Electromagnetic Levitation with a Low-cost Hall Effect Sensor

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ABSTRACT: This paper presents the implementation of magnetic force control for magnetic levitation systems using flux density measurements. Previous levitation systems usually adopted inductive (Eddy current) sensors to measure the airgap between the electromagnet and the guideway. However, inductive gap sensors are rather expensive and the increased system cost makes it difficult to utilize magnetic levitation in industrial areas. Therefore, low-cost Hall effect sensors are used instead of gap sensors to estimate the airgap in this study. The magnet coil current is measured along with the flux density. Then, the airgap is estimated from two signals analytically and numerically. The force equation is used for the analytic solution, and nonlinear curve fitting and principal component analysis are used to obtain the numerical solution. We compared both results and finally applied them to levitate a U-shaped electromagnet, which was built for the experiments.

1 INTRODUCTION

Recently, magnetic levitation system technology is used in many industry areas. Especially, manufacturers of LCD or semiconductor are interested in the levitation system for the clean room application. Generally, dusts occur from the friction of machines. However, the magnetic levitation system makes no dust during its operation because it is a non-contact system. So, the magnetic levitation system can be a good alternative of the conventional conveyor system for the clean room system.

In this paper, a new maglev levitation system is made for experiments. It is a one-DOF system together with an electromagnet and a permanent magnet, and the levitation can be done only by the force of permanent magnets minimizing power consumption.

A magnetically levitation system using the flux density measurement is introduced. Levitation systems usually have used gap sensors to measure the airgap between the electromagnet and the guideway. However, in general inductive gap sensors are rather expensive Therefore, it is necessary to consider a low-cost Hall effect sensor instead of an expensive gap sensor to estimate the air gap.

In this paper, Hall effect sensors are used to measure the flux density which is generated by the current of magnet coils. Then, the air gap is estimated from two signals analytically and numerically.

The force equation is used for analytic solution, and nonlinear curve fitting and principal component analysis are used to obtain the numerical solution. Some experimental results are given to show the stability of the levitation.

2 ELECTROMAGNETIC MODELING

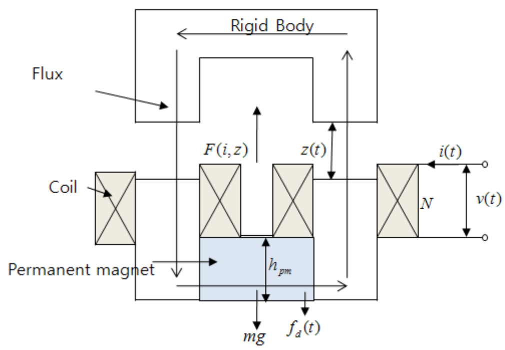


Figure 1. Cross-sectional view of the electromagnet.

To reduce power consumption, a hybrid-type magnet, that is the combined form of an electromagnet and a permanent magnet, is used the hybrid-type. Figure 1 shows the cross-sectional view of the electromagnet. The permanent magnet is attached in the bottom of the U-shaped ferromagnetic core. Electromagnetic coils are wound around the ferromagnetic core. The magnetic flux flows in the direction of the arrow. Levitation force $F(i,z)$, gravity force (mg) and disturbance $f_d(t)$ are shown in Figure 1. The total levitation force is the sum of forces by the permanent magnet and the electromagnet. [1]

The electromagnet is designed to support a 70kg weight including the weight of the electromagnet. Table 1 shows major specifications of the designed electromagnet.

Table 1. Specifications of the designed levitation electromagnet.

Items	Value	Items	Value
Dim.	150×20×60 (L×W×H ㎣)	Initial gap	5mm
Total weight	7.6kg	Nom. gap	3mm
Max. current	±10A	Lev. weight	71.34kg (@ 0A, gap=3mm)

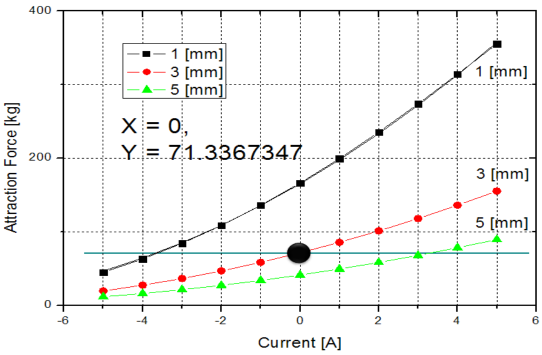


Figure 2. Levitation force vs. coil current.

