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PID control for one dimensional magnetic levitation

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Abstract. This paper presents the one dimensional small magnetic levitation experiment, as fundamental to float an object with the mass is lighter than 100g using basic of electromagnetic theory. The object needs to install a neodymium magnet inside. A solenoid coil is made from a No.25 copper wire entwine 800 rounds of a 1.5×7 cm^2 rod steel. The control algorithm is written in Labview with PID control feature. The object's positions are detected by a Hall Effect Sensor, sending a signal to control system by NI PCI-6251. The result shows that it can levitate the object weight between 36g and 53 g, corresponding to the voltage between 9V and 11V at the distance 2±0.2 cm. from the solenoid coil. The range of proportional, integral and derivative gains is about 10-100, 100-1000 and 0.05 to 0.15 respectively. Both simulation and real tests showed a clear consistency and a good system performance.

1. Introduction

The Electromagnet levitation technique has been popularly used in transport and industrial fields in recent decades, such as high-speed levitation trains, frictionless magnetic bearings, and high precision control in semiconductor manufacturing. Due to its high efficiency and good environmental orientation, the application of this technique is extensively growing. For instance, the attitude of a small-sized satellite can be efficiently controlled by using the electromagnetic force generated from the interaction between the on- board (controlled) electrical field and the earth magnetic field. The principle of electromagnetic levitation can be illustrated by a simple one-dimensional system. By controlling the electric current flowing through coils around a solenoid, a conductible object, e.g., an iron or a steel ball, can be possibly levitated by the generated magnetic force. However, to develop a reliable and efficient levitation system is far from easy with respect to the fact that this kind of system is featured by complexity, nonlinearities, natural instability and large electromagnetic uncertainties. This paper will demonstrate the development of PID control for a one dimensional magnetic levitation system for floating an object at desired position from solenoid coil. The maglev is using a basic of electromagnetic principle for generating electromagnetic force which counteracts the gravitation force on object.

2. System Model and Controller Design

The equation describing the motion of a ferrous object within an electromagnetically generated field is nonlinear. The variables of interest are the distance between the object and magnet, x; and current in the electromagnet coil, i. The force generated by the electromagnet, f, is given by

$$f = -\frac{i^2}{2}\frac{dL}{dx} \tag{1}$$

where L is the total inductance in the system that depend on a position of object. The total inductance is given by

$$L = L_1 + \frac{L_0 x_0}{x} \tag{2}$$

where L_1 is the inductance of coil without object, and L_0 is the additional inductance contributed by object.

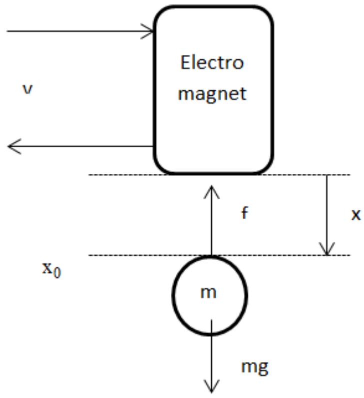

Figure 1 Free body diagram

take (2) into (1), will get

$$f = \frac{L_0 x_0}{2}\left(\frac{i}{x}\right)^2 \tag{3}$$

let $C = \frac{L_0 x_0}{2}$, then the final force equation becomes

$$f = C\left(\frac{i}{x}\right)^2 \tag{4}$$

The actual value of C is determined experimentally.

To produce a tractable model, linearizing the force equation to get

$$f = C\left(\frac{I_0}{X_0}\right)^2 + \left(\frac{2CI_0}{X_0^{\,2}}\right)i - \left(\frac{2CI_0^{\,2}}{X_0^{\,3}}\right)x \tag{5}$$

where I_0 and X_0 are the equilibrium values for these variable and i and x are understood to be incremental variables. At equilibrium, the magnetic force on the object equals the gravitational force like this

$$C\left(\frac{I_0}{X_0}\right)^2 = mg \tag{6}$$

For the electrical equation, assuming that the electromagnet coil is adequately modeled as a series resistor-inductor combination. The voltage-current relationship for the coil is

$$v = Ri + L_1\frac{di}{dt} \tag{7}$$

Take force equation into Newton's equation as

$$m\ddot{x} = mg - f = \left(\frac{2CI_0{}^2}{X_0{}^3}\right)x - \left(\frac{2CI_0}{X_0{}^2}\right)i \tag{8}$$

where m is the mass of the object. Choosing the Hall Effect sensor as a simple gain element at the desired position

$$v_s = \beta x \tag{9}$$

Where v_s is the sensor output voltage and β is relationship between the object position and sensor output voltage.

The mathematical model of this system can be written in a Laplace transform. The overall transfer function between the coil input voltage and the sensor output voltage can be expressed as

$$\frac{V_s(s)}{V(s)} = \frac{-2\beta CI_0/mL_1X_0{}^2}{(s+R/L_1)(s^2-2CI_0{}^2/mX_0{}^3)} \tag{10}$$

Table 1 System parameter

Parameter	Value
Object mass (m)	36 g
Resistance (R)	6 Ohm
Inductance (L_1)	26.568 mH
Equilibrium current (I_0)	1.5 A
Equilibrium position (X_0)	0.02 m
System constant (C)	6.27 x 10^{-5} Nm^2/A^2
Sensor gain (β)	6.75 V/m

Controller Design

A PID Control is a continuous signal controller that is widely used in the industries. The advantage of PID control is it's easily turning gain by trial and error, and get satisfactory gains. PID controller can be separated as 'P' is a proportional gain, 'I' is an Integral gain and 'D' is a derivative gain. The figure 2 shows the schematic diagram of the closed loop PID control.

