, the power consumption of the sensor can be reduced by using optical sensor instead of eddy current sensor.

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