LINEAR CARRIER SYSTEM WITH SELF-SENSING MAGNETIC SUSPENSION TRACKS

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ABSTRACT

A magnetically suspended linear carrier system is developed which has tracks composed of electromagnets for suspension. The electromagnets are operated in the self-sensing mode to omit gap sensors along the tracks. Permanent magnets for power saving are built in the carrier so that the number of permanent magnets is reduced, compared to systems with permanent magnets in the stator. A new combined permanent and electromagnet is developed for the coil currents to overcome only the air-gap reluctance primarily. The magnetic and electrical circuits of the developed hybrid magnet are analyzed to show that the observer-based self-sensing suspension method can be applied. The self-sensing suspension is realized and the virtually zero power suspension is automatically accomplished.

INTRODUCTION

Magnetic suspension systems are particularly suitable for vacuum techniques and clean-room instrument because they have the following characteristics: *no mechanical contact, absence of lubrication*, and *no contaminating wear*. One of the obstacles on the way of industrialization is that they generally need more cost and space than the mechanical suspensions. An effective method of solving these problems is the combined use of electromagnets for force generator and position sensor (Vischer, 1988). This paper applies such self-sensing magnetic suspension to a magnetically suspended linear carrier system. The developed system has tracks composed of electromagnets for suspension. Conventional systems of this configuration have problems related to the measurement of suspension gaps; when probe type gap sensors such as eddy current type sensor are placed on the carrier, wiring or wireless signal transmission from the carrier is necessary; otherwise, a lot of sensors must be placed along the tracks on the stator, which causes high cost in manufacturing and a time-consuming job in calibrating the sensors. This problem can be overcome by operating the electromagnets in the self-sensing mode (Mizuno *et al.*, 1997).

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This paper describes the principal design concepts of the developed magnetically suspended linear carrier system. Since this system uses new-type combined permanent and electromagnet for zero power suspension, the magnetic and electrical circuits of this hybrid magnet are studied analytically. The analysis shows that its dynamics are similar to those of a standard voltage-controlled active magnetic bearing (AMB) so that the observer-based self-sensing suspension method is applicable. The self-sensing suspension is realized in a suspension system with a developed hybrid magnet. It is experimentally confirmed that the virtually zero power suspension is automatically accomplished.

PRINCIPAL DESIGN CONCEPTS

CLASSIFICATION OF CONVENTIONAL LINEAR SUSPENSION SYSTEMS

A number of electromagnetic linear suspension systems of active type have been developed. Most of them can be classified into two types as shown **Fig.1**.

(a)Electromagnets and sensors for suspension are put on the carrier (type I),

(b)Electromagnets and sensors for suspension are placed in the stator (type II).

The type I has an advantage in cost because the number of electromagnets and sensors necessary for suspending a carrier is independent of the length of tracks. However, it has a problem of power supply for suspension. Wiring to the carriage causes contamination and also entanglement. Building a battery in the carrier makes the carrier heavier; the necessity of recharging the on-board battery is also a practical problem.

The type II has not such problems related to power supply. However, the number of electromagnets and sensors increases in proportion to the length of tracks. Placing probe type sensors along the tracks on the stator causes high cost in manufacturing and a time-consuming work in calibrating them. However, this problem can be overcome by using the self-sensing magnetic suspension (Mizuno *et al.*, 1997).