Figure 2 shows the characteristic of the electromagnet. Gaps less than 5mm can be controlled by -5A~5A current.

3 GAP ESTIMATION USING HALL SENSORS

To control the magnetic levitation system, Hall sensors as well as current sensors are used. The basic characteristic of the Hall sensor is shown in Table 2.

Table 2. Specifications of the Hall sensor.

	Hall sensor		Hall sensor
Corporation	Melexis	Sensitivity	2.6~210(mV/mT)
Part NO.	MLX90251	Linearity error	0.2 %
Programmable	O	Output voltage range	0~5 (V)

Table 3 shows measured voltage values of the Hall sensor according to gap and current variations. The Hall sensor has an internal amplifier and is programmed with Rough gain 0, Fine gain 800, and Inverted slope 2.

Table 3. Obtained flux density voltage by the Hall sensor.

(mm) A	2	3	4	5
7	0.420	1.297	1.863	2.284
5	0.895	1.690	2.196	2.575
3	1.372	2.084	2.536	2.865
1	1.860	2.482	2.875	3.160
0	2.105	2.683	3.038	3.310
-1	2.348	2.880	3.212	3.454
-3	2.841	3.272	3.547	3.752
-5	3.332	3.670	3.885	4.048
-7	3.833	4.075	4.229	4.346

To design a magnetic levitation system, related equations are introduced.

Table 3 shows a nonlinear behavior, so it is useful to change the nonlinear system to a linear system. As in the figure 1, if the body is rigid and there is no leakage flux, then the flux density B is as follows.

$$B = \frac{\phi_g}{A_g} = \frac{ai + H_{pm}}{bz + 1} \qquad (1)$$

where i is the current, z the gap, H_{pm} the residual flux density, A_g is the area of the pole. Coefficients a and b are as follows:

$$a = \frac{\mu_p \mu_o N}{h_{pm}} = \frac{1.05\mu_o N}{h_{pm}} \qquad (2)$$

$$b = \frac{2\mu_p}{h_{pm}} = 2\frac{1.05}{h_{pm}} \qquad (3)$$

h_{pm} is the length of the permanent magnet and is the same as the height of the permanent magnet. N is coil turns. μ_{pm} is a relative permeability of the permanent magnet . μ_o represents the permeability of the air. The attractive force F(t) in the air gap is affected by coils and permanent magnets. F(t) is expressed in the form of partial differentiation of the stored magnetic energy W (t) and gap.

$$F(t) = -\frac{\delta W(t)}{\delta z(t)} = \frac{A_g}{\mu_o} B(t)^2$$
$$= \frac{A_g}{\mu_o}\left\{\frac{ai(t) + H_{pm}}{bz(t) + 1}\right\}^2 \qquad (4)$$

Table 4. Specifications of the Hybrid-type Electromagnet.

Hybrid-type Electromagnet	Coil weight	3(kg)
	Coil Turn	720
	permanent magnet	NdFeB
	Residual flux density	1.23(T)
	Air permeability	$4\pi\times10^{-7}$
	Core Width	20(mm)
	Core length	150(mm)
	hpm	20(mm)
	Total Weight	7.6(kg)

Table 4 shows the specifications of the hybrid-type electromagnet. Using the designed parameters of the maglev system, the linear system of the maglev system can be obtained analytically. However, there is a slight difference between actual measurement data and estimated values.

In this paper, the measured values are used to obtain the relevant equation. [2]

$$B = ai + b\frac{1}{z} + cz + d\frac{1}{z} + e \qquad (5)$$

The equation (5) is one possible candidate of polynomial interpolations.

