Zero Power Control for Magnetic Suspension System with Permanent Magnet Motion Control

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***Abstract*-This paper describes a control method of magnetic levitation system which uses actuators and permanent magnets. The control method is pseudo zero power control, in which there is a little power loss during the system is operated near equilibrium. As the adjustment of the air gap length varies the suspension force and stabilizes the system, the zero power control can be achieved by such as a spring force. First an experimental device is introduced and the principle of levitation is explained. Numerical simulations for the zero power control are carried out based on the model of the device, and some experimental examinations are shown.**

I. INTRODUCTION

The need for a very clean environment is increasing in such areas as semiconductor processing, biotechnology experiments, and material processing. Machines and tools used in such areas must be ultra-clean to avoid sample contamination during handling and processing. The conveyance vehicles used with these systems must also generate no contamination. Mechanical contacts are the prime origins of dust and particle generation. A noncontact conveyance mechanism is good design for clean environment applications.

The authors have already proposed a type of mag-lev system which controls attractive force by varying the air gap length[1]. The feature of this system is the use of permanent magnets and actuators. Based on this principle, the mag-lev system which installs magnets, actuators, and sensors on the levitating object has been also developed[2]. This type of mag-lev system is very suitable for a conveyance system. The conveyance pass is easily constructed by setting up the rails of ferromagnetic materials. In this system, however, the actuator must drive the weight of itself, so energy consumption often becomes problems.

In this paper, we proposed that a zero power control method is adopted as a controller which reduces energy losses. The zero power controller consume no energy in the equilibrium state. A springs is used for the zero power control. First, the principle of the levitation system is explained. Second, a prototype system is introduced. Third, a model of the prototype system and a zero power controller are indicated. Last, numerical simulations on the model and experimental result of the prototype system are shown. They support the effectiveness of the zero power controller for the levitation system using permanent magnets and linear actuator.

II. Principle OF LEVITATION

An outline of one typical suspension system is shown in Fig. 1. A suspending object is made of a permanent magnet, an actuator, and a mass. The actuator makes the length between a magnet and a mass longer or shorter. This levitating object is hanged from the ferromagnetic ceiling by the attractive force of magnet. The direction of levitation is vertical, and the equilibrium position is balanced by the gravity force and the magnet force.

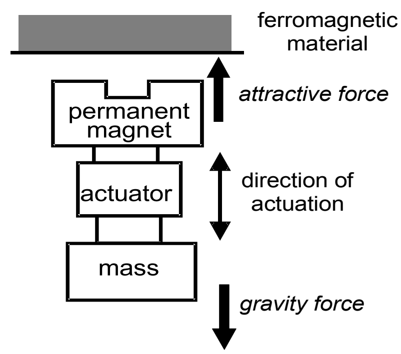

Fig. 1 Outline of suspension system

If the actuator does not actively control the length, the levitating object will either fall or adhere to the ceiling. The control of actuator make this system stable levitation. Because there is a smaller attractive force for a larger air gap between the permanent magnet and the ceiling, the actuator drives its length shorter in response to object movement from its equilibrium position towards the ceiling. Similarly, the actuator drives its length longer in response to object movement away from the ceiling. In this way the object can be stable suspended without contact.

III PROTOTYPE MAGNETIC SUSPENSION SYSTEM

.A *Structure of Magnetic Suspension System*

A photograph of a prototype of a magnetically suspended device is shown in Fig. 2, and a configuration of a experimental setup is in Fig. 3. The suspended device has a weight of 794 (g) and is divided into two parts. One is a part which moves with a permanent magnet and is called as a magnet part. It consists from a magnet, a slider of a voice coil motor, and a sensor target of lower eddy current sensor. They are connected by a rod and corresponding to a permanent magnet part shown in Fig. 1. The magnet part has a weight of 73.8 (g). The other is the remains and is called as a frame part. They are all sensors, a stator of VCM, and a frame of device and so on. They are mass in Fig. 1. The frame part has a weight of 720 (g).

All three sensors are eddy current displacement sensors. Upper two sensors measure the position of the frame part. These sensors have a resolution of 0.5 (μm) and a measurement range of 4 (mm). They are installed on adjustable stays by micrometers as the sensor position can be adjusted very precisely. Two sensors are arranged as the permanent magnet is located at the center of them for solving a non-colocation problem. The position of the frame part is determined based on the average value of two sensor signals.

Lower sensor measures the relative position of the magnet part to the frame part. It has a resolution of 5 (μm) and a measurement range of 10 (mm)

A voice coil motor (VCM) that is adopted for the actuator of the prototype is a type of an actuator which uses Lorentz force. A stator which belongs to the frame part is mainly made by a permanent magnet and an iron core, and a slider belonging to the magnet part is made by only a coil. The features of this actuator is fast responsibility and a direct drive mechanism. To suspend a object without mechanical contacts, fast response and no nonlinear friction are needed for robust stabilization. The VCM has a driving length of 15(mm) and maximum generating force is 10 (N) at a coil current of 2(A).

