Paper

Robust Control of a 4-Pole Electromagnet in Semi-Zero-Power Levitation Scheme with a Disturbance Observer

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Electromagnetic suspension (EMS) has been widely used in many industrial fields because of various advantages in practical use. The U-type magnets are often used to generate the levitation force in the EMS system. This conventional electromagnet, however, can only control 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 this paper. The basic structure and characteristics of the proposed magnet are described first. Next the control system is designed. Luenberger observer, only using gap sensors, is applied to realize zero-power control. The semi-zero-power control with a disturbance observer is proposed to improve the performance, as well as the robustness, of the control system. Finally, the simulation results and corresponding experiments have been presented.

Keywords:
Magnetic levitation, 3 degree-of-freedom, 4-pole type hybrid electromagnet, zero-power control, semi-zero-power control, Luenberger observer.

1. Introduction

Electromagnetic suspension (EMS) technology, in which attractive forces between electromagnets and ferromagnetic materials are utilized as suspension forces, is commonly used in the field of passenger transport vehicles, tool machines, frictionless bearings and conveyor systems[1][2], because of the various advantages, such as, no friction, no abrasion, low noise and small vibration, *etc.*

In the EMS systems, the U-shaped magnets are often used for generating the levitation force. The conventional U-shaped electromagnet, however, can only control one degree of freedom(d.o.f.). It cannot construct a levitation system solely by itself. Multiple magnets must be arranged in a plane and be controlled simultaneously in order to construct a levitation system. A 4-pole yoke combined type hybrid electromagnet is proposed in this paper for a simple and miniature levitation system.

On the other hand, the zero-power control method has been developed and reported to minimize energy consumption[3][4]. The permanent magnet is used to suspend the total weight of the levitated carrier and its loads, despite a change in the load weight. The gap length is changed automatically to the value at which the attractive force due to the permanent magnet balances the total weight of the levitated carrier and its loads. This solution is effective when the track condition is good enough. But, if the track is the stators of linear motor, the periodic disturbance force from the armature side will cause the oscillation. In this paper, the semi-zero-power control is proposed to improve the performance of zero-power controller.

This paper will discuss the following two points of this research in detail:

- The proposed novel 4-pole type hybrid electromagnet, including the basic structure, the characteristics and its linear model.
- The proposed semi-zero-power control method, including the structure, the advantages, the simulation results and the experimental results.

2. 4-Pole Type Hybrid Electromagnet

2.1 Basic structure of the magnet

The proposed novel electromagnet has 4 poles combined through yokes. Each pole consists of a permanent magnet and a coil for controlling current, shown in Fig. 1[5].

2.2 The control methods of magnetic levitation

The proposed magnet can obtain 3 d.o.f.: vertical direction gap z, inclination angle θ around α-axis and angle φ around β-axis respectively as shown in Fig. 2.

In Fig. 2, we assume that there are three virtual winding currents i_z, i_α, i_β, which are used for controlling the vertical direction z, inclination angles θ and φ, respectively. The feedback control system is designed toward each d.o.f. independently. We can also derive the relationship between the virtual currents of each d.o.f. i_z, i_α, i_β and the actual currents

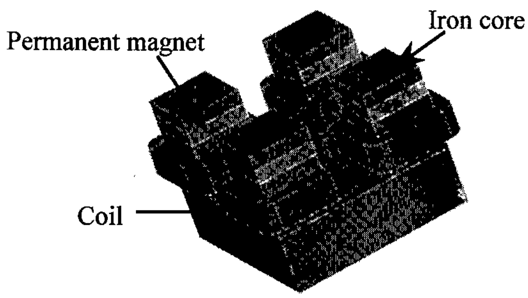


Fig. 1 Basic structure of 4-pole type hybrid electromagnet

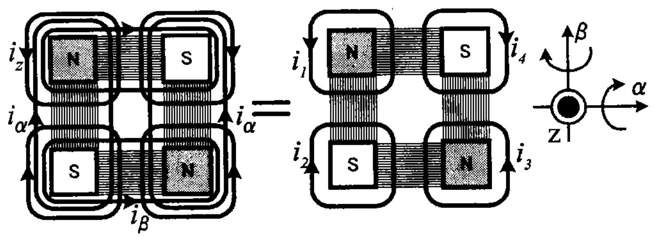


Fig. 2 Control methods of magnetic levitation

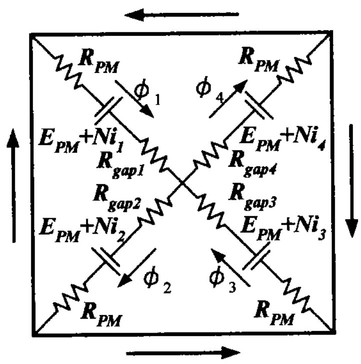


Fig.3 Equivalent magnetic circuit

of each pole i_1, i_2, i_3, i_4, as described in equation(1).

$$\begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{pmatrix} = \begin{pmatrix} 1 & -1 & -1 \\ 1 & 1 & -1 \\ 1 & 1 & 1 \\ 1 & -1 & 1 \end{pmatrix} \begin{pmatrix} i_z \\ i_\alpha \\ i_\beta \end{pmatrix} \tag{1}$$

2.3 The advantages of 4-pole hybrid electromagnet

Compared with the usual U-shaped magnets, the proposed 4-pole type hybrid electromagnet has the following three advantages.

- **It can control 3 d.o.f by using single unit.**

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

- **It can realize zero-power control[3][4].**

The poles are composed by electromagnets and permanent magnets, and the flux of these two types of magnets can be superposed in the levitation gaps. The levitation body can, therefore, suspend itself only using permanent magnet forces, and the steady currents of the electromagnets converge to zero. This characteristic minimizes the energy consumption.

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

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

Because of these three main advantages, this 4-pole type hybrid electromagnet can construct a compact, miniature magnetic levitation system.

