APPLICATION OF SELF-SENSING MAGNETIC SUSPENSION TO A LINEAR CARRIER SYSTEM

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SUMMARY

A magnetically suspended linear carrier system is developed which has electromagnets for suspension on the stator. The electromagnets are used not only for force generation but also for gap sensing so that sensors to be placed along the tracks can be omitted. Permanent magnets for power saving are built in the carrier so that the number of permanent magnets are reduced, compared to systems with permanent magnets in the stator. The virtually zero power suspension is automatically accomplished by applying the observer-based self-sensing suspension method. This paper describes the basic configurations of the developed magnetically suspended carrier system, and demonstrates experimental results on the self-sensing suspension.

INTRODUCTION

Magnetic suspension systems have many advantages over conventional mechanical suspensions:

- no mechanical contact,
- absence of lubrication,
- no contamination due to wear.

Therefore, they are particularly suitable for vacuum and clean-room environments. However, they generally are more costly and need larger space than mechanical suspensions. These are critical obstacles to widening their application fields. The self-sensing or sensorless operation is a promising method of removing these obstacles because it enables the omission of displacement sensors (ref. 1-3).

This paper applies the self-sensing magnetic suspension to a magnetically suspended linear carrier system. The developed system has electromagnets for suspension on the stator. Conventional systems of this configuration have problems related to the measurement of suspension gaps. When probe type gap sensors such as eddy current type sensors 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; this causes high cost in manufacturing and leads to a time-consuming job in calibrating the sensors. This problem can be overcome by using the self-sensing or sensorless magnetic suspension. The combined use of the electromagnets as actuator and sensor can avoid placing many sensors along the tracks.

One of the promising methods of minimizing the energy required to suspend the carrier is to use hybrid magnets, composed of electromagnets and permanent magnets, and to control the electromagnets to maintain air gap length so that the attractive force by the permanent magnet balances the total weight of the carrier (*virtually zero power* suspension) (ref. 4, 5). However, many permanent magnets are necessary in the carrier systems where the suspension magnets are placed on the stator if conventional hybrid magnets are used. In the developed system, permanent magnets are built in the carrier so that the number of permanent magnets are minimized. Moreover, the virtually zero power suspension is automatically accomplished by applying the observer-based self-sensing suspension methods (ref. 3).

This paper describes the basic configurations of the developed magnetically suspended carrier system, and demonstrates some experimental results of the self-sensing suspension.

DESIGN CONCEPTS

Classification of Conventional Linear Suspension Systems

A number of electromagnetic linear suspension systems of the active type have been developed (ref. 6). Most of them are classified into two types as shown in **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 configuration of (a) has an advantage in cost because of the numbers of electromagnets and sensors necessary for suspending a carrier are independent of the length of the 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 (ref. 5) makes the carrier heavier; the necessity of recharging the on-board battery is also a practical problem.

The configuration of (b) has no such problems related to power supply. However, the numbers of electromagnets and sensors increase in proportion to the length of the track. Placing probe type sensors along the tracks on the stator causes high cost in manufacturing and time-consuming work in calibrating them. The main purpose of this paper is to overcome this problem by using the self-sensing magnetic suspension.

Permanent Magnets for Virtually Zero Power Suspension

The virtually zero power suspension is very effective for power saving, where permanent magnets supply an attractive force balancing the total weight of the carrier with its loads (ref. 5). The conventional zero-power systems use a hybrid magnet which is composed of electromagnets and a permanent magnet as shown in **Fig. 2(a)**. However, a lot of permanent magnets are necessary in linear carrier systems of type I when the conventional hybrid magnets are used. The configuration shown in **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 overcomes only the air-gap reluctance although a permanent magnet is built in the carriage.

Self-Sensing Suspension

In the developed linear carriage system, gap sensors to be placed along the track are omitted by the combined use of electromagnets as force generator and position sensor. These are two categories of such self-sensing methods:

(1) using observer-based controller (ref. 1-3),

(2) superimposing a high-frequency alternating excitation (ref. 7-9).

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, the power dissipation in the coils automatically becomes zero if the bias flux is provided by permanent magnets. This means that the virtually zero power control is automatically achieved in self-sensing suspension systems (ref. 3) while more sophisticated control algorithms are necessary for the zero power suspension in conventional magnetic suspension systems with displacement feedback (ref. 4, 5). In this research, therefore, method (1) is applied for realizing self-sensing suspension.