A spring is installed in the object between the frame part and the magnet part. It connects both part serially and generates force instead of the actuator force. As this spring is a primary element of zero power control, detail is explained as further section.

The suspended object are controlled by a DSP controller as shown in Fig. 3. Three sensor signals are converted to digital values and are input to a DSP controller through 12 bit A/D converters. The controller compute a current for the VCM. The computed current value is converted to analog value and is output to a current amplifier.

.B *Model of Suspension System*

A model of the prototype suspension system has been made as shown in Fig. 3. This model is used for feasibility study, confirmation of the stable controller, numerical simulations and calculating feedback gains of the suspension system. Symbols using in the model and analysis are as follows:

m_0, m_1: mass of the frame part and the magnet part,
z_0, z_1: displacement of the frame part and the magnet part (upper direction is positive),
f_a: generating force of the VCM,
f_m: attractive force of the permanent magnet,
k_s : spring constant,
c: dumping coefficient,
d: air gap between the permanent magnet and the ceiling,
kt: propulsive coefficient of the VCM,
i: current of the VCM.

We assume that the spring has no mass, the frame part is supported by spring force and actuator force, and the dumping coefficient c represents dumping in springs, bearings of the VCM, viscosity of the air, and so on. The equations of the motion of the frame parts and the magnet parts are indicated as

$$m_0 \ddot{z}_0 = k_s(z_1 - z_0) + c(\dot{z}_1 - \dot{z}_0) - f_a - m_0 g \quad (1),$$

$$m_1 \ddot{z}_1 = k_s(z_0 - z_1) + c(\dot{z}_0 - \dot{z}_1) + f_m + f_a - m_1 g \quad (2).$$

The relationship of the input current and the generating force of the VCM is in proportion and it is represented by the equation as

$$f_a = k_t i \quad (3).$$

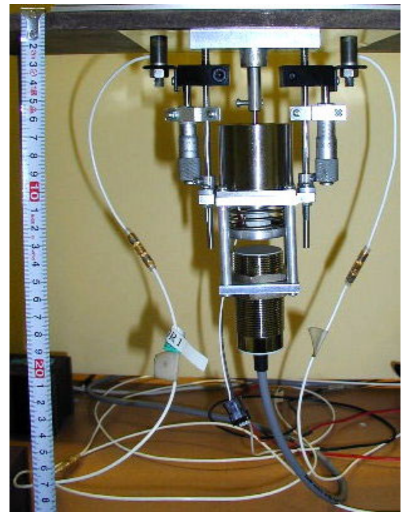

Fig. 2. Photograph of suspension system

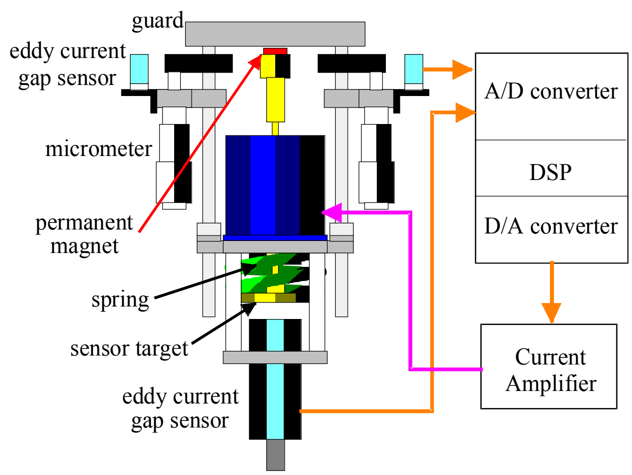

Fig. 3. Configuration of suspension system

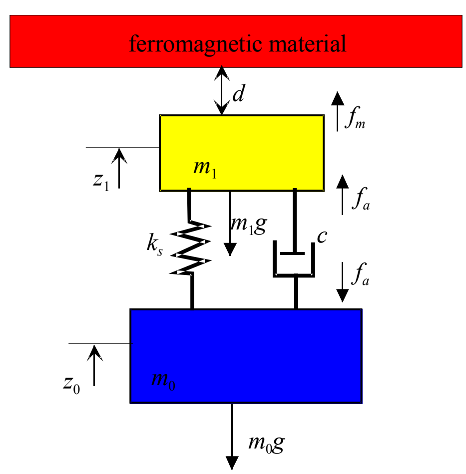

Fig. 4. Model of suspension system

The attractive force of the magnet is assumed as inverse proportion to the square of the air gap length, and represented by the equation as

$$f_m = \frac{k_m}{d^2} \quad (4),$$

where, k_m is a constant.

