3 Degrees of Freedom Zero-Power Control for 4-pole Magnet Levitation System

Jiangheng LIU and Takafumi KOSEKI
Dept. of Electrical Engineering, School of Engineering,
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone: +81-3-5841-6791
Fax: +81-3-5800-5988
E-mail: liujh@sone.t.u-tokyo.ac.jp

Abstract

Electromagnetic suspension (EMS) has been widely used in the convey system today because of the various advantages in a practical use. U-type magnets are often used to generate the levitation force in the EMS system. A conventional electromagnet, however, can control only one degree of freedom. It cannot construct a levitation system solely by itself.

A 4-pole type yoke hybrid electromagnet is proposed instead of the usual U-type magnet and its magnetic levitation control is studied in the paper. The basic structure and characteristics of the proposed magnet are described first. The control system is designed. The zero-power control has been applied to minimize energy consumption. Furthermore, the voltage order type zero-power control method is proposed, that can realize zero-power levitation without current sensors.

Finally, the results of simulation and corresponding experiments have been presented.

Keywords:
3 degree-of-freedom, magnetic levitation, 4-pole type hybrid electromagnet, zero-power control, voltage order type zero-power control.

1 Introduction

The electromagnetic suspension technology (EMS), in which the attractive forces between electromagnets and ferromagnetic materials are utilized as levitation forces, has been widely used in the transport system and several industrial areas of industry. The EMS system has various advantages. Such as: it has little leakage flux, it can be used in the normal temperature, it can obtain the large attractive forces with compacted model, and so on [1].

U-shaped magnets are usually used in the EMS systems. This type of magnets can control only one degree-of-freedom (d.o.f.). Such a levitation system cannot be constructed with a single magnet. Multiple magnets should be arranged in a plane and controlled simultaneously in order to construct a system.

A 4-pole yoke combined type hybrid electromagnet is proposed in this paper for a simple and small levitation system that can be used in the flexible convey system. In addition, the zero-power control has been applied to minimize energy consumption. The levitated body can be suspended only by permanent magnet forces and the average currents of the electromagnets converge to zero by changing the levitation gap length according to the load mass.

The basic structure and characteristic of the novel 4-pole type hybrid electromagnet will be described at first, and the control method will be discussed in this paper in details.

2. 4-Pole Type Hybrid Electromagnet

2.1 Basic Structure

The proposed novel electromagnet has 4 poles combined through yokes. Each pole consists of a permanent magnet and a coil for controlled current as shown in Fig. 1.

2.2 The control method of magnetic levitation

The proposed magnet can obtain 3 d.o.f.: vertical direction gap $z$, inclination angle $\theta$ around $\varphi$ axis and angle $\varphi$ around $\theta$ axis respectively as shown in Fig. 2[2][3].

In Fig. 2, we can assume there are three virtual winding currents $i_0,j_0,i_0$, which are used to control the vertical direction $z$, inclination angle $\theta$ and inclination angle $\varphi$ respectively. The feedback control system is designed toward each d.o.f. independently. We can also derive the relationship between the vertical currents of each d.o.f. $i_0,j_0,i_0$ and the actual currents of each pole $i_1,i_2,j_3,i_4$.

Fig. 1 Basic structure of 4-pole type hybrid electromagnet

Fig. 2 Control method of magnetic levitation
\[ \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} = \begin{bmatrix} 1 & -1 & -1 \\ 1 & 1 & -1 \\ 1 & 1 & 1 \\ 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \end{bmatrix} \] (1)

### 2.3 The characteristics of 4-pole hybrid electromagnetic

Comparing with the usual U-type magnets, the proposed 4-pole type hybrid electromagnet has three characteristics [2][3].

- **It can be controlled in 3 d.o.f even only using one unit.**

  The 4-pole electromagnet has 4 magnetic circuits, as shown in Fig. 3, toward a ferromagnetic track with 1 constraint. It can be controlled in 3 d.o.f. using one unit simultaneously. It solely can fulfill the condition of complete levitation.

- **It can realize zero-power control.**

  The poles are composed by electromagnets and permanent magnets, and the flux of these two type magnets can be overlapped in the levitation gaps. So the levitation body can suspend only using permanent magnet forces, and the currents of the electromagnets converge to zero. This characteristic can minimize the energy consumption.

- **It can generate unbalanced attractive forces by tilting itself.**

  This magnet can generate different attractive forces among 4 poles by tilting the levitation body even at zero-power control mode. This unbalanced force can be used to compensate the unbalanced load. In this way, the zero-power control can be realized even with unbalanced load.

Because of these three main characteristics, this 4-pole type hybrid electromagnet can construct a compact miniaturize magnetic levitation system. It is very suitable for the flexible transport system.