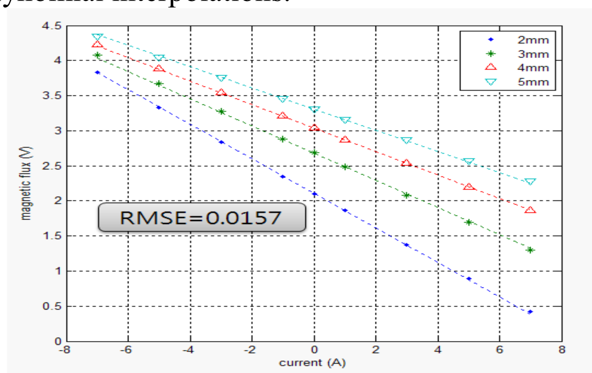


Figure 3. Interpolation with five terms.

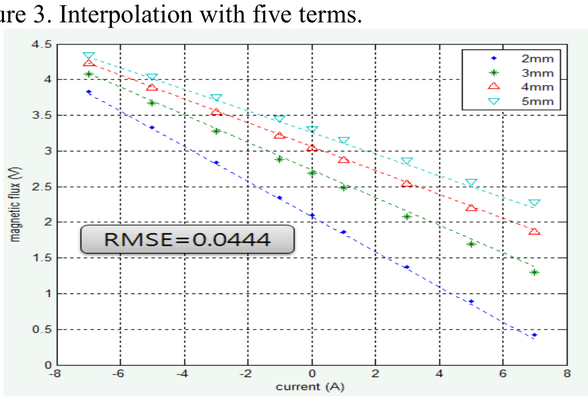


Figure 4. Interpolation with four temrs.

Table 5. Coefficients of interpolations.

	5-terms	4-terms
a	-0.0881	-0.8814
b	-0.3162	-0.3162
c	0.1424	0
d	-2.5754	-3.9254
e	3.1142	4.0459

Table 5 shows the obtained coefficients with four and five terms. Figure.3 depicts the estimation result of the interpolation using five terms, and the estimation Root Mean Squared Error (RMSE) is 0.0157. Figure.4 draws the estimation result of the interpolation with four terms, and the estimation error is 0.0444. Comparing two cases, both cases give sufficiently small estimation errors. Therefore, the interpolation with four terms was used for the sake of simplicity. Then, the gap is estimated from the inverse function of the equation (5). However, this estimation involves in the root and the division operations, which requires more computations and even causes division-by-zero.

Another estimation method is to derive the estimation equation from the measured data directly. Through the least-squares method (LSM), the gap can be estimated by the measured coil current and the measured magnetic flux density.

$$\begin{aligned} z &= c_1 i + c_2 i^2 + c_3 i^3 + c_4 i^4 \\ &+ c_5 iB + c_6 B^2 + c_7 B^3 + c_8 B^4 \\ &+ c_9 iB + c_{10} \end{aligned} \qquad (6)$$

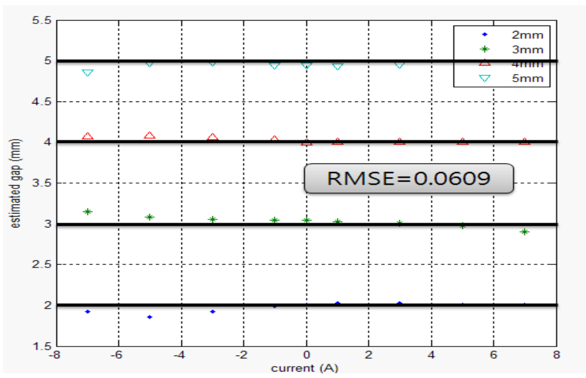


Figure 5. Result of quadratic polynomial interpolation by LSM (without PCA).

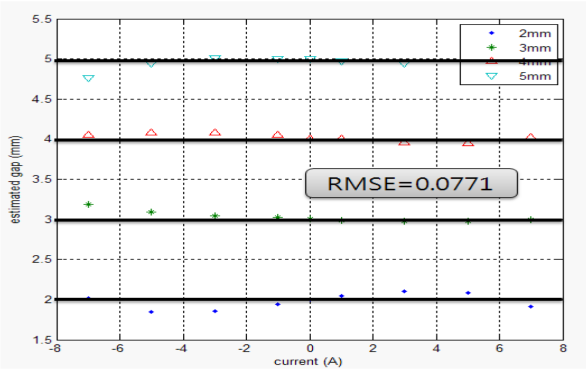


Figure 6. Result of cubic polynomial interpolation by LSM (without PCA).