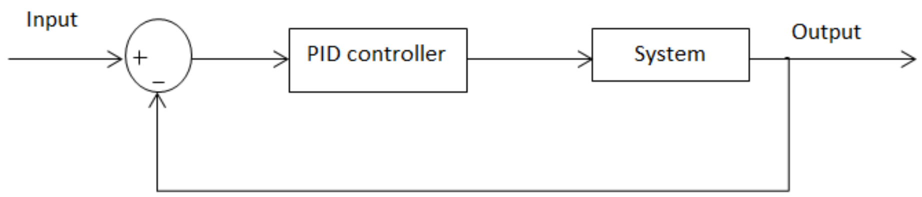

Figure 2 Schematic of PID control

PID control law can be represented by (11)

$$y(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \tag{11}$$

Where k_p = proportional gain, k_i = Integral gain, k_d = derivative gain, and $e(t)$ = Error

3. Experiment Results

The control algorithm is implemented in the National Instruments (NI) LabVIEW environment for Windows XP. A Data Acquisition (DAQ) card typed NI PCI-6251is used as the interface between the physical hardware and the LabVIEW software. The process of PID tuning can be summarized as follows.

1. Set up an experimental equipment and devices.
2. Create a control panel in LabVIEW.
3. Initializing the PID gain.
4. Tuning the range of PID gain that can stabilize the system.
5. Finding the limit of object weight for each supply voltage.

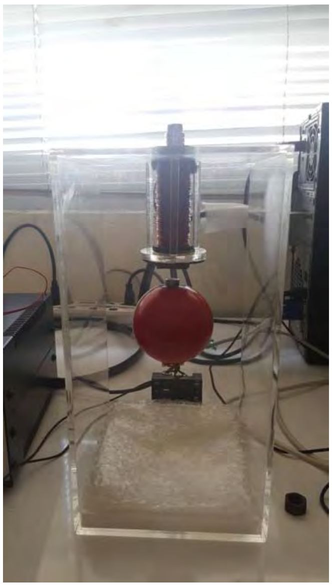

Figure 3 Experimental devices

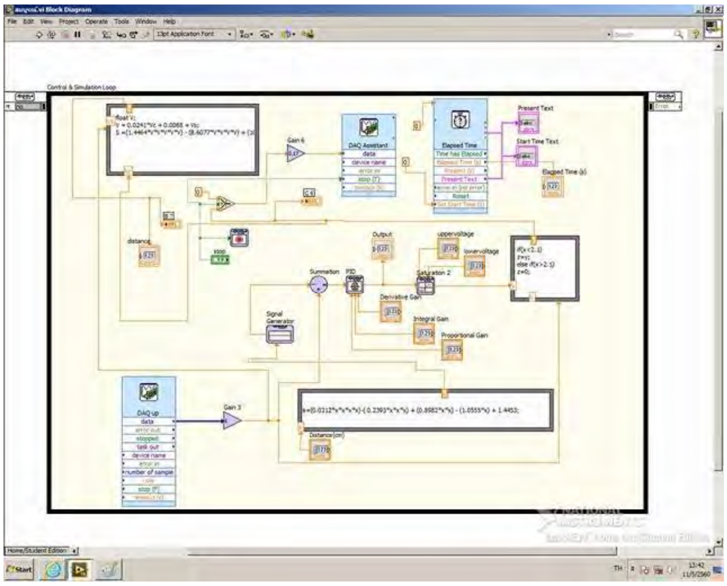

Figure 4 LabVIEW Block diagram

By using the obtained nonlinear model, an analog PID controller is developed and manually tuned based on the Ziegler-Nichols PID tuning method. After tuning the PID gain until the system goes stable. The range of PID gain can be summarized as follow

Table 2 Range of PID gain

Properties	Range
k_p	10-100
k_i	≤1000
k_d	0.05 – 0.15

After knowing the range of controller parameters, one can find a limit of object weight corresponding to the supply voltage.

Table 3 Weight limit

Supply voltage(V)	Weight (g)
9	36
9.5	42
10	45
10.5	48
11	50

From table 3, one can draw conclusion that the levitation weight proportionally varies to the supply voltage which limited by the power supply unit.

The controller is implemented in the LabVIEW program and tested with the physical setup. One test result based on the same set of set-points as for simulation. It can be observed that in principle the controlled physical system has quite similar performance as the simulation model. However, it is also obvious that the controlled physical system has much shorter response time and much larger overshot and oscillation compared with the simulated system performance. The reasons for these deviations could be explained in the following perspectives:

- Imprecise sensor measurement. The Hall Effect Sensor is very sensitive to light disturbances.
- Imprecise sampling rates of DAQ card and PID computation due to the real-time problem of Windows XP operating system. This could cause synchronization problems in data acquisition and control computation.
- the approximation of system constant. For example, in a strict sense, System constant (C) should be displacement dependent. However, we assume it is always constant due to simplicity.

4. Conclusion

The modeling and control of a one dimensional magnetic levitation system with a permanent magnet object is investigated. The entire system model is derived based on the electromagnetic theory and afterward system coefficients are identified through designed experiments. The developed model is validated through performance comparison of the closed-loop model and the controlled physical system.
The PID control is chosen as the control structure at this stage regarding the fact: (1) it is simple and require few computation resources; (2) The developed PID controllers only need the position information, with no need for the current measurement and speed estimation, the developed controllers are implemented in the LabVIEW environment based on a PC running Windows XP. The real-time issues are managed by additional programs. Both simulation and real tests showed a clear consistency and a good system performance.

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