

# Electromagnetic Levitation Control of Contactless Linear Synchronous Drive for Flexible Vertical Transportation

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## Keywords

electromagnetic levitation, elevator, Halbach magnet array, linear synchronous motor

## Abstract

Ropeless elevators have been studied for efficient transportation in high buildings. This system can achieve higher capacity and flexibility of transportation than conventional elevators can. To realize such a system, authors have proposed contactless transportation system which has coreless linear synchronous motor for driving, and four U-shaped hybrid electromagnets for posture control. These electromagnets are also used as field magnets when the cage moves in horizontal direction. In this paper, authors explain the outline of proposed system, results of levitation tests and future works for its vertical and horizontal drive control.

## 1 Introduction

Population density of urban cities in Asian countries like Tokyo, Shang-Hai *etc.*, is extremely large and such cities have the problem of insufficient space. So, increase of high buildings is expected, and high performance of vertical transportation system will be required. However, conventional elevator using wire can drive only one cage in one shaft, and elevators occupy large space in buildings. It is principal obstacle for efficient use of space. For this reason, several Japanese construction companies and elevator manufactures researched about the possibility of the vertical linear drive [1] in early 1990's. According to the results, the most feasible method is a long stator-type linear synchronous motor, in which the moving cages have rare-earth strong permanent magnets as a magnetic field of the synchronous motor.

Authors have also reconsidered the concept, fundamental design and investigated operation method of such a system [2], and summarized as below:

1. For efficient space use and realization of large transportability, we aim to construct new elevator system whose cage moves both vertically and horizontally.
2. From the aspect of flexible movement of cage, we decided to construct elevator system without any mechanical contact.
3. According to the preceding research about the operation of ropeless elevator [2], required speed of cage for large transportability is relatively low. But in the case of horizontal movement, moving performance equivalent to vertical one is demanded.

## 2 Profile of proposed system

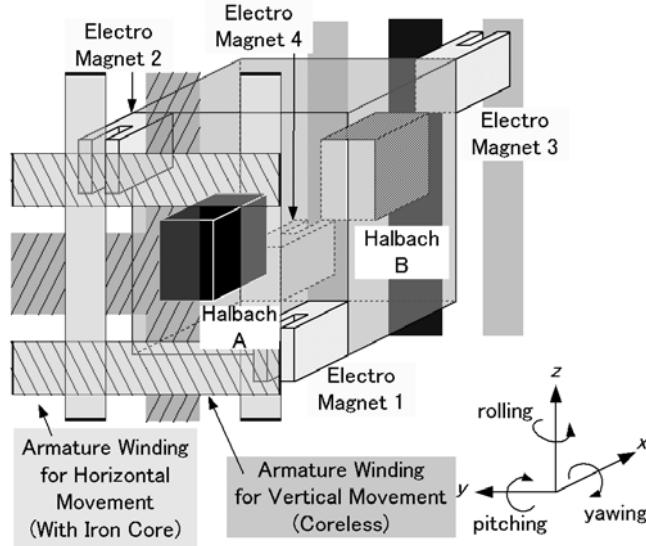
Our system consists of three component parts as below.

1. U-shaped hybrid electromagnets for posture control
2. LSM for vertical movement
3. LSM for horizontal movement

As a posture controlling system, four U-shaped electromagnets are attached in four vertex of the cage and LED gap sensors are attached in the other four vertex. Herewith, we can realize three-degree-of-freedom posture control. And they are also used as field magnets of LSM for horizontal movement.

Hoisting LSM is long stator type, and it has no armature core for avoiding strong normal force. And Halbach magnet array is used in field magnets. So, LSM can generate sufficient hoisting power without core, and also enables suppression of the ripple of hoisting force.

Fig.1 shows the entire structure of our proposed system.



**Fig. 1 Fundamental Structure of our proposed system**

### 3 Posture controlling system

#### 3.1 Basic principle of posture controlling

As above mentioned, posture controlling of cage is conducted by four U-shaped hybrid electromagnets. In the system shown in fig.1, hoisting LSM control the posture of  $z$  direction, and 4 U-shaped electromagnets operate 3-degree-of-freedom posture control, in  $x$  direction, pitching direction and rolling direction. Posture control needs coordinated control of 4 U-shaped electromagnets because they cannot generate repulsive force. In the proposed system, relation between the force generated by electromagnets and controlling force in respective direction is as below.

$$\begin{aligned}
 F_x &= -F_1 - F_2 + F_3 + F_4 \\
 T_p / L_z &= +F_1 - F_2 + F_3 - F_4 \\
 T_r / L_y &= -F_1 + F_2 + F_3 - F_4
 \end{aligned} \tag{1}$$

$F_1, F_2, F_3, F_4$  : Force generated by 4 U-shaped electromagnet respectively.