3. Controller Design

3.1 Requirements to the controller.

The requirements to the controller depend on a specific practical use. As an example of a freight convey system, the requirements to the controller for the experimental machine are described as follows:

(1) The controller must suspend the magnet by controlling the 3 degree of freedom of the magnet, including pitching, rolling. And the overshoot of the step response should be limited under 10%. Active controller is not necessary in yawing and lateral directions since the motion in these directions is originally stable.

(2) In zero-power control mode, the steady currents of the electromagnets converge to zero, even the loads are changed. In this case, the magnet adjust the gap length according to the loads automatically, and the gap length must be kept between 4mm to 10mm, because of the safe limitation and the capacity of air gap sensor.

(3) To realize semi-zero-power control which will be described in details at section 4, the steady errors of gap length should converge to zero in gap length type control mode. That means the gap length must be controlled according to the command, completely, even the loads are changed.

(4) The disturbance forces, such as the load changes which are equal to the payload or the magnetic force from the stator of linear motor, shall not affect the stability of the suspended body.

(5) The low frequency periodic disturbance forces, ranged between 1Hz to 10Hz, which come from the effects of slots and teeth of linear motor stator or the armature flux shall not affect the control system seriously.

3.2 Linear plant model

The electromagnet is not stable in EMS without control. The feedback controller is designed based on the approximated linear model derived in this section[5][6]. We assume that a 4-pole electromagnet is levitated below a plane core track as a plant model. Constants and variables used in this section are summarized as follows:

μ_0	permeability of vacuum
g	gravity acceleration
l_{PM}	thickness of permanent magnets
E_{PM}	magnetomotive force of permanent magnet
S	area of the pole
N	number of turns
m	mass of the electromagnet
R_z, R_α, R_β	the equivalent resistances of each d.o.f.
L_z, L_α, L_β	the equivalent inductances of each d.o.f.
i_z, i_α, i_β	virtual currents of each d.o.f.
i_1, i_2, i_3, i_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 nominal operating point $(z, \theta, \varphi) = (z_0, 0, 0)$ and $(i_z, i_\alpha, i_\beta) = (i_{z_0}, 0, 0)$.

Here, we only derive the vertical direction dynamics because of page limitation. The mathematical formulation of inclination dynamics are the same as the vertical direction.

The vertical motion is expressed as:

$$m\Delta\ddot{z}(t) = f_z(z(t), i_z(t)) - mg - F_d(t) \tag{2}$$

where the vertical attractive force f_z is:

$$f_z(z(t), i_z(t)) = \frac{B^2}{2\mu_0} \cdot S \cdot 4 = \frac{2\mu_0 S(E_{PM} + N i_z(t))^2}{(z(t) + l_{PM})^2} \tag{3}$$

A reasonably accurate linear model may be obtained by using linear approximations of the attraction force for excursions around the nominal equilibrium point (z_0, i_{z_0}). The small perturbation linear equations(discounting second-order effects) of the systems are:

$$\begin{aligned} f_z(z(t), i_z(t)) &= f(z_0 - \Delta z(t),\ \ i_{z_0} + \Delta i_z(t)) \\ &\cong f_z(z_0, i_{z_0}) + K_A \Delta z(t) + K_B \Delta i_z(t) \end{aligned} \tag{4}$$

where

$$K_A = -\left.\frac{\partial f_z}{\partial z}\right|_{(z_0, i_{z0})} = \frac{4\mu_0 S(E_{PM} + N i_{z_0})^2}{(z_0 + l_{PM})^3} \tag{5}$$

$$K_B = \left.\frac{\partial f_z}{\partial i_z}\right|_{(z_0, i_{z0})} = \frac{4\mu_0 SN(E_{PM} + N i_{z0})}{(z_0 + l_{PM})^2} \tag{6}$$

Here, $f_z(z_0, i_{z_0})$ is the attractive force at the nominal equilibrium point, it is equal to the weight of the levitated body---*mg*. Thus equation(2) could be written:

$$m\Delta\ddot{z}(t) = K_A \Delta z(t) + K_B \Delta i_z(t) - F_d(t) \tag{7}$$

and the Laplace transform of the gap length is

$$Z(s) = \frac{K_B}{ms^2 - K_A} \cdot I_z(s) - \frac{1}{ms^2 - K_A} \cdot F_d(s) \tag{8}$$

On the other hand, the electrocircuit dynamics is expressed as:

$$e(t) = R_z i_z(t) + N\frac{d}{dt}\Phi = R_z i_z(t) + \mu_0 NS \frac{d}{dt}\frac{N i_z(t) + E_{PM}}{z(t) + l_{PM}} \tag{9}$$

It can also be linearized nearby the nominal equilibrium point (z_0, i_{z_0}).

$$\Delta e_z(t) = R_z \Delta i_z(t) + L_z \Delta\dot{i}_z(t) + \frac{K_A L_z}{K_B}\Delta\dot{z}(t) \tag{10}$$

and the Laplace transform of the excitation current is

$$I_z(s) = \frac{1}{L_z s + R_z}\left[E_z(s) - \frac{K_A L_z}{K_B} s Z(s)\right] \tag{11}$$

Thus, the linear plant model, including the electrocircuit dynamics, is represented as shown in Fig.4.

3.3 Design of controllers

The plant model is unstable as stated in equation (8). Controllers must be designed to stabilize the magnet. Normally, the controller is designed according to the requirement of the practical use. As to the application of this maglev system, it can construct a freight convey system, used in a clean room of manufactory, such as in a semiconductor manufactory. In this application, the electromagnet must be suspended below a core track. The controller should keep the gap length at a constant distance or change the gap length according to some rules.