SELF-SENSING SUSPENSION

Several methods of self-sensing suspension have been proposed and studied. They are classified into two main categories:

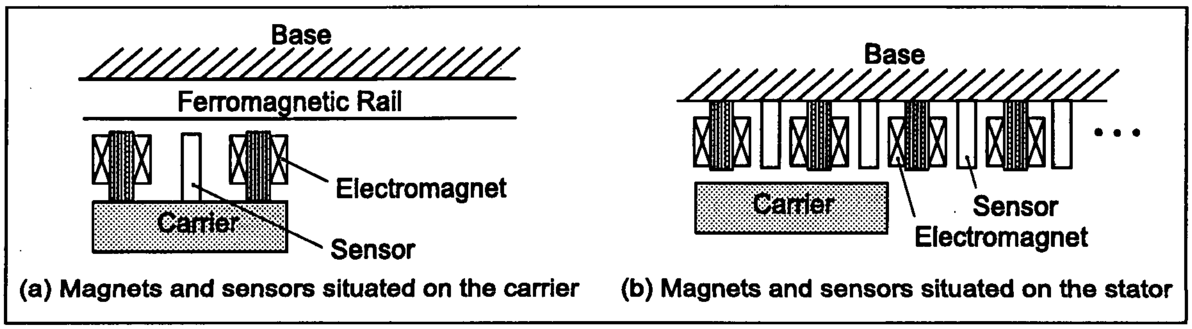

Figure 1. Schematic drawings of linear magnetic suspension systems

(1) using observer-based controller (Vischer, 1988; Vischer and Bleuler, 1990),
(2) superimposing a high-frequency alternating excitation.

The method (1) utilizes the controllability and observability of voltage-controlled magnetic suspension systems in which only the coil currents are sensed. The procedures of the control system design follow the classical state-space approach. First, a state feedback controller is designed on the assumption that all the state variables, *i.e.* displacement, velocity and coil currents, are detected. Next, an observer is constructed for estimating all the states from the measured coil currents. Finally, the estimated signals produced by the observer are used in the feedback controller instead of the actual states.

This type of self-sensing magnetic suspension system has a unique characteristic. The stationary values of the coil currents are independent of static load force acting on the suspended object, and power dissipation in the coils automatically becomes zero if the bias flux is provided by permanent magnets (Mizuno and Bleuler, 1995). This means that the virtually zero power control is automatically achieved in self-sensing suspension systems while more sophisticated control algorithms are necessary for the zero power suspension in conventional magnetic suspension systems with displacement feedback.

The method (2) is to apply a high-frequency signal for the measurement of gap in addition to control signal; its frequency is chosen to be high enough not to disturb the motion of the suspended object. In most cases the gap is estimated as a function of the coil inductance.

