

4 Poles 3 Degrees of Freedom Magnetic Levitation Control and its Coordination with Two-Dimensional Linear Motor

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Abstract:

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, and the control systems are designed. The semi-zero-power controller, with a disturbance observer, is proposed to improve the performance of the control system. Furthermore, the combination with the linear motor is discussed.

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, 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. The basic structure and characteristics of this novel 4-pole type hybrid electromagnet will be described at first. The controllers are designed. The zero-power control method is applied to minimize energy consumption[1] and the semi-zero-power control method is proposed to improve the performance of zero-power control system.

The proposed 4-pole magnetic levitation system can be applied to the flexible conveyance network, when it combines with the linear motors[2]. While normal linear motors are used to provide the thrust, a 2-dimensional linear motor is used to switch the direction. As the preparation and the first step of the studies of coordination with two-dimensional linear motor, the combination with the one-dimensional linear motor will be mainly studied in this paper.

2 4-Pole Type Hybrid Electromagnet

2.1 Basic structure of 4-pole type electromagnet

The proposed novel electromagnet has 4 poles combined through yokes. Each pole consists of a permanent magnet and a coil for controlling current[2][3], shown in Fig. 1.

2.2 The control methods of magnetic levitation

The proposed electromagnet can obtain 3 d.o.f.: vertical direction z , inclination angle θ around α -axis and angle φ around β -axis respectively, as shown 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 systems are designed toward each d.o.f. independently.

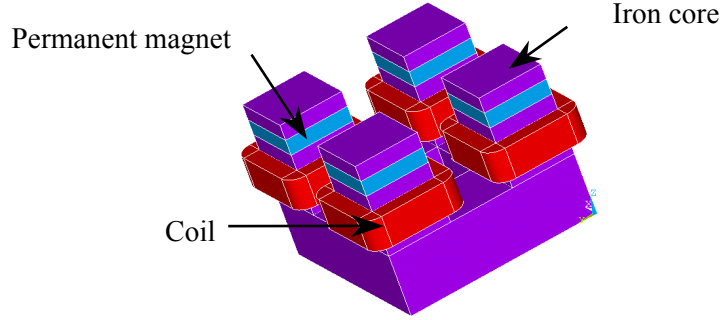


Fig. 1 Basic structure of 4-pole type hybrid electromagnet

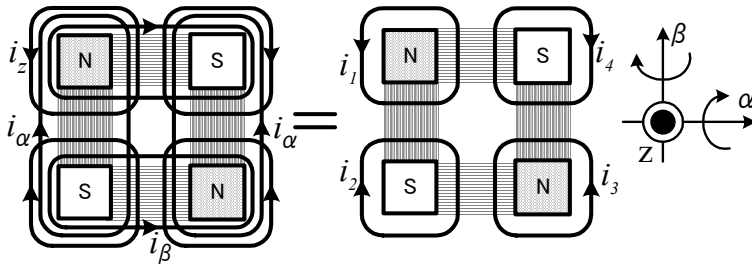


Fig. 2 Control methods of magnetic levitation

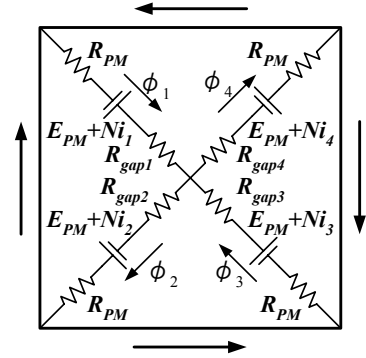


Fig.3 Equivalent magnetic circuit

2.3 The advantages of 4-pole hybrid electromagnet

Compared with the usual U-shaped magnet, 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.**

Each pole of this electromagnet is composed by control coil 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 Controllers Design

The electromagnet is unstable in EMS without control. The feedback controllers are designed based on the approximated linear model. We assume that the 4-pole electromagnet is levitated below a plane core track as a plant model. A reasonably accurate linear model can be obtained by using linear approximations of the attraction force for excursions around the nominal equilibrium point[3]. The linear plant model is represented Fig.4. The state-space equation of the linear plant model can be described as follows:

