Air-gap Control for Superconducting-Hybrid Magnetic Levitation Systems via Linear Matrix Inequality Optimization

Chang Hyun Kim[1], Kyoung Jin Joo[2], and Ju Lee[2]

[1] Department of Electricity, Vision College of Jeonju, Jeonju, Republic of Korea

[2] Department of Electrical Engineering, Hanyang University, Seoul, Republic of Korea

Wed-Af-Po3.07-11[102]

I. Introduction

▣ Using electric magnetic suspension, magnetic levitation (MagLev) systems have been widely applied in various industries for their great characteristics such as non-contact, noise free, cleanness, high speed transportation, and so on.

▣ Especially, superconducting-hybrid electro-magnetic suspension (SH-EMS) is increasingly receiving attention in high-speed transportation because of their properties to compensate the instability of MagLev systems.

▣ The advantages of the proposed method

1) Easiness to design and understand the control method because of transforming the conventional controller to modern optimal controller.

2) Consideration for robust performances and stability to deal with the propulsion disturbance force by FEM analysis and the proposed inner feedback compensator.

3) Applicability of additional input-to-output properties, inherited by the two degree-of-freedom approach

II. Structure and FEM Analysis of SH-EMS

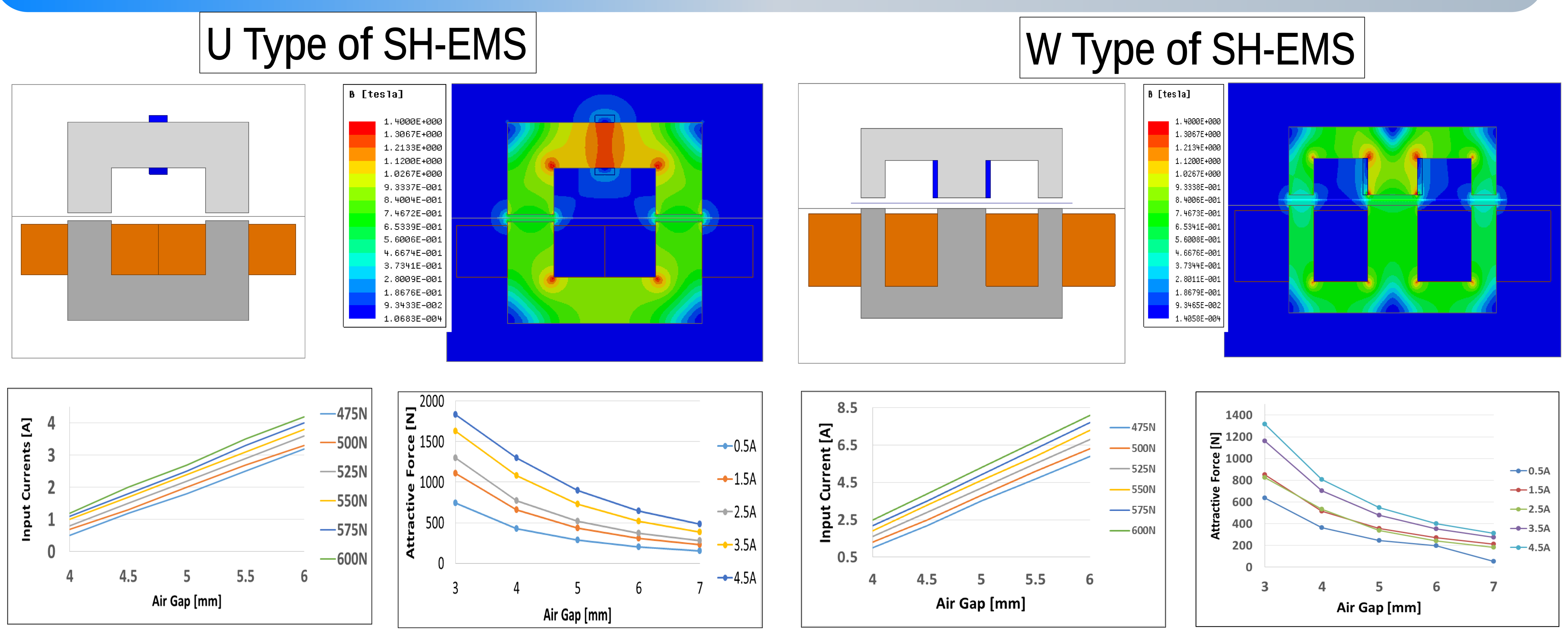


Fig. 1. Construction and Electromagnetic Field Computation of SH-EMS