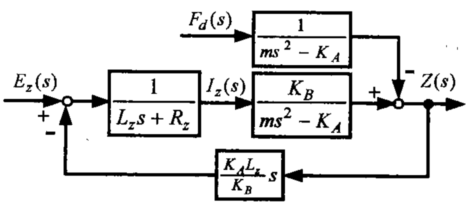


Fig.4 Linear model

First of all, the 3 d.o.f. gap-length type controller has been designed, based on the linear plant model as shown in Fig. 4. This controller should keep the gap length at a constant distance. For example, the gap length is 8mm in HSST-100 and Transrapid TR-06 maglev system. As a freight convey system, the nominal operating point of this magnet is designed at 5.5mm, and the magnet can be suspended between 4mm to 10mm.

By choosing $\Delta z(t), \Delta\dot{z}(t)$ and $\Delta i_z(t)$ as the state variables, the state-space of the plant model of vertical direction dynamics in Fig.4, the disturbance force is disregarded here, is as follows:

$$\frac{d}{dt}\begin{pmatrix}\Delta z(t)\\ \Delta\dot{z}(t)\\ \Delta i_z(t)\end{pmatrix} = \begin{pmatrix} 0 & 1 & 0\\ \frac{K_A}{m} & 0 & \frac{K_B}{m}\\ 0 & -\frac{K_A}{K_B} & -\frac{R_z}{L_z}\end{pmatrix}\begin{pmatrix}\Delta z(t)\\ \Delta\dot{z}(t)\\ \Delta i_z(t)\end{pmatrix} + \begin{pmatrix}0\\ 0\\ \frac{1}{L_z}\end{pmatrix}\Delta e_z(t) \tag{12}$$

The equations solely in *z* direction are written here due to the page limitation. The design of inclination systems is similar to the vertical direction system.

The controller can be constructed by feeding back these three state variables. The block diagram of the feedback control is shown in Fig. 5. The controller component *K* is a preliminary gain, used for eliminating the steady error. Here,

$$\begin{aligned}\dot{x}(t) &= Ax(t) + B(K\, y_{ref}(t) - F\,x(t))\\ &= (A - BF)x(t) + BK\, y_{ref}(t)\end{aligned} \tag{13}$$

$$[sI - (A - BF)]X(s) = BK\, Y_{ref}(s) \tag{14}$$

$$X(s) = [sI - (A - BF)]^{-1} BK\, Y_{ref}(s) \tag{15}$$

$$\therefore\ \ Y(s) = CX(s) = C[sI - (A - BF)]^{-1} BK\, Y_{ref}(s) \tag{16}$$

To let the steady error equal to zero, the output *y(t)* must be converge to 1, when a unit step function input to the system. Using final value theory, the preliminary gain *K* is:

$$K = -[C(A - BF)^{-1}B]^{-1} \tag{17}$$

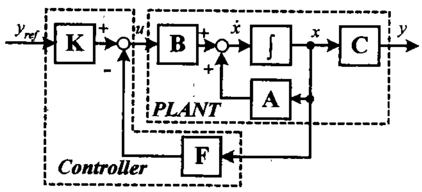
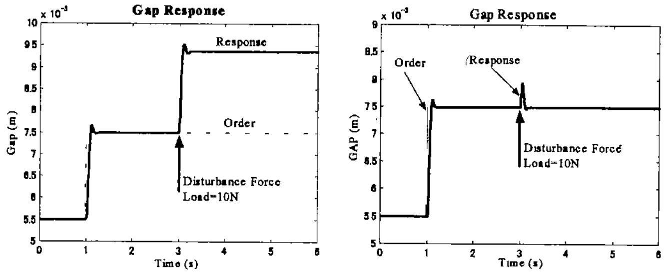


Fig. 5 The block diagram of controller without integral term.



(a) Controller without integral term (b) Controller with integral term

Fig. 6 The simulation results of gap length type controller.

This controller can suspend the electromagnet and change the gap length according to the order, when the suspended body is not affected by disturbance forces. The simulation result is shown in Fig. 6(a). But, the controller can not keep the magnet at a constant gap length, when a load is given to the suspended body. For this reason, this controller is not preferable in a practical case.

To let the steady error of a state variables converge to zero, the integral of this variable deviation is often added to the state space equation as a state variable. The explanation can be found in any text books about control theory. To realize semi-zero-power which will be described in details at section 4, the gap length must be identical to the command completely, even the loads are changed. It means that the steady errors of gap length should converge to zero in gap length type control mode. Here, the integral of the gap deviation is added to the state space equation as a state variable.

$$\frac{d}{dt}\begin{pmatrix}\Delta z(t)\\ \Delta\dot{z}(t)\\ \Delta i_z(t)\\ \int\Delta z(t)dt\end{pmatrix}=\begin{pmatrix}0 & 1 & 0 & 0\\ \frac{K_A}{m} & 0 & \frac{K_B}{m} & 0\\ 0 & -\frac{K_A}{K_B} & -\frac{R_z}{L_z} & 0\\ 1 & 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\Delta z(t)\\ \Delta\dot{z}(t)\\ \Delta i_z(t)\\ \int\Delta z(t)dt\end{pmatrix}+\begin{pmatrix}0\\ 0\\ \frac{1}{L_z}\\ 0\end{pmatrix}\Delta e_z(t) \quad (18)$$

Based on this equation, we can design the gap length type controller by using state feedback method

There are many methods to decide the poles of the controller. Here, we will introduce one of the simplest and practical methods.