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

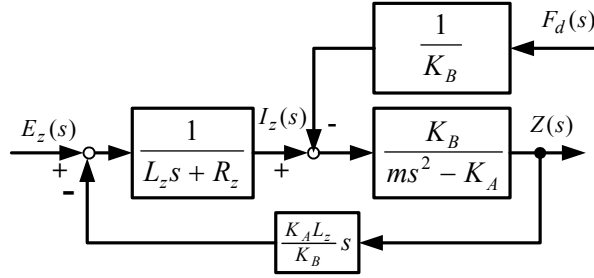


Fig.4 Linear model of z direction

The equation solely in z direction is written here due to the page limitation. The derive methods of inclination systems are similar to the vertical direction system.

3.1 Design of the zero-power controller

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. One of the advantages of this application system is that the levitated body can be supported without contacting. But, in the practical case, the power supply is 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], is a practical solution.

In zero-power control 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[2].

$$\frac{d}{dt} \begin{pmatrix} \Delta z(t) \\ \Delta \dot{z}(t) \\ \Delta i_z(t) \\ \int \Delta i_z(t) dt \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ \frac{K_A}{m} & 0 & \frac{K_B}{m} & 0 \\ 0 & -\frac{K_A}{K_B} & -\frac{R_z}{L_z} & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \Delta z(t) \\ \Delta \dot{z}(t) \\ \Delta i_z(t) \\ \int \Delta i_z(t) dt \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{L_z} \\ 0 \end{pmatrix} \Delta e_z(t) \quad (2)$$

We can design the zero-power controller using state feedback based on this equation. Fig. 5 gives the simulation results of the zero-power control. The step force, $F_d=20\text{N}$, is loaded at $t=1\text{s}$. 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.

3.2 Proposal of the semi-zero-power control

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 is changed periodically. This means that the levitated body oscillates itself. Unfortunately, the steady current cannot converge to zero in this case. The vibration itself is undesirable for transportation quality, too.

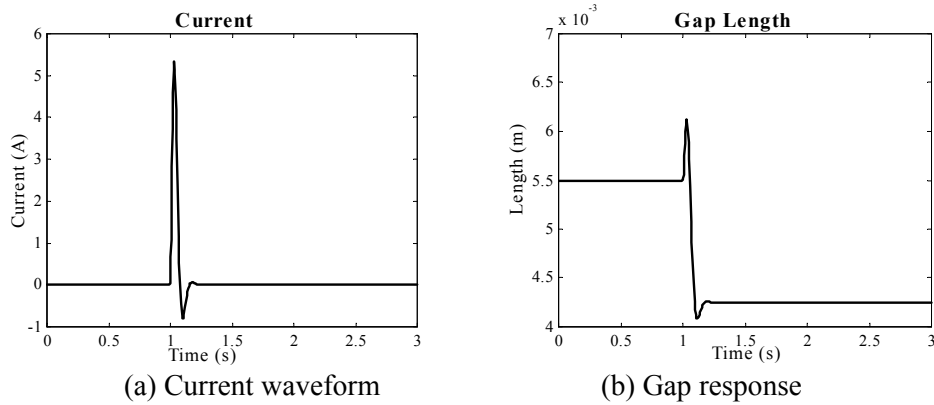


Fig. 5 Simulation results of zero-power controller

The semi-zero-power control method has been, therefore, proposed to solve this problem[3]. The concept of the semi-zero-power control is shown in Fig. 6. The normal gap-length type controller 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. From the estimated disturbance force without the periodic elements, 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. The LPF eliminates the periodic force, and the currents converge to zero slowly. Thus, the gap length will also be adjusted slowly. This controller has an intermediate characteristic between the gap-length and the zero-power controllers. It is, therefore, named as semi-zero-power controller.