IV. Zero Power Control

The gravitational force of the suspended object is balanced by the attractive force of the magnet during levitation. This attractive force is transmitted through the magnet part to the actuator. The actuator support the transmitted force that is equal to the weight of the object. When the VCM generates force, the coil current is needed. Thus energy consumption becomes a problem.

Electromagnetic suspension systems (EMS system) have similar problem. To levitate objects, bias currents of electromagnets are needed for balancing the gravitational forces of the objects. In EMS systems a permanent magnets are used for zero power control[3]. Equivalent fluxes to support levitated objects are generated by permanent magnets.

In suspension systems with linear actuators and permanent magnets, springs can be used for zero power control. A spring is installed between the magnet part and the frame part in prototype suspension system shown in Fig. 2 and Fig. 3. The spring connects both part serially and the spring force assists the force of the VCM force. The resultant force of the spring and the VCM is transmitted from the magnet to the frame. In equilibrium state if the spring force is equal to the gravitational force of the frame part, the VCM force is used for only stabilization of levitation. It is very useful for saving energy.

There are many way to realize zero power control such as using observer, integral feedback of current, estimation of the weight of the object, and so on. In this paper, an integral feedback method is investigated.

A block diagram of zero power control with an integral current feedback loop is shown in Fig. 5. The controller has two large feedback loops. One is a feedback loop about the frame part. It is a lower loop in the figure. In this loop, a PD feedback is used and control the frame part to be in the equilibrium position. The other is a feedback loop for the relative displacements between the frame and magnet parts. It is an upper loop. In this loop, a PID controller is used for stabilization and the servo control for the VCM stroke. If the VCM stroke is required as it is always operated at its center, an integral feedback is used. As the aim of this paper is zero power control, the integral feedback of upper loops is not used.

Zero power control is performed by a local loop before the levitated object block. It is a integral feedback of the VCM current. When currents flow in the VCM circuit, this feedback loop makes the currents to be reduced. The reduction of the currents affects the length between the frame part and the magnet part. This causes the change of the spring length and the generating force of the spring. And finally, the spring force becomes equal to the weight of the frame part and the currents of the VCM is zero.

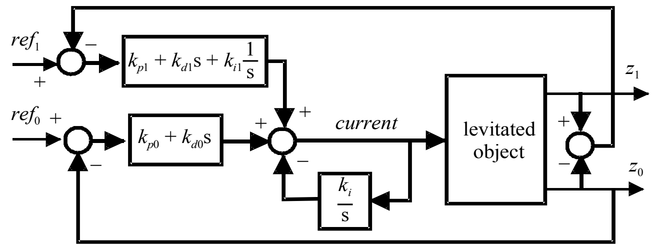

Fig. 5. Block diagram of zero power control system

During this integral control, the air gap between the permanent magnet and the ceiling does not change. It must continued to be a fixed value as that the attractive force is equal to the whole weight of the suspended object.

V. Numerical Simulations and Experimental Results

A. Numerical Simulation

To make the feasibility study more convincing, numerical simulations are carried out with the nonlinearity of the attractive force. Simulations with only PD feedback loops and with zero power control loop in addition to PD loops are examined.

The results are shown in Fig. 6 and Fig. 7. When a weight of 10 (g) was added to the object during levitation, the displacements of the frame part and the magnet part, and current of the VCM were recorded. At 0.1 (s), the weight was added, and until 1 (s), the responses were recorded. The displacements is plotted as the upward direction is positive.

Fig. 6 shows the result of the system without zero power control. The top of the figure indicates the displacement of the magnet part, the middle indicates that of the frame part, and the bottom the current. At the time of adding the weight, the actuator force is controlled as the VCM is lengthen. Thereafter, the magnet moves upward, and the frame moves downward. As the magnet moves upward, the air gap is shorter and the attractive force becomes larger than the initial weight by the added weight. Finally, the system is stabilized by the PD control feedback loops.

The result with zero power control is shown in Fig. 7. The result is similar to the result without zero power control at the beginning of control process. In the steady state of Fig. 7, however, the VCM current converges to zero. Consequently zero power control makes the actuator energy consumption to zero in the equilibrium state and feasibility of the proposed controller is supported by these simulations.