Kessler's canonical form is an effective approach to decide the coefficients of the characteristic polynomial for single input and single output(SISO) system[7]. And the controller designed by this approach always fulfills the requirement to the controller, described at the beginning of this section. To assign the poles of the controller, a reference polynomial, which has the same order with the control system, must be decided at first. The reference polynomial for this system is:

$$a_4s^4+a_3s^3+a_2s^2+a_1s+a_0 \quad (19)$$

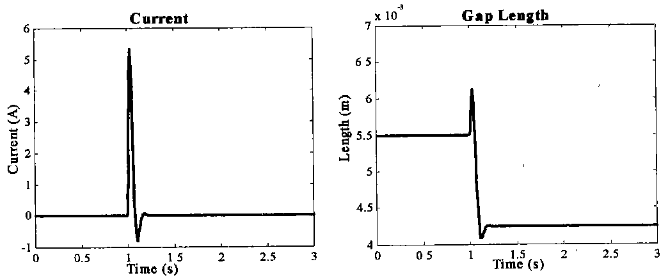
where the coefficients of the polynomial must fulfill the following relationships:

$$\frac{a_3^2}{a_4a_2}=\gamma_3,\quad \frac{a_2^2}{a_3a_1}=\gamma_2,\quad \frac{a_1^2}{a_2a_0}=\gamma_1 \qquad \frac{a_1}{a_0}=\tau \quad (20)$$

The stability indices should be $\gamma_1=\gamma_2=\gamma_3=2$ at Kessler's canonical form. τ is the equivalent time constant, which determines the step response speed of the close loop system.

Letting the reference polynomial equal to zero, and solving this equation, we obtain four roots. These roots are the poles of the state feedback controller. When we expect the equivalent time constant τ is 0.05s, the solution of this equation is $-40\pm 40i$. These roots are used as the poles of controller. The simulation results are shown in Fig. 6(b). The experimental results will be given in section 5.

This section has confirmed that the additional integral term makes the steady error zero even if it is affected by disturbance forces. The controller designed in this section is the base of the semi-zero-power controller which will be proposed in the next section. If the controller can not eliminate the steady error of gap length, it cannot adjust the gap length according to the order. Hence it cannot suspend at the nominal operating point when a load is given to the suspended body. In this case, the observer, which will be designed in the latter part of this section, cannot estimate the state variables and the disturbance forces correctly. The semi-zero-power control scheme can not be realized.



(a) Current waveform (b) Gap response

Fig. 7 Simulation results of zero-power controller

One of the advantages of maglev technology is that the levitated body can be supported without contacting. When this system is used in a practical case, the power supply will be a problem, since the system cannot obtain enough energy from outside without contacting. The zero-power control method, which has been developed and reported by many researchers[1]~[6], is a practical solution. The current-type zero-power control will be described briefly.

In zero-power mode, the levitated body is suspended only by the permanent magnets' forces and the steady currents of the electromagnets converge to zero by changing the levitation gap length according to the load mass. To let the steady currents converge to zero, the integral of the current deviation is added to the state space equation as a state variable.

$$\frac{d}{dt}\begin{pmatrix}\Delta z(t)\\ \Delta\dot{z}(t)\\ \Delta i_z(t)\\ \int\Delta i_z(t)dt\end{pmatrix}=\begin{pmatrix}0 & 1 & 0 & 0\\ \frac{K_A}{m} & 0 & \frac{K_B}{m} & 0\\ 0 & -\frac{K_A}{K_B} & -\frac{R_z}{L_z} & 0\\ 0 & 0 & 1 & 0\end{pmatrix}\begin{pmatrix}\Delta z(t)\\ \Delta\dot{z}(t)\\ \Delta i_z(t)\\ \int\Delta i_z(t)dt\end{pmatrix}+\begin{pmatrix}0\\ 0\\ \frac{1}{L_z}\\ 0\end{pmatrix}\Delta e_z(t) \quad (21)$$

We can design the zero-power controller using state feedback based on this equation. Fig. 7 gives the simulation results of the zero-power control. The step force, F_d=20N, is loaded at t=1s. From the results, we can find that the gap changed from 5.5mm to 4.2mm to compensate the load, and the steady current of the coil converges to zero.

3.4 Effect of a disturbance force to the state estimation

When we designed the controller in previous part, we considered that all of the state variables could be measured. We can detect only the gap length and current directly using gap and current sensors, in fact. The gap velocity cannot be usually measured directly and needs to be estimated or calculated. Luenberger observer has been, therefore, introduced to estimate the state variables, shown in Fig. 8. It has also characteristics of a high order low pass filter[6][8].

The observer designed in ideal condition can estimate the state variables correctly without disturbance. However, any disturbance could affect the levitated body and cause an error in the estimated result. Here, we will analyze the effects of the

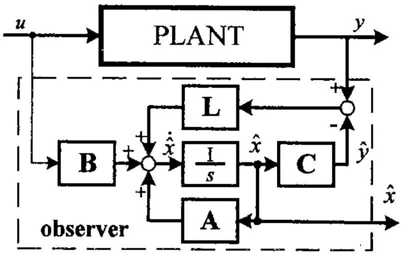


Fig. 8 The structure of the Luenberger observer

disturbance forces to the estimate values. Fig. 9 shows a example. The gap order is changed at t=0.5s and t=2.5s, Fig. 9(b). The disturbance force, F_d=20N, is loaded at t=1.5s and is taken off at t=3.5s, shown in Fig. 9(a). From the simulation result, we could find that the offset, as shown in Fig. 9(c), appears in the estimated gap velocity when the disturbance force loaded to the system.

We introduce a disturbance observer to solve the problem. We extend the state space equation by adding the disturbance force as a state variable.

$$\frac{d}{dt}\begin{pmatrix}\Delta z(t)\\ \Delta \dot{z}(t)\\ \Delta i_z(t)\\ F_d(t)\end{pmatrix}=\begin{pmatrix}0 & 1 & 0 & 0\\ \frac{K_A}{m} & 0 & \frac{K_B}{m} & -\frac{1}{m}\\ 0 & -\frac{K_A}{K_B} & -\frac{R_z}{L_z} & 0\\ 0 & 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\Delta z(t)\\ \Delta \dot{z}(t)\\ \Delta i_z(t)\\ F_d(t)\end{pmatrix}+\begin{pmatrix}0\\ 0\\ \frac{1}{L_z}\\ 0\end{pmatrix}\Delta e_z(t) \quad (22)$$

We can also construct an extended observer based on equation (22). This observer is called as a disturbance observer. The disturbance observer can estimate the state variables correctly even when the disturbance force affect to the system, as shown in Fig. 9(d). The disturbance observer can also estimate the disturbance force at the same time. The estimated disturbance force can be feedforwarded to compensate the effect of the disturbance forces.