DEVELOPED MAGNETICALLY SUSPENDED CARRIAGE SYSTEM

A schematic drawing of the developed linear suspension system is shown by **Fig. 4**. The representative dimensions for the 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 of 865 mm. The acceleration, deceleration and positioning of the carrier in the propulsion direction will be done inside these stations. The carrier runs with inertia between the station where only electromagnets for self-sensing suspension are placed.

EXPERIMENTS

In order to examine the feasibility of the observer-based self-sensing suspension in the developed carrier system, a single-degree-of-freedom model was built for basic experimental study (**Fig. 5**). 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.

The DSP-based digital controller is used for the implementation of the designed observer-based self-sensing controllers. A full-order state observer is used in estimating the state variables. The sampling period is 100 msec.

Figure 6 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 to zero (Fig. 7(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 discussed. The developed system is characterized by

(1) Electromagnets for suspension are placed in the stator.
(2) They 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 a magnetic circuit such that the coil current primarily overcomes only the air-gap reluctance.
(5) Virtually zero power control is automatically performed by using the observer-based self-sensing controller.

The experiments carried out with a single-degree-of-freedom model demonstrated that the self-sensing suspension could be realized in a suspension system with the developed hybrid magnet.

Further experimental work is underway to realize the completely contactless transportation of the carrier with the self-sensing suspension.

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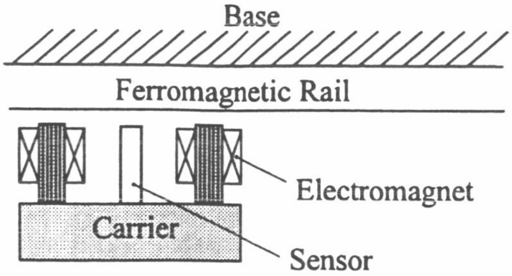
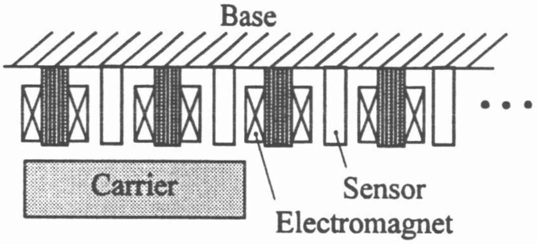
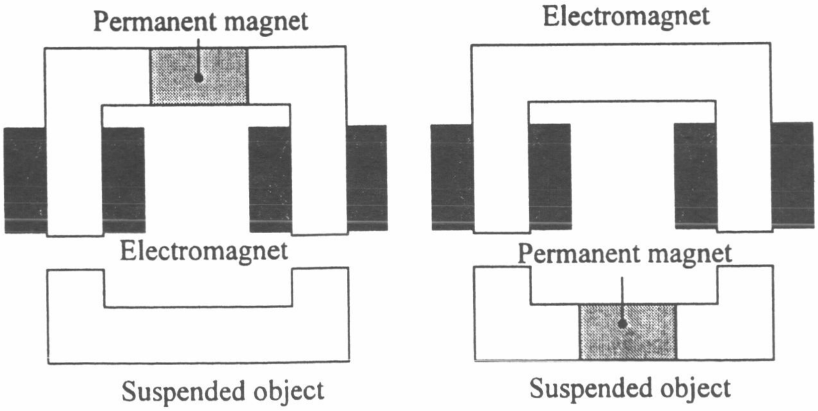


(a) magnets and sensors situated on the carrier



(b) magnets and sensors situated on the stator

Figure 1. Schematic drawing of linear magnetic suspension systems.



(a) conventional

(b) modified

Figure 2. Configuration of a hybrid magnet.

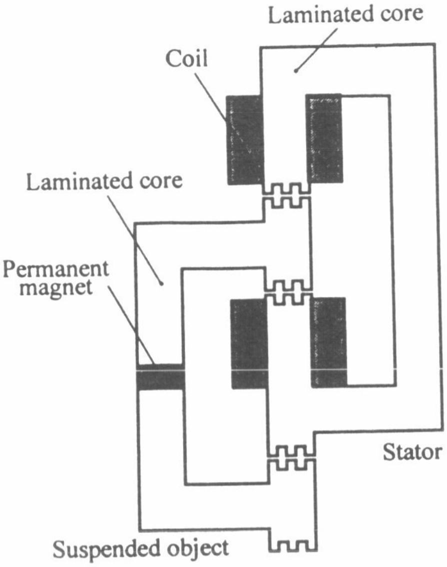


Figure 3. Structure of the developed hybrid magnet.