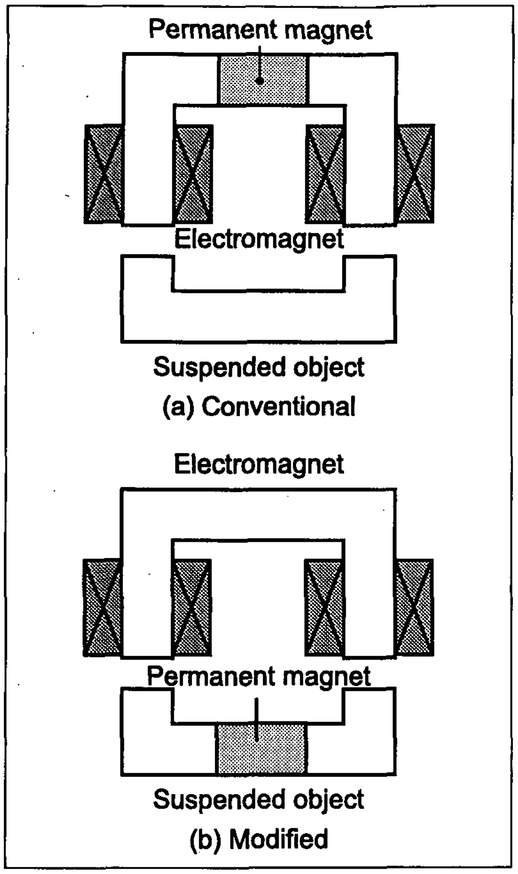

Figure 2. Configuration of a hybrid magnet

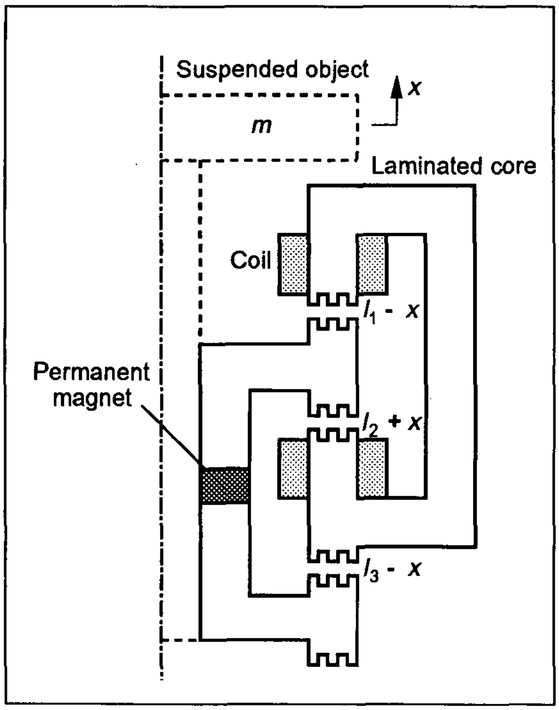

Figure 3. Structure of the developed hybrid magnet

HYBRID MAGNETS FOR VIRTUALLY ZERO POWER SUSPENSION

The virtually zero power suspension is effective for power saving, where permanent magnets supply attractive force balancing the total weight of the carrier with its loads. The conventional zero-power systems use a hybrid magnet which is composed of electromagnets and a permanent magnet as shown by **Fig.2 (a)** (Morishita *et al.*, 1989). However, a lot of permanent magnets are necessary in linear carrier systems of the type II. The configuration shown by **Fig.2 (b)**, where permanent magnets are built in the carrier, enables the number of permanent magnets to be reduced.

Both the configurations shown in Fig.2 have a problem that the coil current must overcome the reluctance of the permanent magnet in addition to the air-gap reluctance. **Figure 3** shows a schematic of the configuration of a hybrid magnet developed in this research. The magnetic circuit is designed so that the coil current primarily overcome only the air-gap reluctance although a permanent magnet is built in the carrier. The magnetic and electrical circuits related to this new-type hybrid magnet will be studied in the next section.

BASIC MODEL

MAGNETIC CIRCUIT

The hybrid magnet shown in Fig.3 has a permanent magnet (PM), two coils and three gaps. It is assumed in the following analysis that

(1) Leakage and fringing effects are neglected.
(2) Magnetic reluctance exist only in the air gaps and the PM; the PM is treated as an air gap of length l_m.
(3) Two windings are connected in series.
(4) The PM produces magnetmotive force $H_c l_m$, which is relatively larger than those produced by the coil current i.

Figure 4 shows an equivalent circuit for the magnetic circuit. The fluxes flowing through the gaps satisfy

$$\Re_1 \Phi_1 + (\Re_m + \Re_3)\Phi_3 = H_c l_m + Ni \tag{1}$$

$$\Re_2 \Phi_2 + (\Re_m + \Re_3)\Phi_3 = H_c l_m - Ni \tag{2}$$

$$\Phi_3 = \Phi_1 + \Phi_2 \tag{3}$$

where N is the winding number of each coil and $\Re_k$ is the magnetic reluctance due to the kth gap (k=1, 2, 3) or the permanent magnet ($k=m$). From (1) to (3), we get

$$\Phi_1 = \frac{2(\Re_m + \Re_3)Ni + \Re_2(H_c l_m + Ni)}{\Re_2(\Re_m + \Re_3) + \Re_1(\Re_m + \Re_2 + \Re_3)}, \tag{4}$$

$$\Phi_2 = \frac{-2(\Re_m + \Re_3)Ni + \Re_1(H_c l_m - Ni)}{\Re_2(\Re_m + \Re_3) + \Re_1(\Re_m + \Re_2 + \Re_3)}, \tag{5}$$

$$\Phi_3 = \frac{\Re_1(H_c l_m - Ni) + \Re_2(H_c l_m + Ni)}{\Re_2(\Re_m + \Re_3) + \Re_1(\Re_m + \Re_2 + \Re_3)}. \tag{6}$$