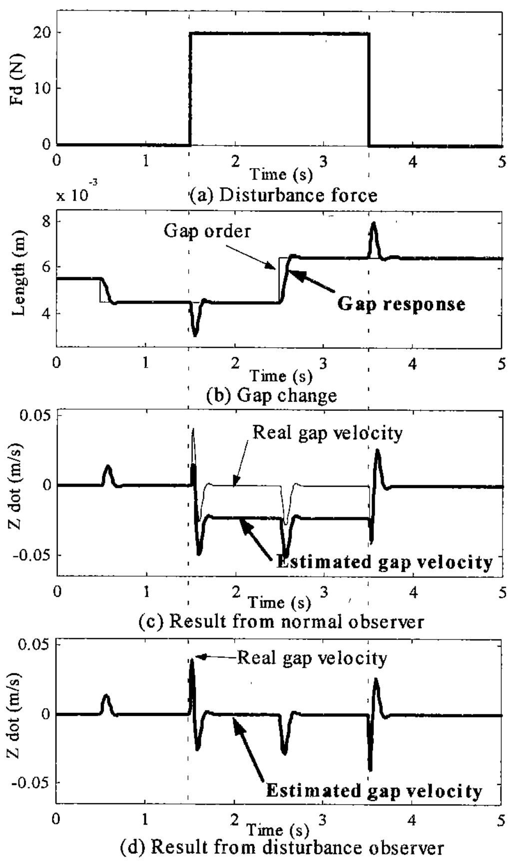


Fig. 9 Effect of disturbance observer

4. Proposal of Semi-Zero-Power Control with a Disturbance Observer

4.1 Proposal of semi-zero-power control

Zero-power control will change the levitation gap length according to the load mass, the steady current will converge to zero. The gap length will also be changed when there are disturbance forces.

The steady current must converge to zero as soon as possible in the zero-power control scheme. If the disturbance force is a periodic signal, the gap length will be changed periodically. This means that the levitated body oscillates itself. The steady current will not converge to zero in this case. The vibration itself is undesirable for transportation quality, too.

The semi-zero-power control method has been, therefore, proposed to solve this problem. The concept of the semi-zero-power control is shown in Fig. 10.

The gap-length type controller, designed in section 3.2, works as the fundamental controller. The disturbance observer is used for estimating the disturbance force. And a low pass filter is used for eliminating the periodic disturbance signal with high frequency. After the disturbance force without the periodic elements is estimated, we can calculate how much the gap length distance should be changed to let the current converge to zero. This result is input to the gap-length controller as the command. Because of the LPF for eliminating the periodic forces, the currents will converge to zero slowly. Thus, the gap length will be also adjusted slowly. This controller gives the performance between the gap-length and the zero-power controllers. It is, therefore, named as semi-zero-power controller.

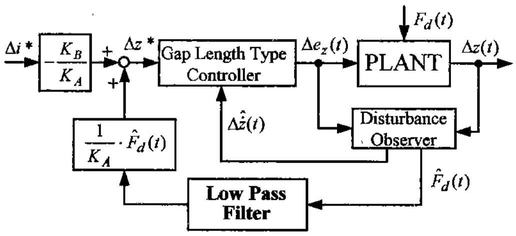
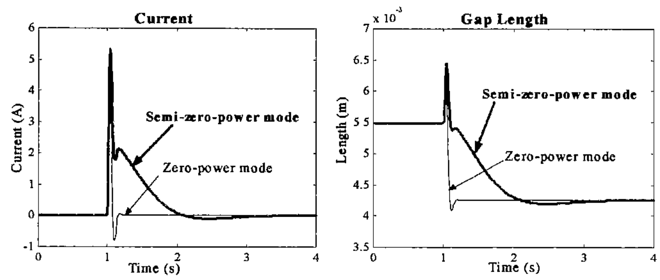
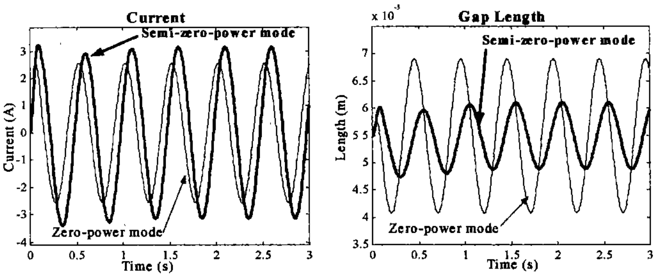


Fig. 10 Concept of semi-zero-power control



(a) Current waveform (b) Gap response

Fig. 11 Simulation results of semi-zero-power with step disturbance



(a) Current waveform (b) Gap response

Fig. 12 Simulation results of semi-zero-power with periodic disturbance

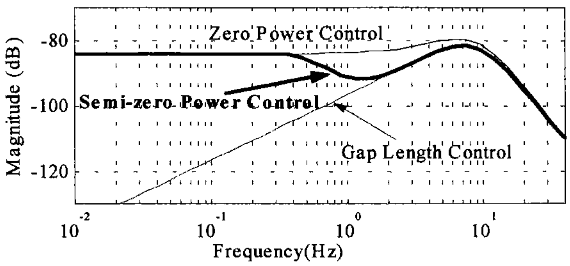
Fig. 11 and Fig. 12 show the simulation results, where the cut-off frequency of the LPF is f_c=0.5(Hz). Fig. 11 is the simulation results when a step disturbance force affects the suspended body. The current of electromagnet converges to zero slowly. Fig.12 is the simulation results when a periodic disturbance force, the frequency of the periodic force is f_{F_d}=2(Hz), affects the suspended body.