### 3. Analysis of the Plant

The electromagnet is not stable in EMS without control. The feedback controller is designed based on the approximated linear model derived in this section. We assume as a plant model that a 4-pole electromagnet is levitated below a plane core track. Constants and variables used in this section are summarized as follows:

- \( \Phi \) Permeability of vacuum
- \( g \) Gravity acceleration
- \( \Delta \) Thickness of permanent magnets
- \( E_{PM} \) Magnetomotive force of permanent magnet
- \( S \) Area of pole
- \( N \) Number of turns
- \( m \) Mass of electromagnet
- \( J_0, J \) Moment of electromagnet
- \( i_z, i_d, i_0 \) Vertical currents of each d.o.f.
- \( i_{1,2,3,4} \) Actual currents of each pole.

We assume that:

- magnetic resistance of the core,
- saturation, hysteresis and eddy current, and
- flux leakage and fringing

can be disregarded for simplifying the analysis. And the approximated linear model of each d.o.f. is derived nearby the operating point \( (z_0,0,0) \) and \( (z,\theta,\phi) \equiv (i_z,i_d,0,0) \).

- **Vertical Direction Dynamics**

  The vertical motion is expressed as
  \[ m \ddot{z} = mg - f_z(z,i_z) \] (2)
  where the vertical attractive force \( f_z \) is:
  \[ f_z(z,i_z) = \frac{B^2}{2\mu_0} \cdot s \cdot 4 \]
  \[ = 2\mu_0 \left( E_{PM} + Ni_z \right)^2 \] (3)
  it can be linearized nearby the operating point \((z_0,i_z)\) as:
  \[ f_z(z,i_z) \equiv f_z(z_0,i_z) - A \cdot (z-z_0) + B \cdot (i_z-i_z) \] (4)
  where
  \[ A = \left. \frac{\partial f_z}{\partial z} \right|_{(z_0,i_z)} = \left. 4\mu_0, S \left( E_{PM} + Ni_z \right)^2 \right|_{z_0} \] (5)
  \[ B = \left. \frac{\partial f_z}{\partial i_z} \right|_{(z_0,i_z)} = \left. 4\mu_0, S \left( E_{PM} + Ni_z \right)^2 \right|_{z_0} \] (6)

Here, \( f_z(z_0,i_z) \) is the attractive force at operating point, it is equal to the weight of electromagnet---\( mg \). The symbols \( z' \) and \( i_z' \) are slight variations from the operating point. The symbols \( z \) and \( i_z \) will be used to instead of \( z' \) and \( i_z' \). In the zero-power control mode, the equilibrium current \( i_{z,0} \) is set to zero.

  The transfer function is:
  \[ \frac{z(s)}{i_z(s)} = \frac{B}{ms^2 - A} \] (7)

![Fig.3 Equivalent magnetic circuit](image)

![Fig.4 Linear model](image)
The inclination motions around $\alpha$ and $\beta$ axis can be derived in the same way. The linear plant model is represented as shown in Fig.4.

From Fig. 4, we can find that each d.o.f has an identical structure, so each control system can be designed separately toward each mode.

4. Controller Design and Simulation

In this section, two kinds of controllers, the 3 d.o.f. gap length type controller and the 3 d.o.f. zero-power levitation controller, are designed based on the linear plant model as shown in Fig. 4. And the result of simulation will be discussed [2][3].

4.1 The design of gap length type controller

The state space plant model for vertical direction dynamics in Fig.4 is as follows:

$$\frac{d}{dt} \begin{pmatrix} z \\ \dot{z} \\ i_z \\ \int z dt \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & -\frac{\beta}{m} \\ 0 & 0 & -\frac{\beta}{L_z} \\ 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} z \\ \dot{z} \\ i_z \\ \int z dt \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{L_z} \\ 0 \end{pmatrix} e_z$$ (8)

The magnetic levitation system can be realized by using the state feedback control toward 4-dimensional extended system to which the integral of the gap deviation are added. That is:

$$\frac{d}{dt} \begin{pmatrix} z \\ \dot{z} \\ i_z \\ \int z dt \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & -\frac{\beta}{m} \\ 0 & 0 & -\frac{\beta}{L_z} \\ 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} z \\ \dot{z} \\ i_z \\ \int z dt \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{L_z} \\ 0 \end{pmatrix} e_z$$ (9)

The equations solely in $z$ direction are written now for the page limitation. The design of inclination system is similar with the vertical direction system.

Fig. 5 shows the construction of the gap length type controller. The result of simulation is shown in Fig. 6. The unbalanced step load is load at $t=1s$. From the result, the system can return steady state within $0.2s$.