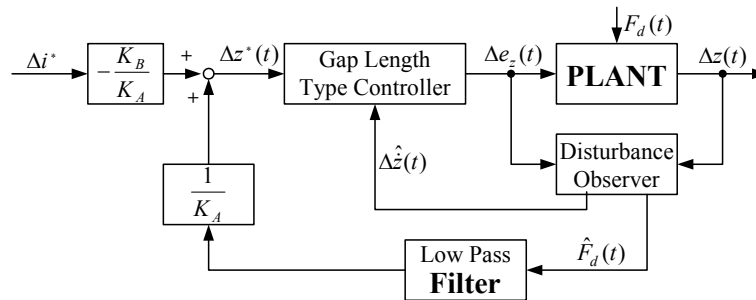


Fig. 6 Concept of semi-zero-power control

Fig. 7 and Fig. 8 show the simulation results, where the cut-off frequency of the LPF is $f_c = 0.5(\text{Hz})$. Fig. 7 is the simulation results when a step disturbance force affects the suspended body. The current of electromagnet converges to zero slowly. Fig.8 is the simulation results when a periodic disturbance force, the frequency of the periodic force is $f_{F_d} = 2(\text{Hz})$, affects the suspended body.

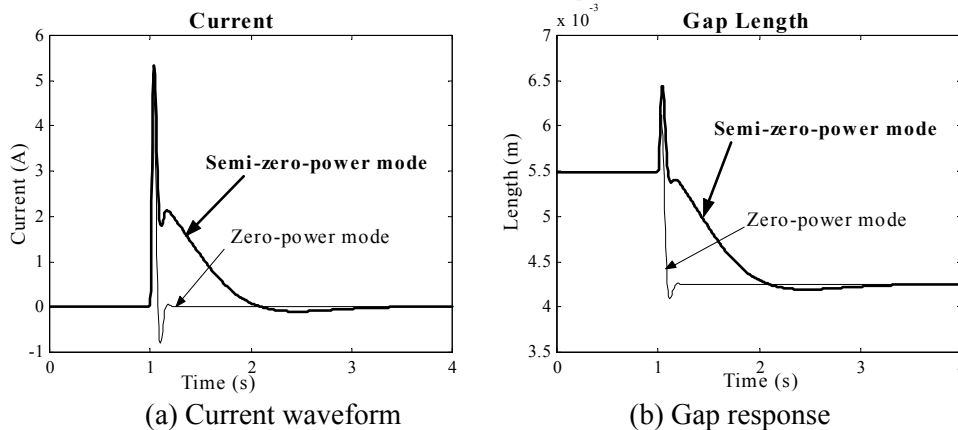


Fig. 7 Simulation results of semi-zero-power with a step disturbance

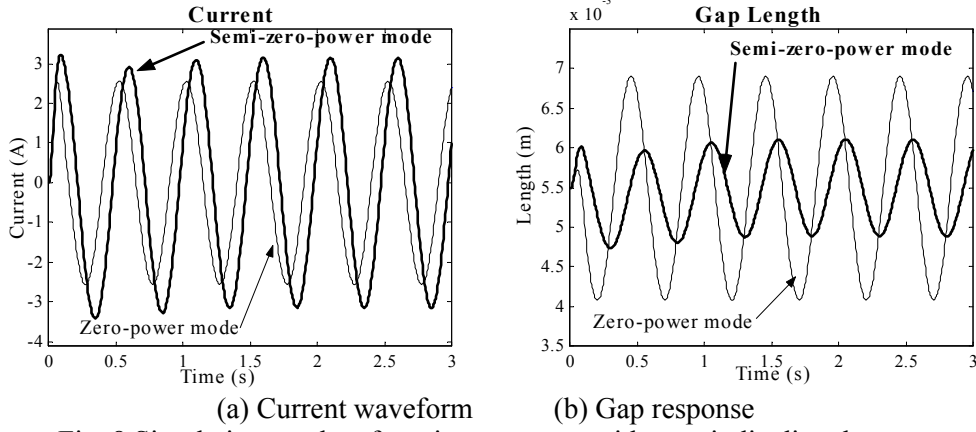


Fig. 8 Simulation results of semi-zero-power with a periodic disturbance

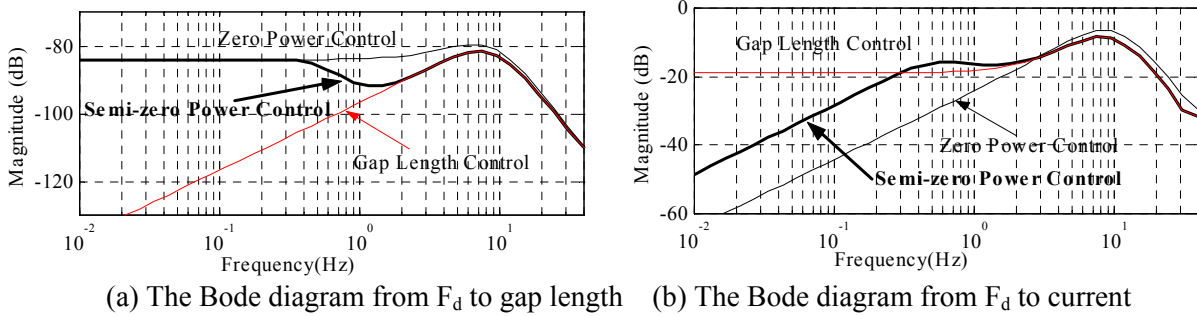


Fig. 9 The Bode diagram when the cut-off frequency of the LPF $f_c = 0.5(\text{Hz})$

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. 9 shows the Bode diagrams from disturbance force F_d to the gap length and to current. 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.

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 a user wants to eliminate in the actual environment. Moreover adjustment of the frequency will not affect the stability of the controller system.

4 Coordination with Linear Motor

4.1 Two methods of combination with linear motor

