HANGING TYPE MAG-LEV SYSTEM WITH PERMANENT MAGNET MOTION CONTROL

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ABSTRACT

A type of mag-lev system with permanent magnet motion control is proposed, analyzed, and examined experimentally. This mag-lev system has the structure that the levitating object hangs on the upper iron rail and such parts as magnets, sensors, and actuators are installed on the object. This type of levitation system is very useful for noncontact conveyance system, because the conveyance path is very easy to make. This paper describe the success of the construction of the hanging type magnetic levitation system using magnet motion control mechanism.

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 (Oka and Higuchi, 1994). 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 is proposed. 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 the selection of actuator is very important.

In this paper, the authors introduce mag-lev systems using piezoelectric actuators. First, the principle of the levitation mechanism is explained. A 1 d.o.f. experimental system is introduced and the theoretical feasibility of levitation is examined. Some experimental examinations are carried out. A 3 d.o.f. levitation system is also introduced.

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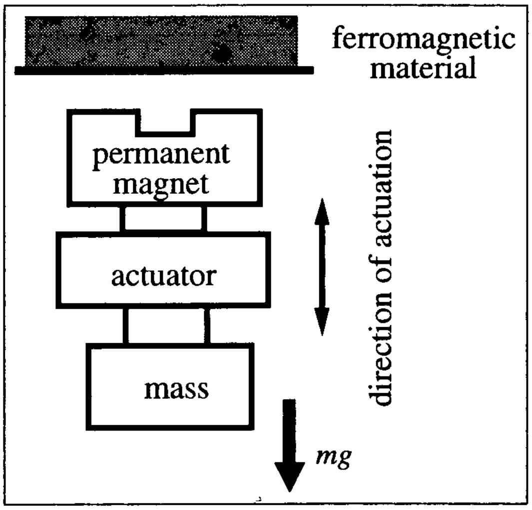

Figure 1. Outline of hanging type mag-lev system

PRINCIPLE OF LEVITATION

An outline of one typical proposed system is shown in Figure 1. A levitating 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.

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. 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.

1 D.O.F. LEVITATION SYSTEM

PIEZOELECTRIC ACTUATOR

Because the proposed levitation system has a actuator on the levitating object, the actuator needs not only driving force but supporting force itself. Piezoelectric elements have the advantages that they are small, light, and the generating force is strong, but have a weak point that displacement range is small. To compensate for this weak point, the displacement is magnified with a mechanism shown in Figure 2. The photograph of the actuator is in Figure 3. As shown in the figures, two levers are used. The specifications of the actuator are 500 μm displacement and 10 N force at 130 V input voltage, 0.35 kg mass, 120 mm height, and 5 mm thickness.

The relation of input voltage and displacement was examined as a basic characteristic and is shown in Figure 4. In the figure, black circles are results of raising the voltage, and white

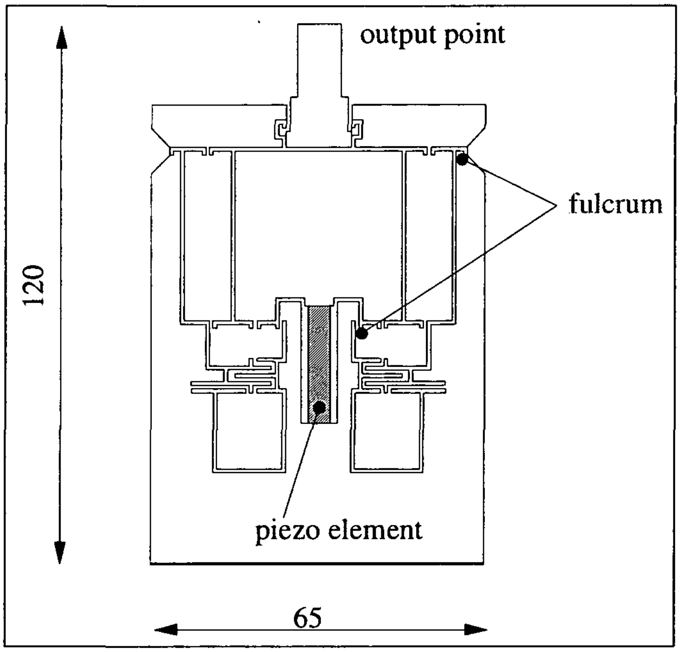

Figure 2. Schematic of piezoelectric actuator

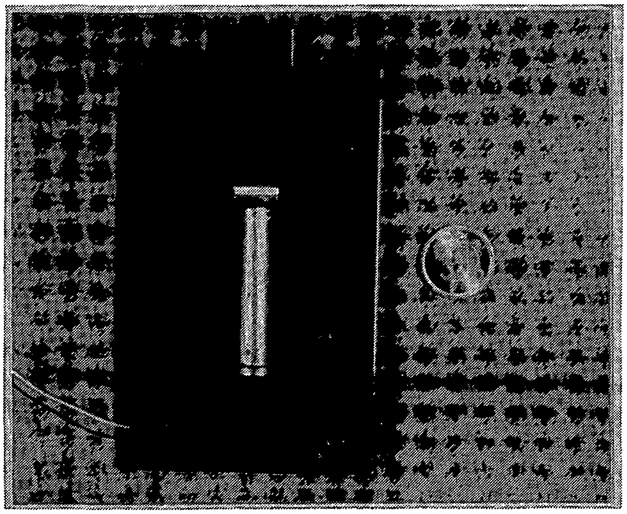

Figure 3. Photograph of actuator

circles are results of lowering the voltage. We can see a little hysteresis, but it may be not a problem to make the levitation system stable.

