Controlled Position Navigation of Single Degree Magnetic Levitation

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Abstract—A permanent magnet is levitated following the electromagnetic suspension principle using the attractive magnetic force of a wire-wound electromagnet with a hall-effect sensor for position feedback. Taking the hall-effect voltage as an analog parameter and feedback signal to the microcontroller, the strength of the electromagnet is controlled by adjusting the current using the Pulse Width Modulation technique in order to levitate the permanent magnet. The stability of the levitated magnet is enhanced by the use of PID algorithm in the embedded system. Use of Laplace transform for simplification of differential equations and Taylor series for the linearization of system function supports the mathematical computation required for the levitation. Furthermore, by making the feedback signal from hall-effect sensor dependent only on the magnetic field of levitating magnet, an advancement in levitation phenomenon is achieved that aids the levitation with a greater flexibility of changing the position of the levitating magnet along the gravitational axis within a specified range.

Keywords—Magnetic Levitation (Maglev), PID, Pulse Width Modulation (PWM), MATLAB, Electromagnet

I. INTRODUCTION

Electromagnetic levitation has been the topic of interest to researchers and engineers for quite a time now. This contactless moving system has a wide range of applications ranging from the maglev train to maglev suspension and many more. As permanent magnet provides little to no method of controlling the flux, electromagnet can be a valuable asset in such areas. But the major problem is to provide a steady flow of current to a precisely calibrated electromagnetic system such that the levitating magnet is capable of resisting the gravitational pull and levitate. A position feedback system with PWM mechanism can aid the levitation process in terms of supplying the appropriate amount of current to the electromagnet through respective power electronics circuit.

Since the levitation phenomenon is inherently unstable system, a well-designed PID compensation system can lead it to a greatest stability. Appropriate calibration of PID values is an essence for the stable levitation. By taking the analog reading of feedback transducer continuously in a constant loop time and implementing the PID loop accordingly can support the levitation with the flexibility of changing the position of levitating magnet within a specified range.

This paper depicts about the mathematical modelling, software simulation, 3D simulation and real life hardware implementation of magnetic levitation with position control.

II. MATHEMATICAL MODELLING

For an electromagnet with resistance $R$, inductance $L$, time constant $\tau$ and current $i$ flowing through it, the expression for voltage is:

$$v = i \times R + L \frac{di}{dt}$$

Using Laplace transform, the transfer function is:

$$\frac{I(s)}{V(s)} = \frac{1}{\tau s + 1}$$
For the proposed system,
\[ R = 1.9 \, \Omega, \quad L = 5.63 \, mH, \quad \tau = \frac{L}{R} = 0.002963 \]

\[ I(s) = \frac{0.5263}{0.001963s + 1} \]

According to [5], the electromagnetic force is given as:
\[ F_e = K_f \times \left( \frac{d}{d_{ss}} \right)^2 \]

where,
- \( K_f \) = magnetic force constant in (N. \ m^2)/A^2
- \( d \) = distance between electromagnet and levitating magnet
- \( i \) = current flowing through electromagnet

For steady state condition, electromagnetic force is equal to the gravitational force which is shown as:
\[ K_f \times \left( \frac{d}{d_{ss}} \right)^2 = mg \]

\[ d_{ss} = \frac{\sqrt{mg/K_f}}{2} \]

where, \( d_{ss} \) = Steady state distance
\( iss \) = Steady state current

Then,
\[ \Delta i = i(t) - iss \]
\[ \Delta d = d(t) - d_{ss} \]
\[ m \frac{d^2 x}{dt^2} = K_f \left( \frac{iss + \Delta i}{dss + \Delta d} \right) - mg \]

Linearizing the above function using Taylor Series about \( \Delta i = 0 \) \( \Delta d = 0 \)

\[ \frac{d^2 x}{dt^2} = \frac{2Kf \times iss^2}{d^3 m} - \frac{2Kf \times iss}{d^2 m} i \]

\[ s^2 X(s) = \frac{2Kf \times iss^2}{d^3 m} \times X(s) - \frac{2Kf \times iss}{d^2 m} \times I(s) \]

\[ \frac{X(s)}{I(s)} = \frac{\frac{2Kf \times iss}{d^2 m}}{s^2 - \frac{2Kf \times iss^2}{d^2 m}} \]

In the proposed system,
\[ K_f = 1.97 \times 10^{-4} (N. \ m^2)/A^2 \]
\[ m = 30 \times 10^{-3} \, kg \]
\[ A = 0.000314 \, m^2 \]
\[ iss = 0.185 \, A \]
\[ d_{ss} = 1.5 \, cm \]

\[ X(s) = \frac{10.798}{s^2 - 133.18} \]

So, overall transfer function of the proposed system is shown in Fig. 1,

**III. SOFTWARE SIMULATION**

Electromagnetic Levitation can be simulated in MATLAB/Simulink software for the analysis of the system to the closest approach of real life hardware implementation. MATLAB simulation was performed proposed maglev system.
The MATLAB/Simulink simulation mainly comprised of three sections/blocks:

1. Force Scaling: This block mainly comprises of an input of set-point and an output of attractive Electromagnetic force. It is responsible for producing necessary attractive electromagnetic force with respect to the distance between the levitating object and electromagnet. As the levitating object moves apart from electromagnet, the attractive electromagnetic force increases and vice versa.