The proposed 4-pole type electromagnet can fulfill the condition of complete levitation. It, however, cannot move along the track without propulsion system. The linear drive system is used to prove the thrust force.

This 4-pole type electromagnet has 4 poles; each pole contains a permanent magnet. It constructs a linear permanent magnet synchronous motor[4], while it combines with the linear motor. There are two methods to combine the electromagnet with linear motor, as shown in Fig. 10. The first method, as shown in Fig. 10(a), needs two linear motors, which can control independently, combined through yokes. The frequencies of coil currents of these two motors are same, and the phase difference is 180° . The second method, as shown in Fig. 10(b), only needs one linear motor. The electromagnet is rotated 45° around the center.

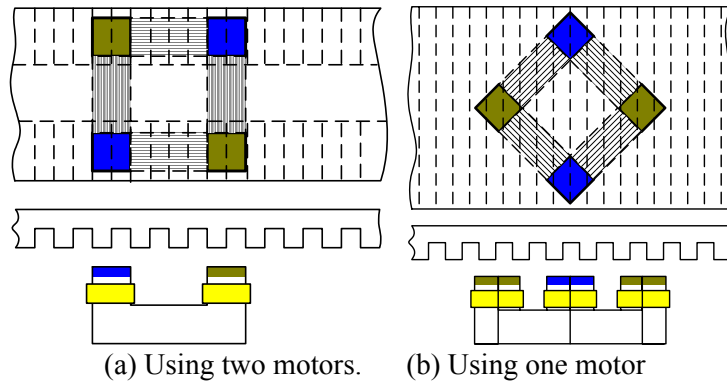


Fig.10 Combination with linear motor

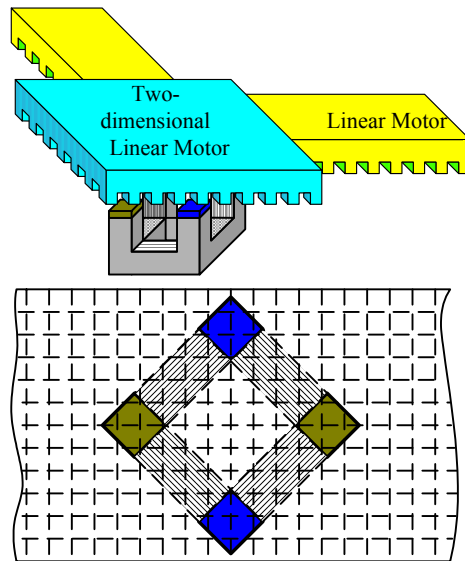


Fig.11 Combination with two-dimensional linear motor

On the other hand, the two-dimensional linear motor is used to switch the direction in the flexible conveyance network. Because this magnet has 4-pole and it has a symmetrical structure, it is suitable for combine with two-dimensional linear motor, as shown in Fig. 11. The mover can move to any direction by control the amplitude and the phase difference of the current of each direction.