Table 1. Parameters of the MagLev Systems

Parameter	Description	Value
N	Coil Turns	730 turns
N_{SC}	Superconductor Coil Turns	100 turns
A	Pole Area of Coil	0.005 (m^2)
g	Gravitational Constant	9.80665 (m/s^2)
M	Mass of the Levitated Vehicle	50 (kg)
e(t)	Applied Voltage	(Volt)
i(t)	Current of Coil	(Amp)
I_{SC}	Current of Superconductor Coil	3.6 (Amp)
z(t)	Gap Position	(m)
z_{ref}	Desired Gap Reference	0.005 (m)

SH-EMS Model Equation

$$\dot{x}_1(t) = x_2(t)$$

$$\dot{x}_2(t) = g - \frac{\mu_0 A}{4M}\left(\frac{N_{SC}I_{SC} + Ni(t)}{x_1(t) + z_{ref}}\right)^2 + \frac{1}{M}F_d(t)$$

$x_1(t)$: the gap position error $z(t) - z_{ref}$

$F_d(t)$: the disturbance force.

Linearized SH-EMS Model

$$\dot{x}(t) = Ax(t) + B_w F_d(t) + B_u u(t)$$

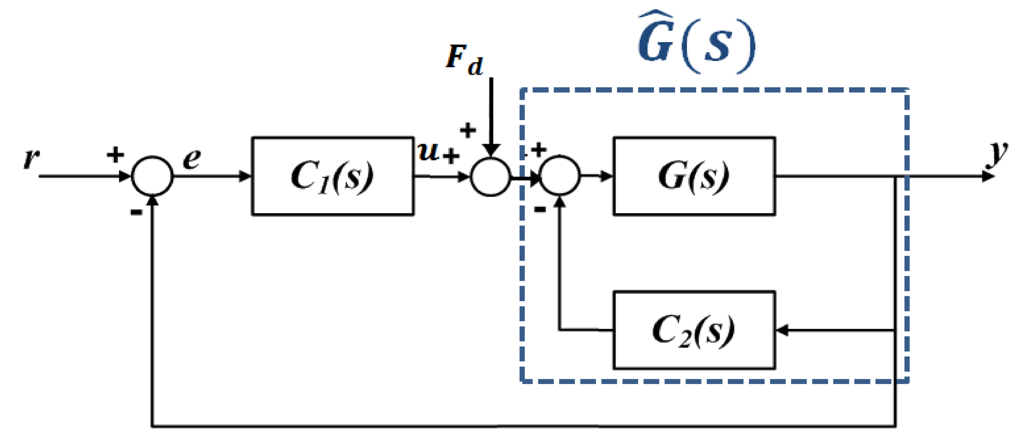
$$y(t) = x_1(t)$$

where $x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$, $A = \begin{bmatrix} 0 & 1 \\ \frac{1}{M}\frac{\mu_0 A(N_{SC}^2 I_{SC}^2 + N^2 i_0^2)}{2z_0^3} & 0 \end{bmatrix}$,

$B_u = \begin{bmatrix} 0 \\ -\frac{1}{M}\frac{\mu_0 N^2 A}{2}\frac{i_0}{z_0^2} \end{bmatrix}$, $B_w = \begin{bmatrix} 0 \\ \frac{1}{M} \end{bmatrix}$,

$x_1(t) = z(t) - z_0,\ x_2(t) = \dot{z}(t) - \dot{z}_0,\ u(t) = i(t) - i_0$

III. Proposed Robust Control



$$C_1(s) = \frac{1+\beta-\lambda}{1+\beta}K_{p1} + \frac{1-\lambda}{\lambda}K_{d1}s + \frac{K_{p1}}{K_{i1}}\frac{1}{s}$$