$F_x$  : Controlling power in  $x$  direction

$T_p, T_r$  : Controlling torque in pitching or rolling direction

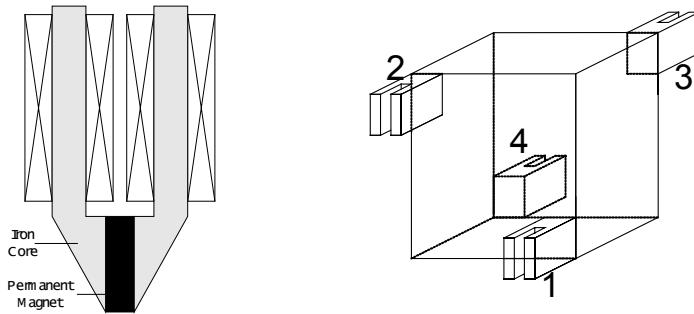
$L_y, L_z$  : Displacement of electromagnets in  $x$  or  $y$  direction from center of gravity of cage

And, allocated attractive forces are represented by equations below.

$$\begin{aligned}
 F_1 &= 0.5F_{\max} - F_x / 4 + T_p / 4L_z - T_r / 4L_y \\
 F_2 &= 0.5F_{\max} - F_x / 4 - T_p / 4L_z + T_r / 4L_y \\
 F_3 &= 0.5F_{\max} + F_x / 4 + T_p / 4L_z + T_r / 4L_y \\
 F_4 &= 0.5F_{\max} + F_x / 4 - T_p / 4L_z - T_r / 4L_y
 \end{aligned} \quad (2)$$

$F_{\max}$  : Maximum attractive force of actuator

Thus, 3-degree-of-freedom control is operated. Additionally, by using electromagnet and permanent magnet in combination, for generating attractive force  $0.5F_{\max}$  with zero controlling current, consumption of electric power can be reduced greatly and can enable control system easier. Fig.2 shows the structure of the U-shaped hybrid electromagnet used for posture controlling.



**Fig. 2 Structure of electromagnets and their layout**

### 3.2 Controlling method

Experiment of posture controlling is operated by two methods, I-PD controlling and state feedback control with observer, for the comparison of their performance.

First, attractive force of U-shaped hybrid electromagnet is represented as the equation below.

$$F = k \frac{(i + i_G)^2}{(g_a + G)^2} = k \frac{(i + i_G)^2}{g^2} \quad (3)$$

$i_G$  : Current equivalent value of magnetomotive force of permanent magnet

$G$  : Airgap equivalent value of permanent magnet and iron core of electromagnet

And conducting linearization of equation(3) around the nominal point  $i=0, g=g_0$ , we can represent attractive force as below.

$$F \cong F_0 - A\Delta g + Bi \quad (4)$$

$$\text{where, } F_0 = F \Big|_{i=0, g=g_0}, \quad A = -\frac{\partial F}{\partial g} \Big|_{i=0}, \quad B = \frac{\partial F}{\partial i} \Big|_{g=g_0}, \quad \Delta g = g - g_0$$

Here, we must pay attention to the existence of permanent magnet installed in U-shaped hybrid electromagnet. Without permanent magnets, the value of  $B$  in equation(4) becomes zero because attractive force of electromagnet is proportional to the square value of coil current. But by installing permanent magnets and moving nominal point, we can avoid above-mentioned problem and can design controller easily. Moreover, electrical energy consumption decreases because the  $F/I$  slope around

nominal point becomes large.

Fig. 3 shows the block diagram of controller of  $x$ -direction. Controlling of pitching direction and rolling direction is the same way.

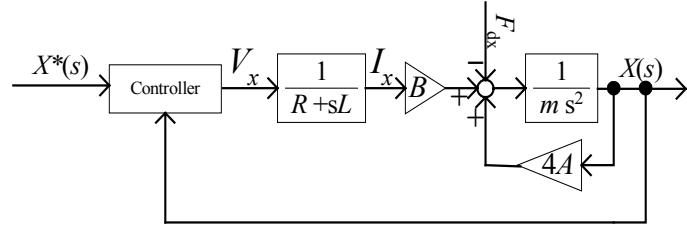


Fig.3 Linear Plant Model of Posture Controlling System (x-axis)

### 3.2.1 Designing of controller (I-PD)

I/O gain of I-PD controller is represented as below using the constants  $K_P$ ,  $K_I$ ,  $K_D$ .

$$\frac{X}{X^*} = \frac{K_I B}{m L s^4 + m R s^3 - (4 A L + K_D B) s^2 - (4 A R + B K_P) s + K_I B} \quad (5)$$

Comparing the denominator polynomial of equation(5) to Kessler standard form, we can decide three constants as below.