From the simulation results, the vibration of the levitated body, caused by the periodic force whose frequency is higher than the cut-off frequency of the LPF, has been suppressed. The control current, however, increased.

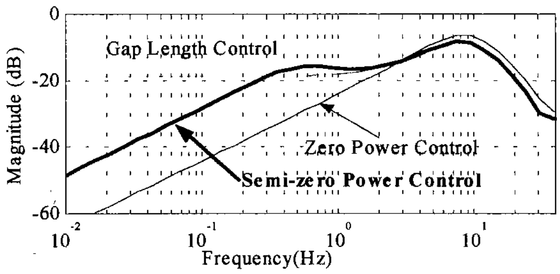
In fact, the semi-zero-power controller method can only eliminate a specific part of periodic vibration with special frequency, which depends on the cut-off frequency of the LPF.

Fig.13 and Fig. 14 show the Bode diagrams from disturbance force F_d to the gap length and to current, with different cut-off frequency of the LPF.

From the Bode diagrams, we can conclude that the semi-zero-power controller gives the intermediate performance between the zero-power and the gap-length controllers. The performance can be adjusted by the cut-off frequency of the LPF.

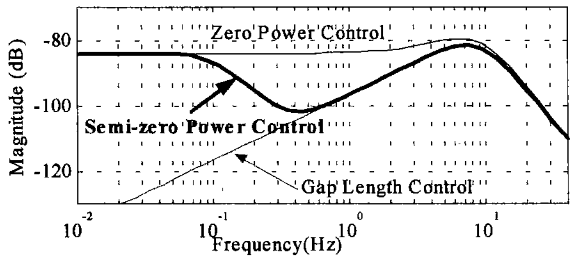


(a) The Bode diagram from F_d to gap length

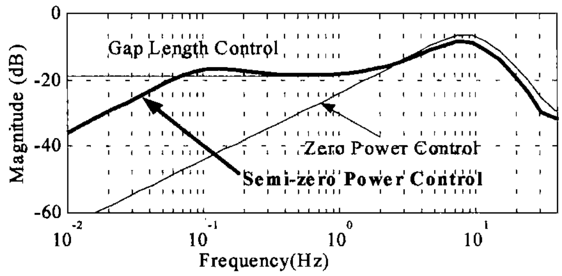


(b) The Bode diagram from F_d to current

Fig. 13 The Bode diagram when the cut-off frequency of the LPF f_c=0.5(Hz)



(a) The Bode diagram from F_d to gap length



(b) The Bode diagram from F_d to current

Fig. 14 The Bode diagram when the cut-off frequency of the LPF f_c=0.1(Hz)

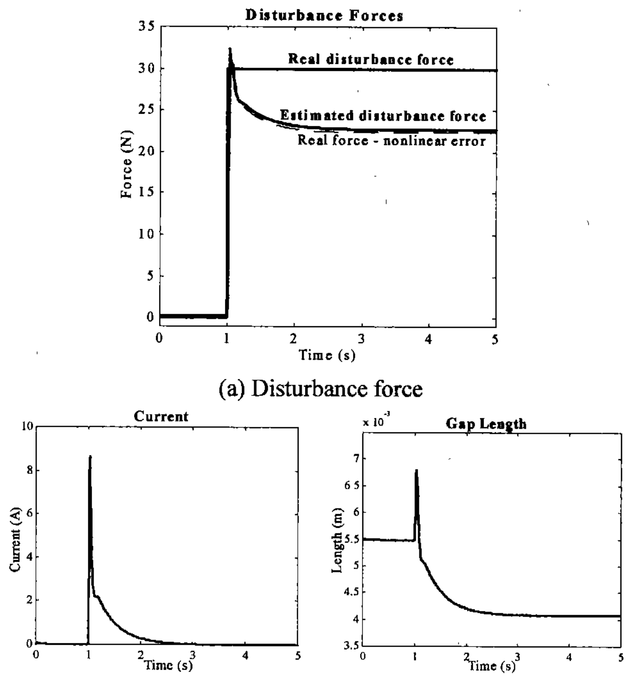
It will act as the zero-power controller if the cut-off frequency of the LPF is large enough, or it will act as the gap-length controller if the cut-off frequency is equal to zero. Normally, the cut-off frequency can be adjusted according to the frequency which an user wants to eliminate in the actual environment. Moreover adjustment of the frequency will not affect the stability of the controller system.

On the other hand, the semi-zero-power control is designed based on a linearized model. Although the disturbance observer can collect possible modeling errors, because the controller does not use the integral loop of current deviation, the steady current can not really converge to zero in some cases, especially, when the magnetomotive force of permanent magnet is weaken after a long time running.

4.2 Function of the disturbance observer for nominalizing plant

Although the observer was designed based on the linear model nearby the nominal point, the real plant is nonlinear. Hence, there is a considerable error between the estimated and real disturbance forces, as shown in Fig. 15.

Fig. 16 illustrates the difference between the real nonlinear attractive force dependency and the linear force dependency of the nominal model used for both controller and observer designs. When a step force is loaded to the levitated body, the magnet changes its operating point to a new position according to the nonlinear relation. The observer estimates the disturbance force according to the linear relation using the new gap length and variable. We can see that the estimation error is caused by the modeling error. We can obtain the modeling error from the nominal point to new operating point. If we subtract the modeling error from the real force, the result is almost equal to the



(a) Disturbance force

(b) Current waveform (c) Gap response

Fig. 15 Estimation error of disturbance observer

estimated force, shown in Fig. 15 (a).