The magnetic reluctances are given by

$$\Re_1 = \frac{l_1 - x}{\mu_0 S}, \quad \Re_2 = \frac{l_2 + x}{\mu_0 S}, \quad \Re_3 = \frac{l_3 - x}{\mu_0 S}, \quad \Re_m = \frac{l_m}{\mu_0 S}, \qquad (7), (8), (9), (10)$$

where S is the cross section area of the magnetic circuit, l_k is the length of the kth gap at the equilibrium position (k=1, 2, 3) and x is the displacement of the suspended object from the equilibrium position.

Assuming that deviations from the equilibrium position are small and the length of the PM is large compared to the air gaps, the fluxes are approximately given by

$$\Phi_1 \cong \mu_0 S \frac{(l_2 + x)H_c l_m + (2l_m + 2l_3 + l_2)Ni}{(l_1 + l_2)(l_m + l_3) + l_1 l_2}, \tag{11}$$

$$\Phi_2 \cong \mu_0 S \frac{(l_1 - x)H_c l_m - (2l_m + 2l_3 + l_1)Ni}{(l_1 + l_2)(l_m + l_3) + l_1 l_2}, \tag{12}$$

$$\Phi_3 \cong \mu_0 S \frac{(l_1 + l_2)H_c l_m + (l_2 - l_1 - 2x)Ni}{(l_1 + l_2)(l_m + l_3) + l_1 l_2}. \tag{13}$$