2. Force Block: This block behaves as the filter for the system to manipulate the electromagnetic force in order to make the neodymium magnet levitate with great stability. It uses the force supplied by the Force Scaling block with a condition such that levitation is achieved. When the instantaneous position is greater than set-point then the force is decreased and reduced to zero in minimal time and similarly when the position is less than set-point then the force increases in order to attract the levitating object which ultimately results in levitation phenomenon.

3. PID controller: It enhances the stabilization in levitation phenomenon.

The PID controller is easy to design and very effective way for the stabilization of the system. The PID controller of the proposed system is shown below in Fig. 2,

![Fig. 2: PID Controller](image)

For the effective 3D visualization of the levitation system, 3D simulation can be performed in MATLAB using Virtual Reality Toolbox as shown below in Fig. 3,

![Fig. 3: VR Model of Electromagnetic Levitation System](image)

Along with the 3D visualization, Graphical analysis can also be performed for different position responses of the levitation system during the real time simulation as:

The position response of the proposed system for a set point 7, without fine tuning is shown below in Fig. 4,

![Fig. 4: Position response of system without fine tuning of PID](image)

The position response of the proposed system for a set point 7, with fine tuning is shown below in Fig. 5,
As this paper mainly focuses on control of position navigation, it can be achieved using an input transducer like potentiometer to feed the position as input to the system and system responses accordingly which can be visualized in VR toolbox in real time.

The position response of the proposed system for a variable set-point (7-6), with fine tuning is shown below in Fig. 6,

The position response of system with fine PID tuning

The overall setup of the proposed magnetic levitation system is shown below in Fig. 7,

Fig. 6: Position response of variable set-point with fine PID tuning

The hardware implementation

The system comprises of an electromagnet, levitating magnet (neodymium), hall-effect sensor for position feedback, H-Bridge to supply the appropriate amount of current to electromagnet governing PWM technique and a ATMEGA32 microcontroller for the programming purpose.

In the proposed system, the hall sensor is placed just below the electromagnet. The hall sensor receives change in magnetic field from both the electromagnet and levitating magnet. So the hall sensor should to be made independent of electromagnet’s field such that position feedback is dependent only in change in magnetic field of levitating magnet. So for it, the hall sensor’s analog value is taken at the OFF period of PWM duty cycle where the current in electromagnet is approximately zero. This makes analog value of hall value taken at the frequency of 5KHZ and independent of electromagnet’s magnetic field. For the levitation phenomenon the instantaneous hall value is compared to the given set point and thus obtained error is fed to the PID algorithm which generates the required PWM signal to drive the electromagnet

Fig. 7: Electromagnetic Levitation

PWM is the technique used to generate analogue signals from a digital device like a microcontroller unit. The microcontroller Atmega32 has 3 timers:
TIMER0, TIMER1 and TIMER2 and two types of PWM: fast PWM and Phase correct PWM. In the proposed system, timers are set as: TIMER0 at 1KHZ, TIMER1 at 5KHZ and TIMER2 at 2KHZ in fast PWM mode and used them to generate PWM signals for PID loop time, driving electromagnet and taking analog value for position change respectively.

The PID algorithm holds the following equation:

\[ y(t) = kp * \text{error} + \int ki * \text{error} * dt + kd * \frac{d(kd \text{error})}{dt} \]

The above equation can be executed in following steps:

- \( kp \text{error} = \text{Input Hall value} - \text{Set point} \)
- \( ki \text{error} += kp \text{error} \)
- \( kd \text{error} = \text{Input Hall value} - \text{Last Input Hall Value} \)
- \( \text{Output} = kp * kp \text{error} + ki * ki \text{error} + kd * kd \text{error} \)
- \( \text{Last Input Hall Value} = \text{Input Hall value} \)

where, \( kp, ki \) and \( kd \) are the Proportional, Integral and Derivative constants.

By fine tuning of PID constants and using input transducer to change the set point can lead to a stable magnetic levitation with control of changing the position.

V. CONCLUSION

This paper shows the overall process for the stable magnetic levitation supporting the flexibility of changing the position of levitating magnet in gravitational axis. Definite timing of taking the analog reading of input transducers, proper control of current through electromagnet and PID implementation with fine tuning, are the essences of levitation phenomenon. Further work will focus on extending the flexibility of levitation system to change position in 2D and 3D.

REFERENCES