However, the estimation errors are very important information. That is to say, the estimated disturbance force does include not only the real disturbance force, but also other modeling errors of the mechanical dynamics. When a disturbance force is given to the suspended body, the controller adjust the gap length or the control current to compensate the disturbance force. It means the system works on a new operating point. It will cause a modeling errors of the mechanical dynamics. The relation of attractive force against the gap length and the current is represented as a nonlinear curved surface, shown in Fig. 16.

The disturbance observer has been designed based on a linear model, in which the relation of attractive force against the gap length and the current is approximated as a plane nearby the nominal point. As described in the second line of equation (19),

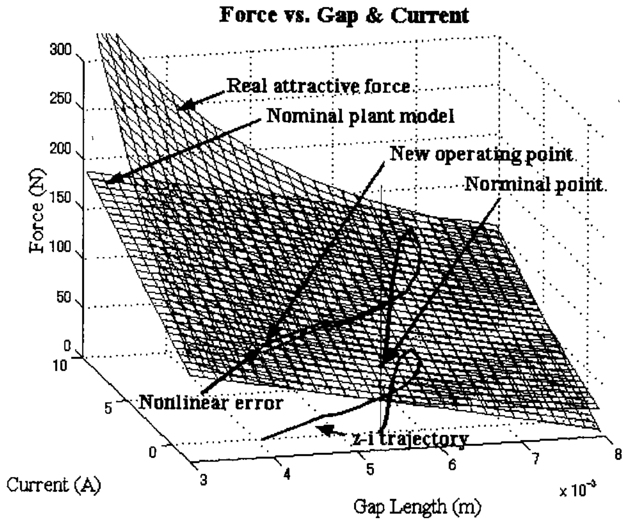


Fig. 16 Nonlinear error of the levitation system

$$\Delta\ddot{z}(t) = \frac{K_A}{m}\Delta z(t) + \frac{K_B}{m}\Delta i_z(t) - \frac{1}{m}F_d(t) \qquad (23)$$

the modeling errors in steady state will be collected to the estimated disturbance force.

If we feedforward this estimated result, all the collected errors in the mechanical dynamics can be compensated as well as the disturbance force, if the observer estimation is sufficiently fast. In other words, the disturbance observer collects the possible mechanical modeling errors into one variable $\hat{F}_d$. The $\hat{F}_d$ feedforward modifies the plant mechanical dynamics to the linearized nominal plant.

In the linearized model, the estimated disturbance force can be approximately written as:

$$\hat{F}_d(t) = K_A \Delta z(t) + K_B \Delta i_z(t) \qquad (24)$$

In Fig. 10, we can calculate the order of gap length type controller, z^*:

$$\begin{aligned}\Delta z^* &= -\frac{K_B}{K_A}\cdot \Delta i^* + \frac{1}{K_A}(K_A \Delta z(t) + K_B \Delta i_z(t)) \\ &= \frac{K_B}{K_A}(\Delta i_z(t) - \Delta i^*) + \Delta z(t)\end{aligned} \qquad (25)$$

Δz^* is the input signal of gap length type controller, the system will arrive at a new equilibrium point, where $\Delta z(t)$ is equal to Δz^*. That is why we must add the integral of the gap deviation to the state space equation as a state variable in section 3.3. From equation (25), the steady current $\Delta i_z(t)$ will converge to the order Δi^*. In the proposed semi-zero-power control, Δi^* is always equal to zero. That means the steady current will converge to zero. This is the substantial reason why the steady current can always converge to zero in the proposed semi-zero-power control scheme.

4.3 The advantages of semi-zero-power control with the disturbance observer

Compared with the zero-power control, the proposed semi-zero-power control has the following three advantages.

① It can reduce the vibration of the magnet when there is a periodic disturbance force.

② The disturbance observer can also estimate other mechanical dynamics errors from the nominal model when it estimates the disturbance force. The control system can be robust to any disturbances.

③ There are three parts of the control system: gap-length controller, zero-power calculator and low pass filter. These three parts can be designed independently. We can change the parameters of the low pass filter according to the actual environment without affecting the performance and stability of the gap controller.

5. Experimental Verification

After we completed the analysis and the design of controller, the experimental machine was built to verify the analysis. Fig. 17 shows the structure of the experimental machine. This control system is a digital controller, which consists of a personal computer and A/D & D/A boards. The A/D board converts analogue sensor output to a digital signal, the personal computer

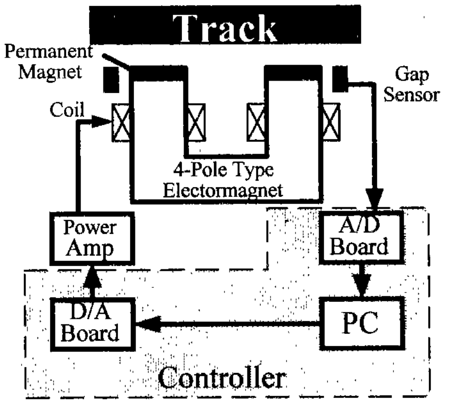


Fig. 17 The structure of the experimental machine

Table.1 Specifications of the experimental machine

Mass	m	6.7[kg]	Equilibrium gap	z_0	5.49 [mm]
Moment	J	0.0195 [kg・m^2]	Equilibrium current	i_{z0}	0[A]
Turns	N	100	Area of each pole	S	12.3 [cm^2]
Resistance of coil	R	0.55[Ω]	MMF of PM	E_{PM}	1488 [AT]
Inductance of coil	L	0.00605 [H]	Thickness of PM	l_{PM}	2.2 [mm]

calculates the output according to the control algorithm, and output the control signal through the D/A board. Table 1 gives the specifications of the experimental machine.

Fig. 18 is a photograph of the 3 d.o.f. complete suspension in the zero-power mode. Fig. 19 shows the experimental results of gap length type controller. Fig. 19(a) shows step response of the gap length and control voltage when the step command is changed form 5mm to 7mm. Fig. 19(b) shows the gap response and the voltage waveform when a 1kg mass is loaded to the suspended magnet.