The attractive forces are also given by

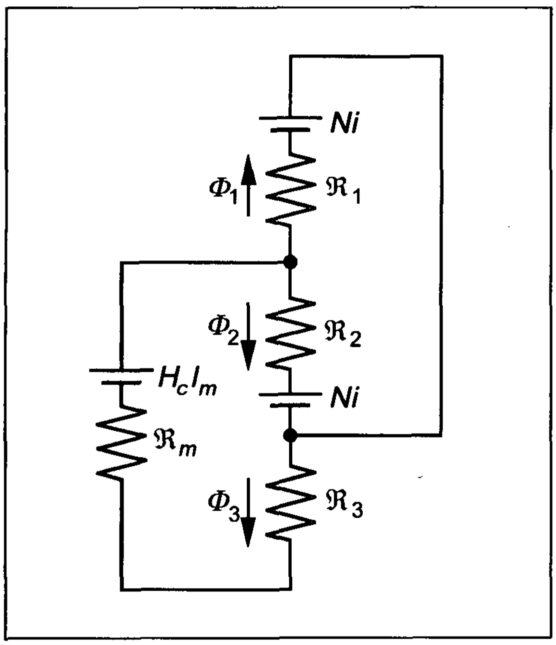

Figure 4. Equivalent circuit

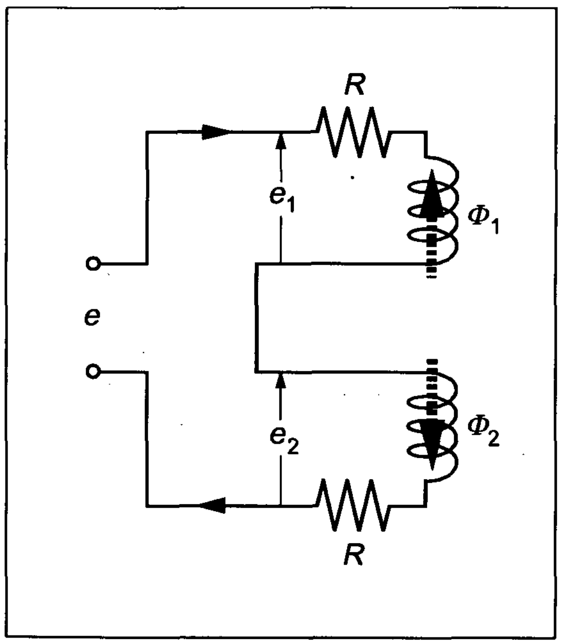

Figure 5. Electrical circuit

$$F_1 = \frac{\Phi_1^2}{\mu_0 S} \cong \mu_0 S \frac{l_2^2 (H_c l_m)^2 + 2l_2 (H_c l_m)^2 x + 2l_2 (2l_m + 2l_3 + l_2)(H_c l_m) Ni}{\{(l_1 + l_2)(l_m + l_3) + l_1 l_2\}^2}, \tag{14}$$

$$F_2 = \frac{\Phi_2^2}{\mu_0 S} \cong \mu_0 S \frac{l_1^2 (H_c l_m)^2 - 2l_1 (H_c l_m)^2 x - 2l_1 (2l_m + 2l_3 + l_1)(H_c l_m) Ni}{\{(l_1 + l_2)(l_m + l_3) + l_1 l_2\}^2}, \tag{15}$$

$$F_3 = \frac{\Phi_3^2}{\mu_0 S} \cong \mu_0 S \frac{(l_1^2 + l_2^2)(H_c l_m)^2 + 2(l_2^2 - l_1^2)(H_c l_m) Ni}{\{(l_1 + l_2)(l_m + l_3) + l_1 l_2\}^2}. \tag{16}$$

EQUATION OF MOTION

It is assumed for simplicity that the suspended object moves only in the vertical direction. The linearized equation of motion about the equilibrium states becomes

$$\begin{aligned} m\ddot{x} &= F_1 - F_2 + F_3 - mg \\ &\cong K_s x + K_i i \end{aligned}, \tag{17}$$

where m is the equivalent mass of the suspended object and

$$K_s = 2\mu_0 S \frac{(l_1 + l_2)(H_c l_m)^2}{\{(l_1 + l_2)(l_m + l_3) + l_1 l_2\}^2}, \quad K_i = 2\mu_0 S \frac{2(l_m + l_3)(l_1 + l_2) + 2l_2^2}{(l_1 + l_2)(l_m + l_3) + l_1 l_2} (H_c l_m) N.$$

ELECTRICAL CIRCUIT

Figure 5 shows a schematic diagram of the electrical circuit related to the hybrid magnet, where e represents the output voltage of an power amplifier. The voltage across each coil is given by

$$\begin{aligned} e_1 &= Ri + \frac{\mathrm{d}}{\mathrm{d}t}\Phi_1 \\ &\cong Ri + \mu_0 S\left(\frac{H_c l_m}{(l_1 + l_2)(l_m + l_3) + l_1 l_2}\frac{\mathrm{d}x}{\mathrm{d}t} + \frac{2l_m + 2l_3 + l_2}{(l_1 + l_2)(l_m + l_3) + l_1 l_2} N \frac{\mathrm{d}i}{\mathrm{d}t}\right), \end{aligned} \tag{18}$$

$$\begin{aligned} e_2 &= Ri - \frac{\mathrm{d}}{\mathrm{d}t}\Phi_2 \\ &\cong Ri + \mu_0 S\left(\frac{H_c l_m}{(l_1 + l_2)(l_m + l_3) + l_1 l_2}\frac{\mathrm{d}x}{\mathrm{d}t} + \frac{2l_m + 2l_3 + l_1}{(l_1 + l_2)(l_m + l_3) + l_1 l_2} N \frac{\mathrm{d}i}{\mathrm{d}t}\right). \end{aligned} \tag{19}$$

Since the two coils are connected in series, the sum of these voltage is equal to the supply voltage.