When the levitation magnet combines with the linear motor, some parameters of plant model deviate from the normal model, and some other problems should occur. The coordination with linear motor, especially with two-dimensional linear motor, must be studied. As the preparation and the first step of the studies, to estimate the parameter deviation and some other problems of combination with two-dimensional linear motor, the model of combination with one-dimensional linear motor is analyzed at first.

4.2 The parameter deviation of levitation system

When the levitation magnet combines with the linear motor, the linear motor stators are used instead of the iron track. The parameters of plant model deviate from the normal model.

The attractive force is discussed at first. When the magnet suspended below the linear motor stators, the effective area for the levitation is smaller than iron track, because of the existing of the slots and teeth of linear motor stator. Let the width of the teeth is w_t , the interval of the teeth is p_t , as shown in Fig. 12. If the interval of the teeth is constant, the attractive force decreases with the decreasing of the width of the teeth. Tab. 1 shows the analysis results, when the widths of teeth are 100%(iron track), 75%, 50% and 25% of the interval of the teeth, and the gap length are 3mm, 4mm, 5mm, 6mm, 7mm, respectively. For the attractive forces are not same at different gap length, the forces are standardized, the attractive force is considered as 1 when the width of the teeth is 100%. The decrease curves are shown in Fig. 13.

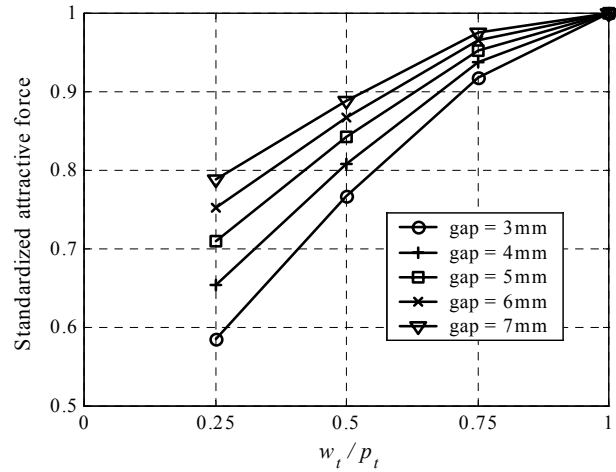
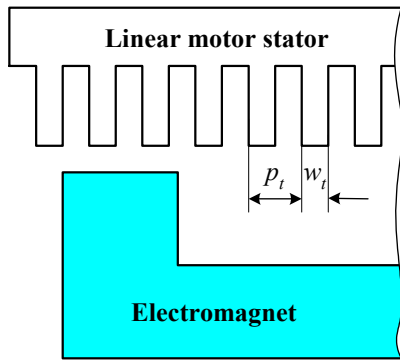


Fig. 12 Definition of the linear motor parameters Fig. 13 Attractive force and teeth width of motor

Tab. 1 The decrease of the attractive forces

	3mm	4mm	5mm	6mm	7mm
$w_t/p_t=1.00$	1	1	1	1	1
$w_t/p_t=0.75$	0.918	0.937	0.953	0.965	0.975
$w_t/p_t=0.50$	0.767	0.809	0.843	0.868	0.889
$w_t/p_t=0.25$	0.586	0.654	0.710	0.752	0.788

Next, the inductances of the magnet coil are discussed. When the electromagnet combines with the linear motor, the self-inductance and mutual inductance decrease, too. Fig. 14 shows the deviation of inductances. The analysis preconditions are:

LSM: $N_2=200$; pole pitch=33mm; $w_t=7$ mm; $p_t=11$ mm

Magnet: $B_r=1.2$ T; $l_{PM}=3$ mm; $N_I=200$; pole pitch=99mm; pole area=40x40mm²

The deviations are little enough to be ignored. Furthermore, the alteration of the inductance is little enough in the whole levitation range when the levitation body moves along the linear motor. The parameters, obtains from the normal model, can be used without adjustment when the magnet combines with the linear motor.