Fig. 20 shows the gap response and input voltage waveform when a 1kg mass loads to the magnet in semi-zero-power control mode. The suspended body decreases the gap length to compensate the loads, the input voltage converge to zero. Fig. 21 shows the experimental results when an unbalanced load is given to the suspended body in semi-zero-power control mode. Fig. 21(a) is an illustration for this experiment. A 0.4kg mass loads to the middle point of the pole 1 and the pole 4. Because this magnet can generate unbalanced attractive forces by tilting itself, the pole 1 and pole 4 will decrease the gap length to increase the attractive forces for compensating this unbalanced load. At the same time, the gap length of the pole 2 and the pole 3 almost does not change, as shown in Fig. 21(b). The initial gap length of pole2 was smaller than pole1, since the magnetomotive force of the permanent magnet in pole2 was weaken than others. It is also confirmed that this magnet can realize unbalanced zero-power control. The gap length of the pole1 and pole4 will return to the original place after the unbalanced load is removed.

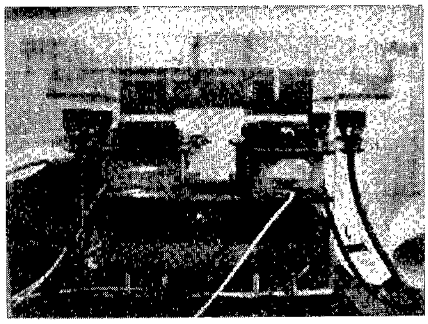
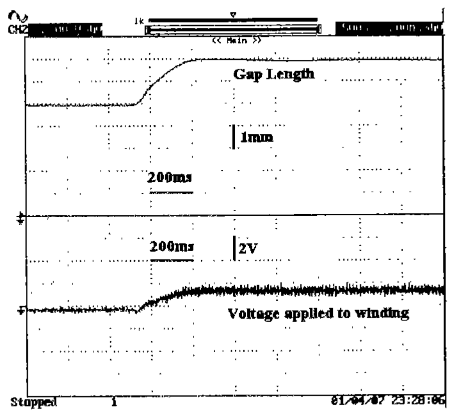
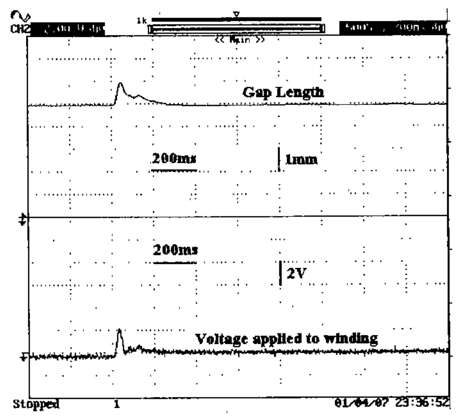


Fig. 18 A photograph of magnetic levitation



(a) Step response from 5mm to 7mm



(b) Response to a step disturbance force of 1kg

Fig. 19 Experimental results of gap-length control

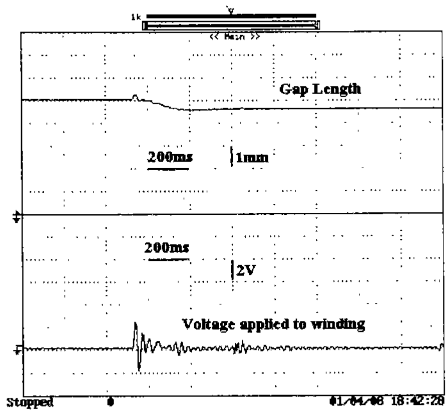
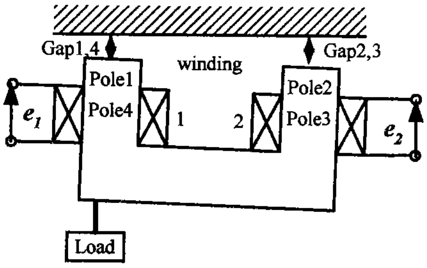
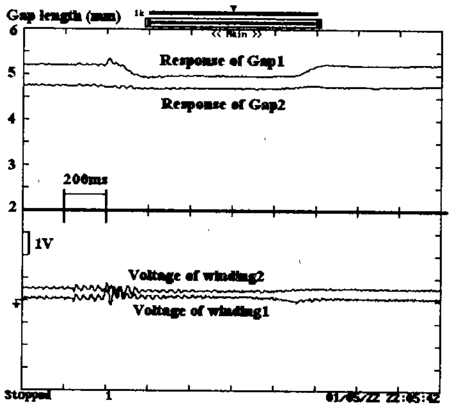


Fig. 20 Semi-zero-power control



(a) Experiment with unbalanced load



(b) Gap and control voltage responses

Fig. 21 Experimental results with unbalanced load

It can be confirmed that the magnet adjusts the gap length according to the load automatically, and the steady voltages of coils converge to zero. It can minimize energy consumption in steady state. This is a significant advantage in the convey system in which the energy is supplied to the conveyer by batteries.

6. Conclusions

A novel 4-pole 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 convey system, can be constructed by using this kind of electromagnet.

The semi-zero-power control method has been also proposed. This method can improve the performance of the zero-power levitation system. It is robust against modeling errors as well as a persistent disturbance force.

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. The combination with a linear motor and the magnet design method for reducing the weight are being studied for the next step. We expect that the proposed semi-zero-power scheme with a disturbance observer will be useful for the rejection of the armature flux interference to the magnetic levitation in the combination with a linear motor.

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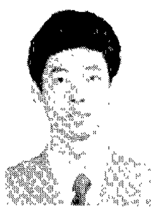

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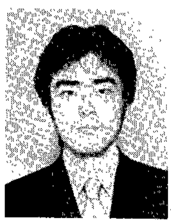

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