$$e = e_1 + e_2$$
$$\cong R_s i + K_b \frac{dx}{dt} + L\frac{di}{dt}, \tag{20}$$

where

$$R_s = 2R, \quad K_b = 2\mu_0 S \frac{H_c l_m}{(l_1 + l_2)(l_m + l_3) + l_1 l_2}, \quad L = \mu_0 SN \frac{l_1 + l_2 + 2(l_m + l_3)}{(l_1 + l_2)(l_m + l_3) + l_1 l_2}.$$

It is to be noted that the inductance L becomes

$$L \cong \frac{2\mu_0 SN}{l_1 + l_2} \tag{21}$$

when $l_m >> l_1, l_2$. Equation (21) means that L is independent of the displacement of the suspended object x so that the self-sensing method (2) is not applicable in this case.

STATE SPACE EQUATION

From (17) and (20), we get

$$\frac{d}{dt}\begin{bmatrix} x \\ \dot{x} \\ i \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ a_{21} & 0 & a_{23} \\ 0 & -a_{32} & -a_{33} \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ b \end{bmatrix} e, \tag{22}$$

where

$$a_{21} = \frac{K_s}{m}, \quad a_{23} = \frac{K_i}{m}, \quad a_{32} = \frac{K_b}{L}, \quad a_{33} = \frac{R_s}{L}, \quad b = \frac{1}{L}.$$

Equation (22) is same as the state-space equation describing the dynamics of voltage-controlled active magnetic bearings. Therefore, the self-sensing method (1) can be applied.

DEVELOPED MAGNETICALLY SUSPENDED CARRIER SYSTEM

OUTLINE

A schematic drawing of the developed linear suspension system is shown by **Fig.6**. The representative dimensions for this system are listed in **Table 1**. In this system, the vertical position, roll and pitch of the carrier are actively controlled by four electromagnets in the stator. The lateral position and yaw are passively supported. To strengthen the stiffness in the passive direction, grooves are cut on the pole surfaces of the magnets.

Two stations are located at the ends of the track having a length 865 mm; only electromagnets for self-sensing suspension are placed between them. The acceleration, deceleration and positioning of the carrier in the propulsion direction are performed at these stations while the carrier runs with inertia between them.

TABLE 1 SPECIFICATIONS FOR THE DEVELOPED CARRIER SYSTEM

Carrier dimensions	193 mm L × 106 mm W × 133 mm H
Carrier weight	4 kg
Stator (with a track) dimensions	865 mm L × 182 mm W × 177 mm H
Permanent magnet	Neodymium-boron-iron magnet