### 3.2.2 Designing of controller (state feedback)

Fig. 3 can represent like equation(6) using state equation.

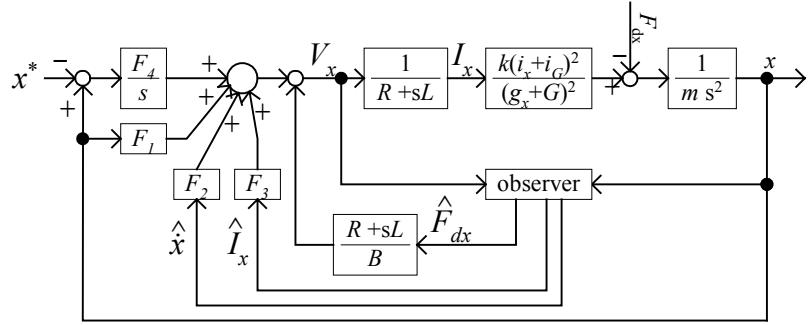
$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}e_x, y = \mathbf{C}\mathbf{x} \quad (6)$$

$$\text{where, } \mathbf{A} = \begin{pmatrix} 0 & 1 & 0 \\ 4A/m & 0 & B/m \\ 0 & 0 & -R/L \end{pmatrix}, \mathbf{x} = \begin{pmatrix} x \\ \dot{x} \\ i_x \end{pmatrix}, \mathbf{B} = (0 \ 0 \ 1/L)^T, \mathbf{C} = (1 \ 0 \ 0)$$

Here, we add the integral of displacement to state variable for removing the steady-state deviation. At this time, state equation is represented as below, and block diagram is expressed as fig. 4.

$$\dot{\mathbf{x}}' = \mathbf{A}'\mathbf{x}' + \mathbf{B}'e_x \quad (7)$$

$$\text{where, } \mathbf{A}' = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 4A/m & 0 & B/m & 0 \\ 0 & 0 & -R/L & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}, \mathbf{x}' = \begin{pmatrix} x \\ \dot{x} \\ i_x \\ \int x dt \end{pmatrix}, \mathbf{B}' = (0 \ 0 \ 1/L \ 0)^T$$



**Fig.4 Block Diagram of State Feedback Control**

And respective feedback gain can be calculated as follows.

If we let the feedback gain  $\mathbf{F} = (F_1, F_2, F_3, F_4)$ , characteristic polynomial can is as below.

$$|z\mathbf{I} - (\mathbf{A} + \mathbf{B}\mathbf{F})| = 0 \quad (8)$$

Comparing the left part of equation(8) to Kessler standard form, we can calculate respective feedback gains as follows.

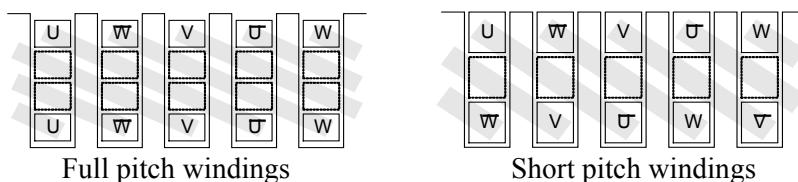
$$F_{1x} = -\frac{32AL}{B\tau} - \frac{64mL}{B\tau^3}, F_{2x} = -\frac{4AL}{B} - \frac{32mL}{\tau^2 B}, F_{3x} = R - \frac{8L}{\tau}, F_{4x} = -\frac{64mL}{B\tau^4} \quad (9)$$

And we adopted minimal order observer. Only gap length between iron core and electromagnet is measured, and other variables are calculated by observer. Observer is designed by Gopinath's method.

### 3.3 Vertical transport system

#### 3.3.1 Armature windings

In our proposed system, vertical driving is operated by Linear Synchronous Motor (LSM). For avoiding strong normal force, we adopted coreless armature. Moreover, for obtaining strong thrust and for decreasing thrust ripple, we adopted short pitch windings. Generally, short pitch windings is inferior to full pitch windings in the aspect of thrust, but fig.5 indicates that the space of slot occupied by copper is larger when we adopted short pitch windings. So, also from the aspect of the thrust value, it is valid to adopt short pitch windings.



**Fig.5 Difference of both windings**

#### 3.3.2 Field magnets

In field magnets, we adopted Halbach magnet array. Magnetic field generated by Halbach magnet array is shown in fig.6. Halbach magnet array generates strong and sinusoidal magnetic field on only one side. This array enables the reduction of thrust ripple and increase of thrust value. So, we can obtain

enough thrust value without armature core.