Figure 5 and Figure 6 are gap estimation results using the equation (6). Figure 5 and 6 use the quadratic and cubic polynomials, respectively.

Principal Component Analysis (PCA) can be used to choose significant terms among all candidate terms in (6). During the PCA process, Singular Value Decomposition (SVD) is widely used because this method has the advantage of numerical stability.

Table 6. Result of SVD.

	s (singular value)
c1	5671.784
c2	1152.443
c3	262.459
c4	29.083
c5	25.696
c6	13.320
c7	2.419
c8	0.434
c9	0.115
c10	0

Table 6 summarizes the result of SVD. Generally, elements associated with singular values within one percent of the largest one are used in the estimation. However, the six elements are selected for more precise control.

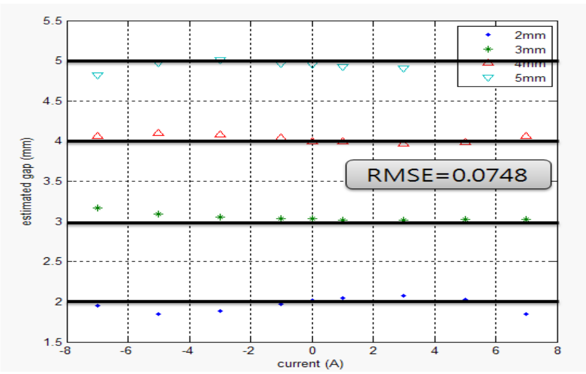


Figure 7. Result of quadratic polynomial interpolation by LSM (with PCA).

Figure 7 shows the result of the quadratic polynomial interpolation applying principal component analysis.

Table 7. Coefficients of interpolations (LSM).

	Quadratic	Cubic	Quadratic (with PCA)
c1	-0.0488	-0.0743	0
c2	-0.0027	-0.0057	-0.0069
c3	0.0016	0.0014	0.0017
c4	-8.9592	0	-0.000042
c5	-1.7795	-0.1961	0
c6	1.1490	-0.2211	0
c7	-0.2571	0.1740	0.0549
c8	0.0449	0	0.0146
c9	0.1857	0.1981	0.1675
c10	2.1838	1.7646	1.2163

Table 7 represents the used coefficients of direct estimations, using the least squares coefficient. With PCA, the unused terms (c1, c5, and c6) in the equation (6) can be recognized.

4 EXPERIMENTAL RESULTS

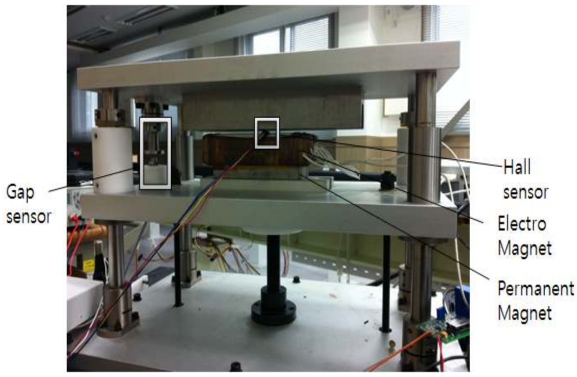


Figure 8. 1-DOF Hybrid-type electromagnet levitation system.

Figure8 shows a magnetic levitation system which has one electromagnet. A Hall sensor is attached in the middle of the magnet. When the current is fed to electromagnet, the gap is estimated from the current sensor and the attached Hall sensor. A gap sensor is also installed to compare the estimation result of the Hall sensor. Using MATLAB Simulink, the levitation controller was designed based on phase lead-lag compensator.