B. Examinations on Prototype System

Noncontact levitation examination carried out on the system shown in Fig. 2 and Fig. 3 succeeded. Examinations with and without zero power control were also carried out in condition that is same as the numerical simulations. Results are shown in Fig. 8 and Fig. 9. Fig. 8 indicates a result without zero power control, and Fig. 9 indicates a result with control. The both results of the currents are signals through low pass filters. As shown in the figures, the response with zero power control is vibrational. The reason is that the

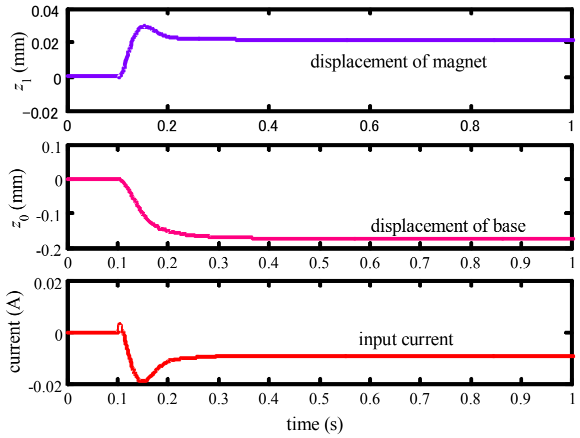

Fig. 6 Simulation results without zero power control

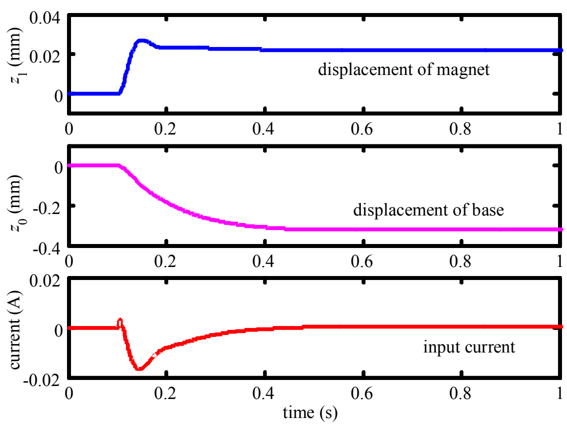

Fig. 7 Simulation results with zero power control

system phase delay is relative large and the feedback gains are not proper values. However it can be seen that the current is converging on zero. These results support that a zero power control method can be made by a local integral feedback loop. Therefore, we may conclude that the proposal of this paper succeeded.

VI. Conclusion

Zero power control of hanging type levitation systems using permanent magnets and linear actuators were proposed for saving energy. This proposal ware examined on a prototype system. The actuator of prototype system is a VCM. The aim of this paper is to reduce the VCM current in equilibrium state. An integral feedback loop is added to the controller for zero power control. Numerical simulations on a prototype model and experimental examinations were carried out. The results support the feasibility and the effectiveness of zero power control.

The experimental result with zero power control has a problems of dumping efficiency. Vibration of the system with control remains longer. The feedback gains must be improved. On the other hand, there are many way to perform zero power control. Other control methods must be examined from view of robustness and control performance. They are further study.

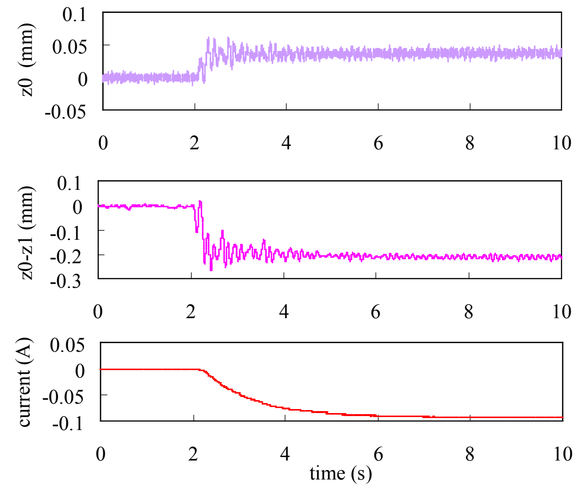

Fig. 8 Experimental results without zero power control

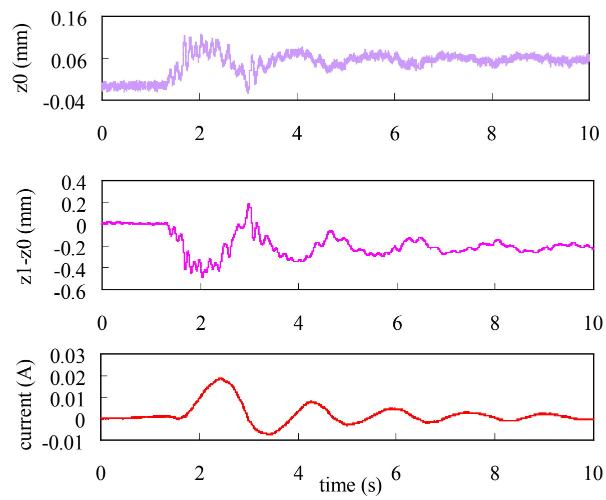

Fig. 9 Experimental results with zero power control

Acknowledgment

The authors gratefully acknowledges Mr. Yusuke Yoshida for his helpful contributions. A part of this work is financially supported by the Grant-in-Aid for Scientific Research (B)(2) (12450099) of Japan Society for the Promotion of Science.

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