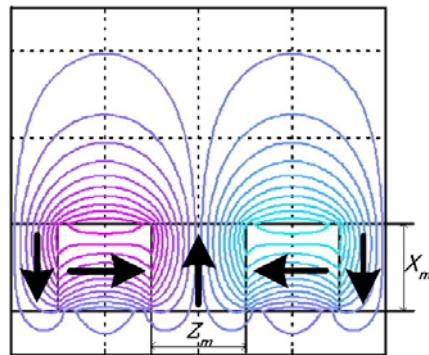


Fig.6 Magnetic field generated by Halbach magnet array

## 4 Result of experiment

We conducted the test of posture controlling using our prototype. Fig.7 shows the appearance of our prototype. In experiment, cage is stringed for posture controlling. For comparison, we conducted posture controlling by two different method, I-PD controlling and state feedback controlling.

Result of experiment is shown in fig.8. When  $t=10[s]$ , we change the commanded value from  $0[\text{mm}]$  to  $-0.5[\text{mm}]$ .

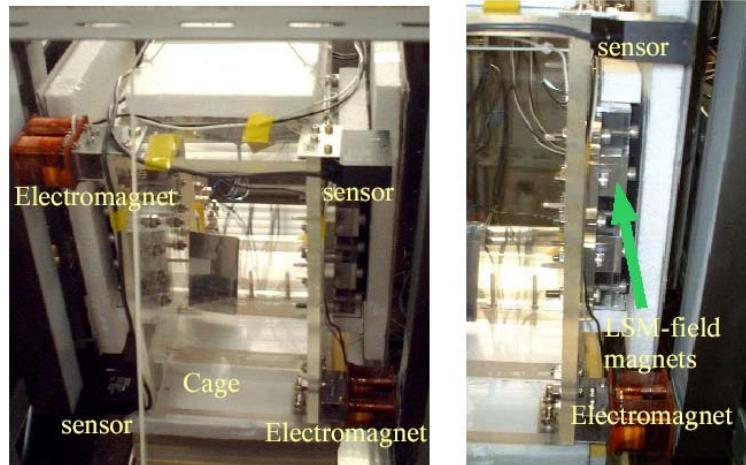


Fig.7 Appearance of our prototype

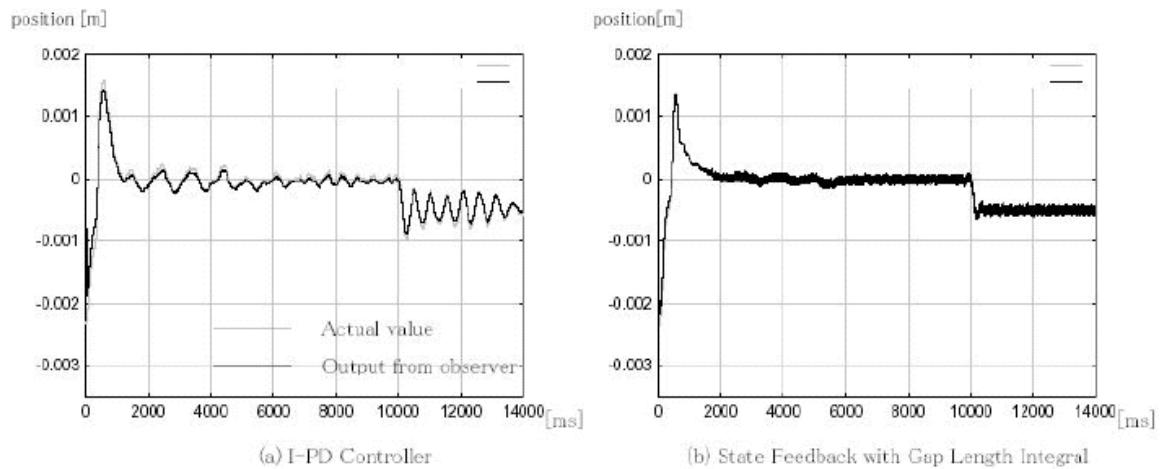


Fig.8 Posture controlling experimental results and the comparison of two different controllers.

## 5 Conclusion

In this paper, we proposed contactless vertical transport system with coreless LSM for vertical drive and four U-shaped electromagnets for posture controlling. And posture controlling in three directions,  $x$ -direction, pitching direction, yawing direction, by using both I-PD controller and state feedback controller. From the experiment result, vibration after reaching commanded position is lower when we adopted state feedback controller.

And our future works are to install the system for horizontal movement to prototype.

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