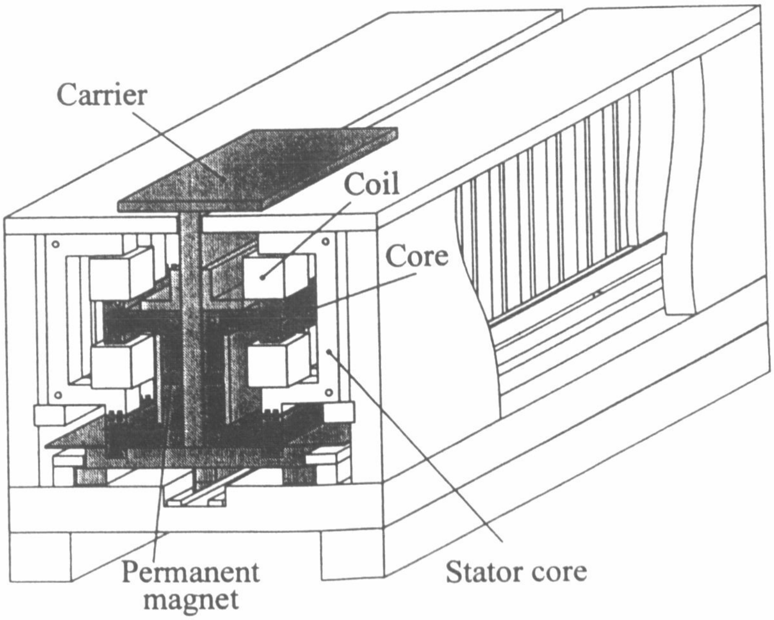


Figure 4. Developed magnetically suspended linear carrier system.

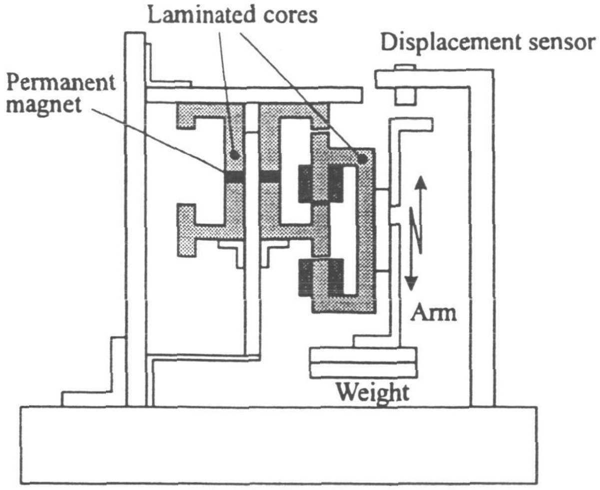
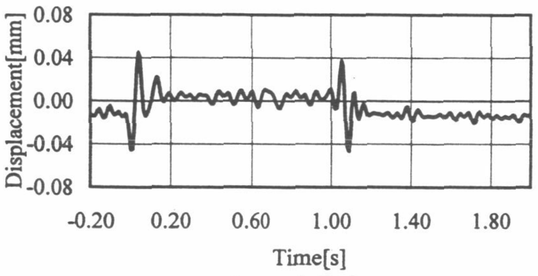
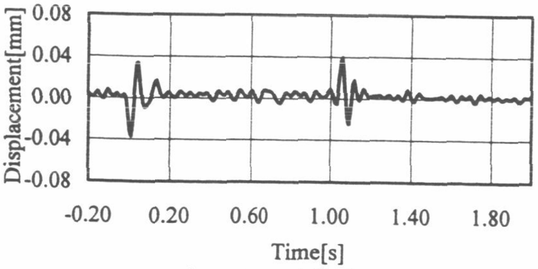


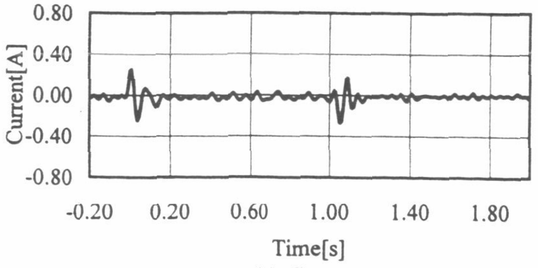
Figure 5. Experimental setup.



(a) Measured displacement



(b) Estimated displacement



(c) Current

Figure 6. Response of the self-sensing magnetic suspension system when a step-wise disturbance acts on the suspended object.

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