4.2 The design of zero-power controller

In zero-power control mode, the levitation body is suspended only using permanent magnet forces and the currents of the electromagnets converge to zero. The integral of the current deviation is added to state feedback control. That is:

$$\frac{d}{dt} \begin{pmatrix} z \\ \dot{z} \\ i_z \\ \int i_z dt \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{\beta}{m} & 0 \\ 0 & 0 & -\frac{\beta}{L_z} & 0 \\ 0 & 0 & 0 & \frac{1}{L_z} \end{pmatrix} \begin{pmatrix} z \\ \dot{z} \\ i_z \\ \int i_z dt \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{L_z} \end{pmatrix} e_z$$ (10)

The result of simulation is shown in Fig. 7. The unbalanced step load, $f_{d1}=5[N]$, $T_{d1}=-0.02[N \cdot m]$, $T_{d0}=-0.01[N \cdot m]$, is load at $t=1s$. From the result, the system can return steady state within $0.2s$. The simulation results show that unbalanced zero-power levitation has been realized by tilting the levitation angle to $(\theta, \phi, \psi)=[0.0032, 0.005, 0.0025]$ at steady state.

4.3 Proposal of voltage order type zero-power control system

Zero-power control without current sensors can be realized by developing the idea of the previous section.

Here we consider the following extended system in which the integral of the control input $e_i$ itself is included into the state variable.

$$\frac{d}{dt} \begin{pmatrix} z \\ \dot{z} \\ i_z \\ \int e_i dt \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{\beta}{m} & 0 \\ 0 & 0 & -\frac{\beta}{L_z} & 0 \\ 0 & 0 & 0 & \frac{1}{L_z} \end{pmatrix} \begin{pmatrix} z \\ \dot{z} \\ i_z \\ \int e_i dt \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{L_z} \end{pmatrix} e_z$$ (11)

Although this extended system does not satisfy the condition of the observability totally, the added variable, $\int e_i dt$, can be calculated directly from the input $e_i$, and other state variables can be estimated based on Luenberger observer.

This system can be, therefore, stabilized by state feedback based on Luenberger observer using only the...
gap length. In this system zero-power control can be realized by the control input $\int e \, dt \rightarrow 0$ directly. Any current sensors are not needed this scheme [2]. We call the proposed scheme as “voltage order type zero-power control”.

On the other hands, $\int e \, dt$ directly means the magnetic flux produced by a coil. Therefore, this scheme has a substantial meaning that one keeps the control flux to zero.

5. Experimental Verification

After we finish the analysis and the design of controller, the experimental machine is built to verify the analysis. Fig. 8 shows the structure of the experimental machine. And Table. 1 gives the specifications of the machine.

Fig. 9 is a photograph of the 3 d.o.f. completed suspension in the zero-power control mode. Fig. 10 shows the input voltage waveform of each coil of the experimental machine in the zero-power control mode.

It can be confirmed that the unbalanced zero-power control, which compensates the unbalanced load by tilting the body, has been realized. It can minimize energy consumption in steady state. This is a significant advantage in the flexible transport system in which the conveyer is often supplied by batteries.

Table.1 Specifications of the experimental machine

<table>
<thead>
<tr>
<th>Mass</th>
<th>$M$</th>
<th>6.7[kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equilibrium gap</td>
<td>$z_0$</td>
<td>5.49 [mm]</td>
</tr>
<tr>
<td>Moment</td>
<td>$J$</td>
<td>0.0195 [kg*m$^2$]</td>
</tr>
<tr>
<td>Equilibrium current</td>
<td>$i_0$</td>
<td>0[A]</td>
</tr>
<tr>
<td>Turns</td>
<td>$N$</td>
<td>100</td>
</tr>
<tr>
<td>Area of each pole</td>
<td>$s$</td>
<td>12.3 [cm$^2$]</td>
</tr>
<tr>
<td>Resistance of coil</td>
<td>$R$</td>
<td>0.55 [$\Omega$]</td>
</tr>
<tr>
<td>MMF of PM</td>
<td>$E_{PM}$</td>
<td>1488 [AT]</td>
</tr>
<tr>
<td>Inductance of coil</td>
<td>$L$</td>
<td>0.00605 [H]</td>
</tr>
<tr>
<td>Thickness of PM</td>
<td>$l_{PM}$</td>
<td>2.2 [mm]</td>
</tr>
</tbody>
</table>

6. Conclusions

A novel 4pole type hybrid electromagnet has been proposed. This electromagnet has the following three characteristics:

- it can construct a levitation system singly,
- it can realize zero-power control, and
- it can generate unbalanced attractive forces by tilting itself.

It is expected that a compact, light and simple magnetic levitation, which is suitable for a flexible transport system, can be constructed by using this kind of electromagnet.

The proposed magnet, its power source and the controller, should be optimized for implementing all the active parts into the mover for a real application. A compact and light mover, including the magnets, controller and power supply, should be designed for the flexible transport system. And the combination with linear motor will be studied in the next step.

References