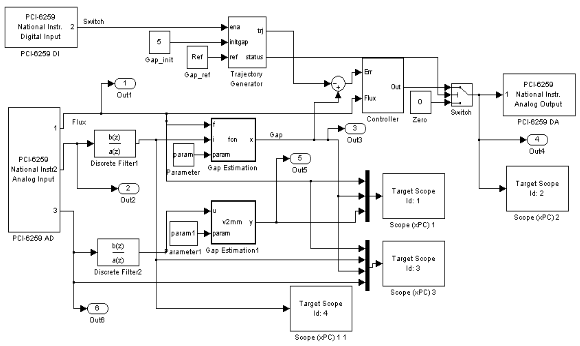
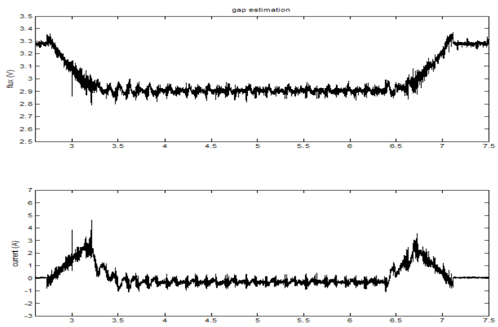
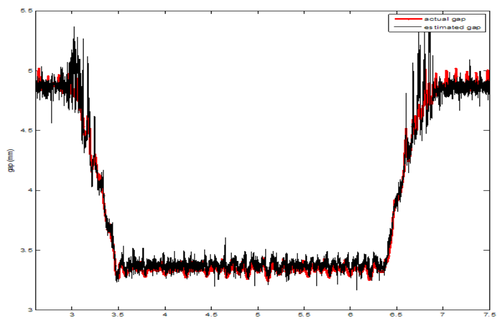


Figure 9. Simulink model of the levitation control.

Through the repetitive processes, Figure.9 shows the final block diagram of the levitation controller.



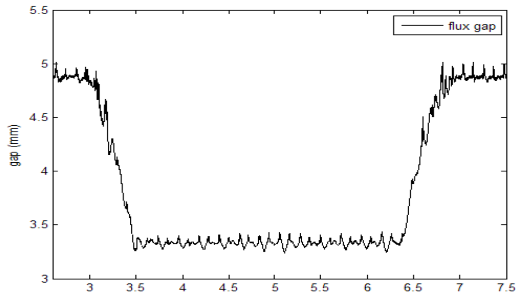
(a) Flux density and current.



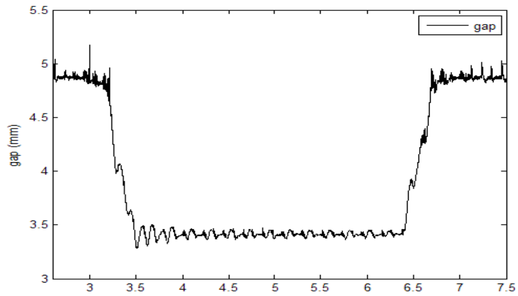
(b) Measured gap and estimated gap.

Figure 10. Gap estimation with the Hall sensor.

In Figure 10, the levitation result is given. Signals from the Hall sensor and the current sensor are used to estimate the gap which is fed to the controller. The upper figure shows the measured flux and current. The lower figure displays the measured gap and the estimated gap. As shown in the figure, flux and current have high-frequency components, and they are also observed in the estimated gap. It is confirmed that the measured gap and the estimated gap are almost same.



(a) Estimated gap by the Hall sensor.



(b) Estimated gap by the gap sensor

Figure 11. Experimented levitation results

Figure 11 shows the levitation results using the gap sensor and the Hall sensor, respectively. In (a), the estimation gap from the Hall sensor is used for control. And in (b), the measured gap of the gap sensor is used for control. The results with gap sensor and Hall sensor are similar, and the gap is tracking the reference gap in both cases.

5 CONCLUSIONS

In this paper, alternative sensor of the gap sensor in the levitation system was studied. Same electromagnets, control method, and gains are used as in the actual maglev carrier system. In other words, experiment is carried out in the same conditions as possible.

As shown in experiments, results of the gap sensor and the Hall sensor are similar. Also, the settling time and stability are similar during the levitation.

As a result, the Hall sensor is a good alternative for the levitation system. In the future, study about a system with 4 electromagnets will be continued. Also, the stabilization of signal processing method will be studied.

6 REFERENCES

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