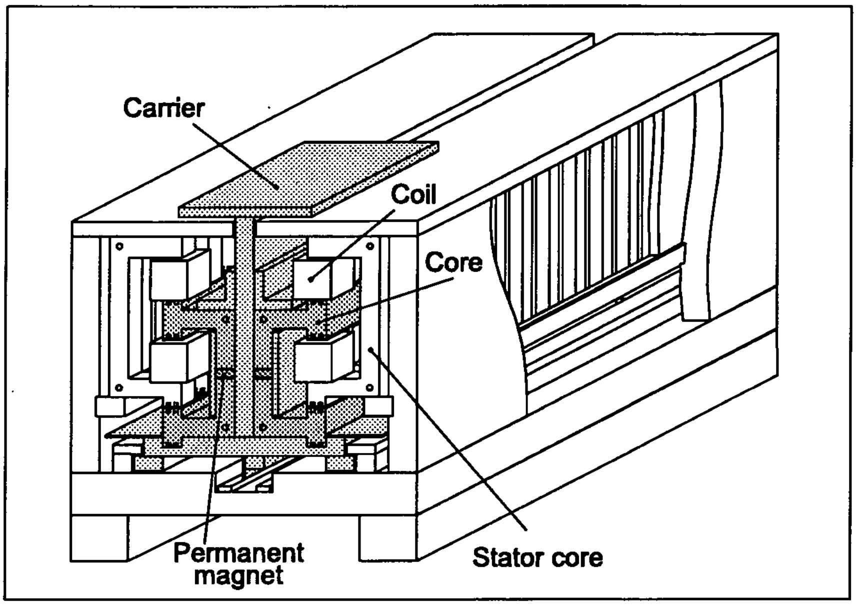

Figure 6. Magnetically suspended linear conveyer system

EXPERIMENTS

In order to examine the feasibility of the observer-based self-sensing suspension in the developed system, a single-degree-of-freedom model is built for basic experimental study (**Fig.7**). In this model, the fixed and suspended elements are interchanged with each other because it is technically difficult to constrain the motions of the carrier to one degree of freedom. An electromagnet to be placed in the stator is fixed to an arm, which will be an object to be suspended. This arm is supported at an end with a ball bearing pivot so that it has a single-degree-of-freedom motion. The carrier is fixed to the base.

Designed observer-based controllers are implemented with a DSP-based digital controller; the DSP is a TMS320C40. The sampling period is 100 μsec.

Figure 8 shows the response of one of the designed self-sensing suspension systems when a step-wise disturbance acts on the suspended object. Comparing the detected displacement (a) with its estimated signal (b), we observe that both agree well in the transient, but differ in the stationary; the stationary value of the estimated displacement does not change due to static disturbance acting on the suspended object. The steady value of the coil current also converges