$$C_2(s) = \frac{\lambda}{1+\beta}K_{p1} + K_{d1}s$$

$$\dot{x}_c(t) = \begin{bmatrix} 0 & 1 \quad 0 \\ 0 & [A - B_u K_2] \\ 0 & \end{bmatrix} x_c(t) - \begin{bmatrix} 0_{1\times3} \\ B_u K_1 \end{bmatrix} x_c(t) + \begin{bmatrix} 0_{1\times3} \\ B_u K_1 \end{bmatrix} r_c(t) + \begin{bmatrix} 0_{1\times1} \\ B_w \end{bmatrix} F_d(t)$$

$$x_c(t) = \begin{bmatrix} \int x(t) \\ x(t) \\ \frac{dx(t)}{dt} \end{bmatrix}, r_c(t) = \begin{bmatrix} \int r(t) \\ r(t) \\ \frac{dr(t)}{dt} \end{bmatrix}, K_1 = \begin{bmatrix} K_{p1} \\ K_{i1} \\ K_{d1} \end{bmatrix}^T, K_2 = [K_p \quad K_d]$$

convex optimization problem

minimize $\phi_{obj}(\lambda) = b_1\alpha_{OS} + b_2\beta_{rt} + b_3\gamma_{st}$

subject to $\alpha_{OS1}\lambda + \alpha_{OS2}(1-\lambda) \le \alpha_{desire}$,

$\beta_{rt1}\lambda + \beta_{rt2}(1-\lambda) \le \beta_{desire}$,

$\gamma_{st1}\lambda + \gamma_{st2}(1-\lambda) \le \gamma_{desire}$

bounded to $0 \le \lambda \le 1$

where b_1, b_3, b_3, are weighting factors to regulate the importance of the system specifications. And $\alpha_{desire}, \beta_{desire}$, and γ_{desire} are the desired time domain specifications such as overshoot, rise time, and settling time. $\alpha_{OS1}, \beta_{rt1}, \gamma_{st1}, \alpha_{OS2}, \beta_{rt2}$, and γ_{st2} are the systems responses, obtained from the design performance of the envelop curve.

IV. Simulation Results

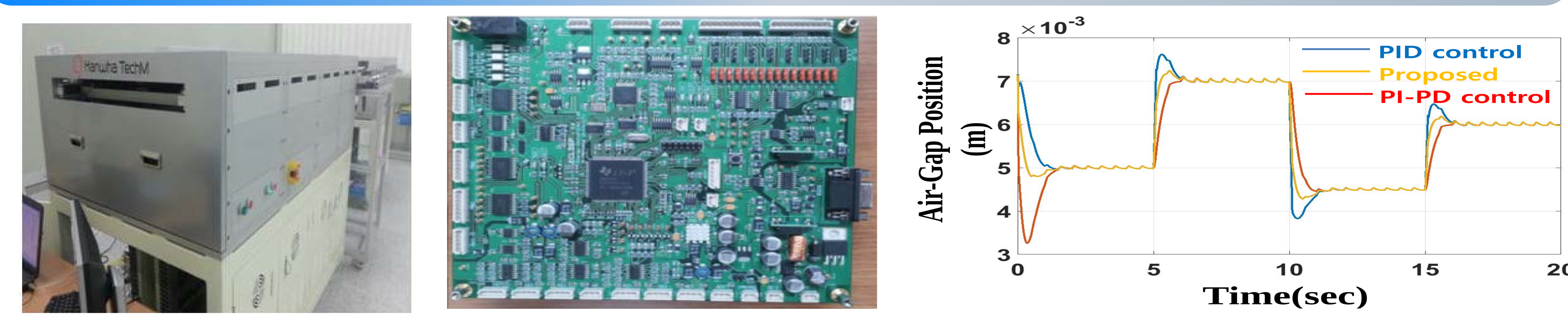


Fig. 2. (a) OLED Maglev Machine (b) Input Current (c) Comparison of Proposed Control

V. Conclusions

▣ The novel robust air-gap controller with inner feedback loop for SH-MagLev systems is proposed, formulating a convex combination set to envelope the performance limitation satisfying the time-domain specifications.

▣ The derived LMI approach to design the proposed controller is applicable to consider extended performances with respect to the input-output relation, using LMI optimization.

Presented at 25th International Conference on Magnet Technology, 2017 Aug. 27 – Sep. 1, RAI-Amsterdam; Session: E4-Levitaion and Magnetic Bearing; Contribution I.D. number: 704