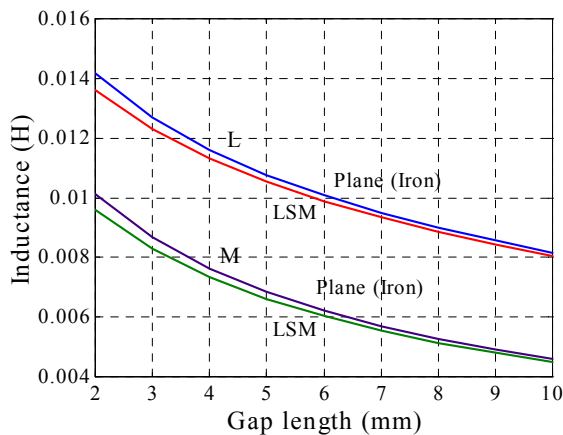


Fig. 14 The deviation of inductances

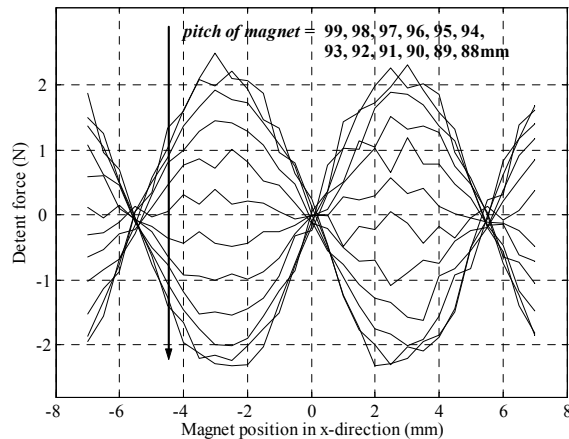


Fig. 15 Detent force and the magnet pole pitch

On the other hand, when the levitation magnet moves along the linear motor, the reluctance of linear motor and the equivalent area for levitation are changed depending on the magnet place. The magnet always tends to a place, where the reluctance is the smallest, according to the electrical machine theory. There are pulsations appear in the thrust forces and attractive forces.

This problem can be solved if the magnet pole pitch is not match the linear motor pole pitch, strictly. The error between the magnet pole pitch and the linear motor pole pitch is helpful for decreasing the pulsation of thrust forces and attractive forces. Fig. 15 shows a calculate result, where

the linear motor pole pitch is equal to 33mm, the magnet pole pitch is changed from 99mm to 88mm. From the calculate results, the pulsation in minimum if the magnet pole pitch shifts 5.5mm, which is the half of a tooth pitch of linear motor, from the strict times of pole pitch of linear motor.

5 Experimental Verification

Here, the experimental machine is built to verify the levitation system at first. Fig. 16 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 calculates the output according to the control algorithm, and output the control signal through the D/A board. Table 2 gives the specifications of the experimental machine. Fig. 17 is a photograph of the 3 d.o.f. complete suspension.

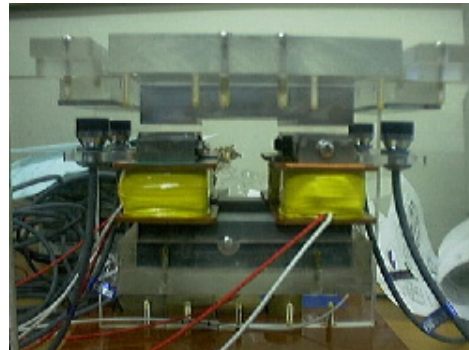
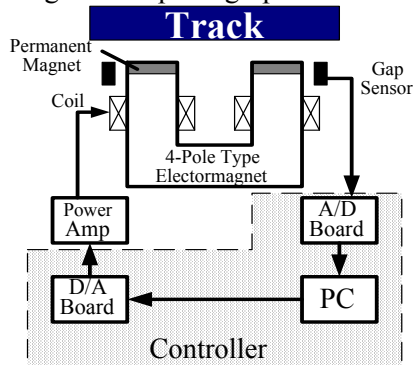