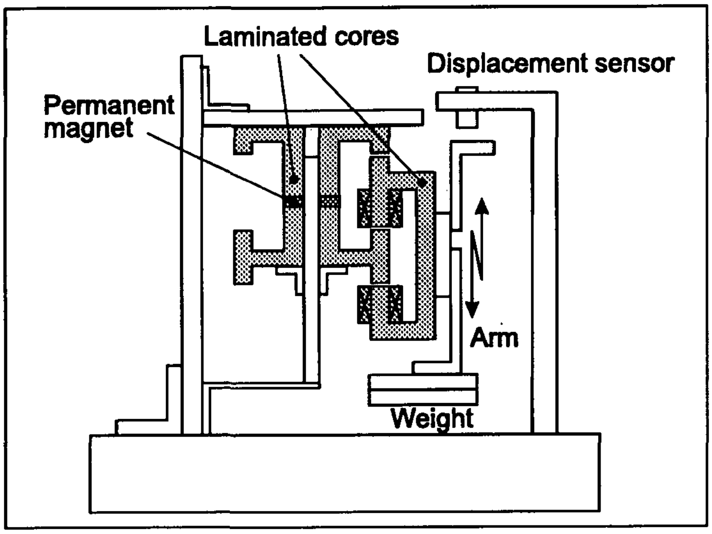

Figure 7. Experimental setup

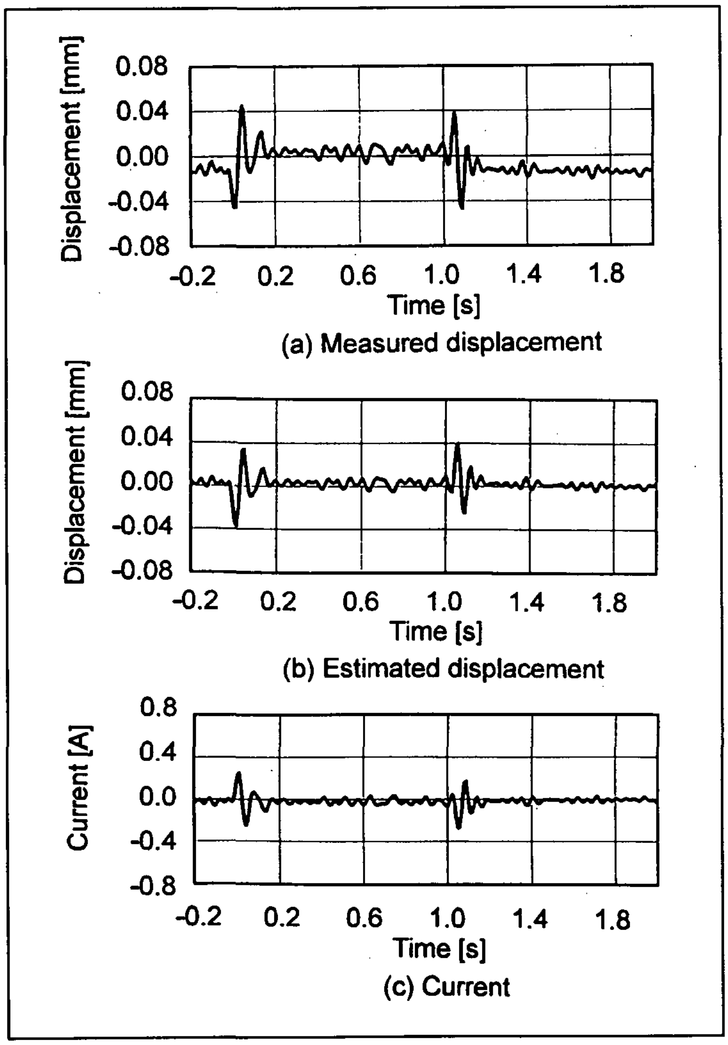

Figure 8. Responses of the self-sensing suspension system when a step-wise disturbance acts on the suspended object

to zero (Fig.8 (c)). These results demonstrate well the characteristics of the observer-based self-sensing suspension systems.

CONCLUSIONS

The design concepts of the developed magnetically suspended carrier system were presented. The developed system has several characteristics:

(1) Tracks are composed of electromagnets for magnetic suspension.

(2) The electromagnets work both for force generator and gap sensor (self-sensing operation).

(3) Permanent magnets for power saving are built in the carrier.

(4) The developed hybrid magnet has such a magnetic circuit that the coil current primarily overcome only the air-gap reluctance.

(5) The dynamics of a single-degree-of-freedom suspension system with a developed hybrid magnet is similar to the dynamics of a standard voltage-controlled magnetic bearing.

The experiments carried out with a single-degree-of-freedom model demonstrated that the observer-based self-sensing suspension was successfully implemented and virtually zero power control was automatically achieved.

Further experimental works necessary for the realization of contactless transportation,

(i) self-sensing suspension of the carrier by three-degree-of-freedom active control,

(ii) switching actuated magnets according to the movement of the carrier,

are under way.

ACKNOWLEDGMENT

This work is supported in part by Electro-Mechanic Technology Advancing Foundation, The Mikiya Science and Technology Foundation and Foundation for Promotion of Advanced Automation Technology.

REFERENCES

Mizuno, T. and H. Bleuler. 1995. "Self-Sensing Magnetic Bearing Control System Design Using the Geometric Approach," *Control Engineering Practice*, 3(7): 925-932.

Mizuno, T., E. Kitahara and K. Araki. 1997. "Application of Self-sensing Magnetic Suspension to a Linear Carrier System," *Preliminary Proc. 4th International Symposium on Magnetic Suspension Technology*.

Morishita, M., T. Azukizawa, S. Kanda, N. Tamura and Yokoyama, T. 1989. "A New Maglev System for Magnetically Levitated Carrier System," *IEEE Trans. on Vehicular Technology*, 38(4): 230-236.

Vischer, D. 1988. "Sensorlose und spannungsgesteuerte Magnetlager," *Doctor Thesis* Nr.8665, ETH Zürich.

Vischer, D. and H. Bleuler. 1990. "A New Approach to Sensorless and Voltage Controlled AMBs Based on Network Theory Concept," *Proc. 2nd International Symposium on Magnetic Bearings*, Univ. of Tokyo: 301-306.