Fig. 16 The structure of the experimental machine

Fig. 17 A photograph of magnetic levitation

Table.2 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]

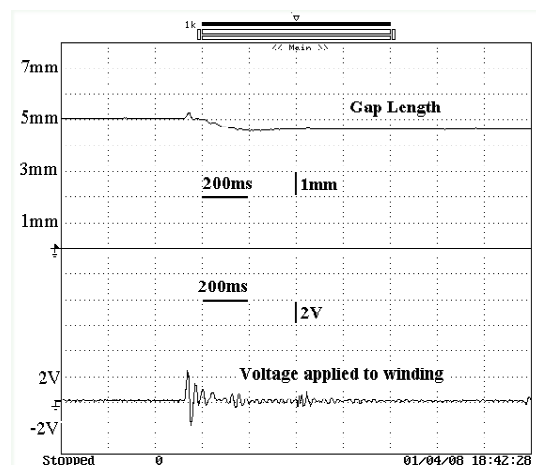


Fig. 18 Response in semi-zero-power control

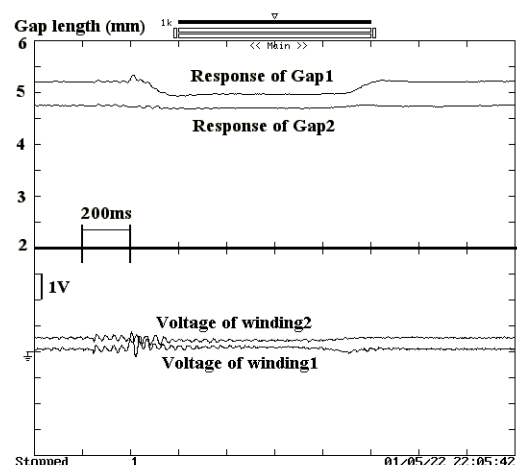


Fig. 19 Experimental results with unbalanced load

Fig. 18 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. 19 shows the experimental results when an unbalanced load is given to the suspended body in semi-zero-power control mode. 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 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 do not change. The gap length of the pole 1 and pole 4 return to the original place after the unbalanced load is removed.

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 conveyor by batteries.

The test machine for combination with linear drive is being built now, as shown in Fig. 20.

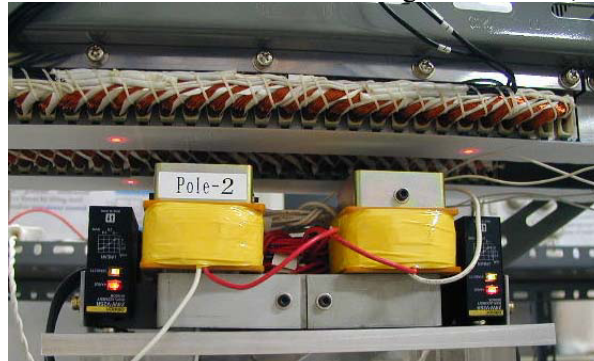


Fig.20 A photograph of test machine for combination with linear motor

6 Conclusions

A novel 4-pole type hybrid electromagnet and its coordination with two-dimensional linear motor have been proposed in this paper. 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 the proposed electromagnet. The semi-zero-power control method has been also proposed. This method can improve the performance of the energy-saving levitation system. It can minimize the energy consumption and reduce vibration when the magnet is combined with the linear motor.

The method of combination with a linear motor has been discussed, too. The effects of linear motor slot, the relation between the detent forces and the pole pitch of linear motor and electromagnet, have been studied, as the preparation and the first step of the studies and the experiment of coordination with two-dimensional linear motor. A test bench for the combination with a linear drive is being prepared, and we expect the experimental results of the linear drive can be presented at the next step.

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