The frequency responses were examined and are shown in Figure 5 as a Bode diagram. The range of the frequency is from 0.01 Hz to 1 kHz. The resonance frequency is 340 Hz. From this result, we can assume that the actuator is a second order system. The details specifications of this actuator by experimental results are 0.328 kg mass, 58.23 kN/m spring constant, 526 Ns/m damping constant, 0.218 N/V force constant.

EXPERIMENTAL SETUP

A 1 d.o.f. experimental system was made and the construction is shown in the Figure 6. The levitating object has two displacement sensors which are arranged symmetric to a

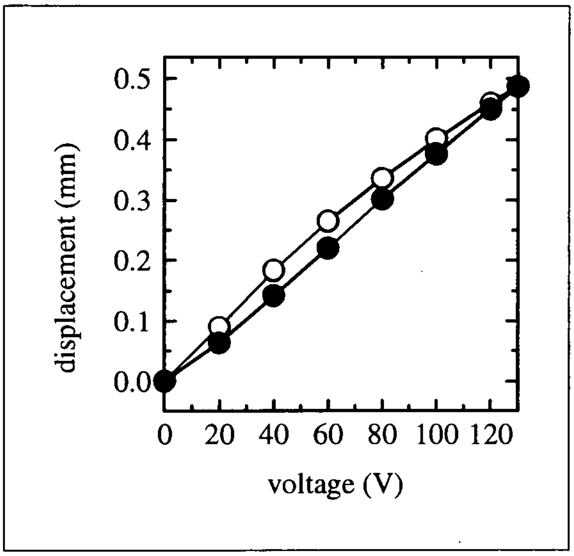

Figure 4. Extension about input voltage

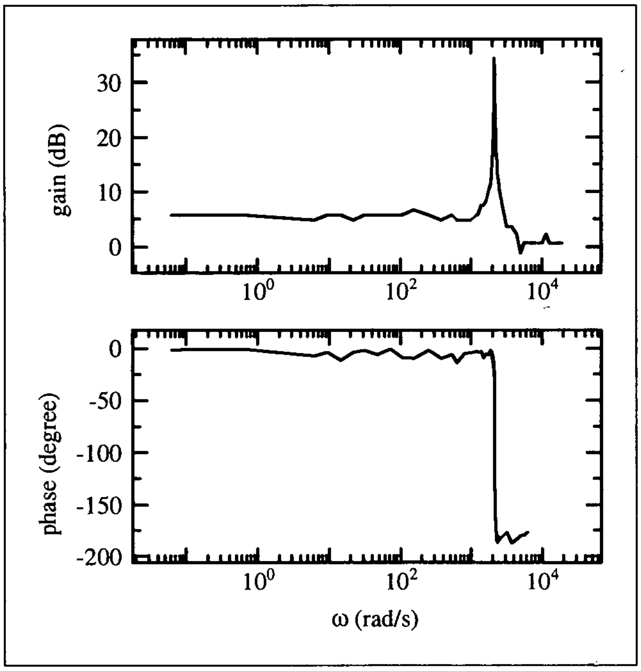

Figure 5. Bode diagram of actuator

permanent magnet as shown in the figure. The purpose is not only balancing the object but eliminating the affect of sensing the object swinging. If the object swings, its noise signal can be canceled the sum of both sensor output signals.

The mass of the levitating object is 666 g. Because minus voltage can not supplied to a piezoelectric actuator, a 70 V offset is added to the input signal of the actuator. The controller is a digital PD controller using DSP. The permanent magnet is a cylinder 10 mm diameter and 5 mm height. The material is neodymium and cobalt with a flux density 0.35 T. The material of ceiling is iron with 0.35 % carbon.

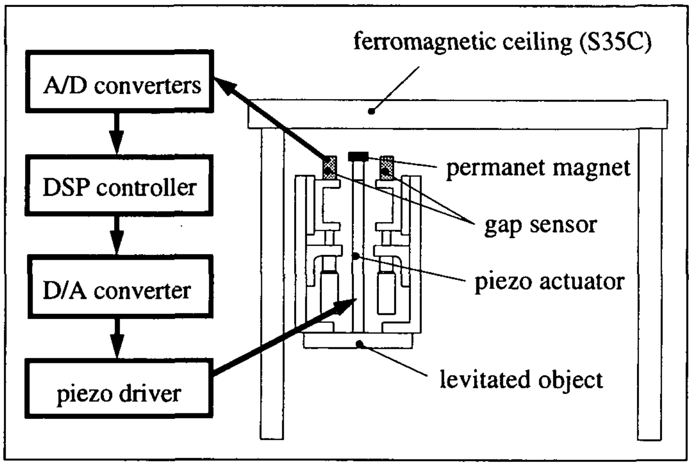

Figure 6. Magnetic levitation system

MODEL AND FEASIBILITY

The feasibility of the proposed levitation system was investigated on a linear model. The controllability and the observablity of the experimental system were checked with the model shown in Figure 7. The input of the system is the voltage to the actuator. We assume the voltage is proportional to the generating force of the actuator. This force acts on both magnet part (part of m_1) and the other part (part of m_0). The direction of expansion is positive. The output of the system is the position of the object (position of m_0). The equations of the motion are

$$m_0\ddot{z}_0 = k_1(z_1 - z_0) + \xi(\dot{z}_1 - \dot{z}_0) - f_a - m_0. \tag{1}$$

$$m_1\ddot{z}_1 = k_1(z_0 - z_1) + \xi(\dot{z}_0 - \dot{z}_1) + f_a + f_m - m_1. \tag{2}$$

The attractive force, f_m, is represented as a nonlinear function of the length of the air gap and it becomes larger as the gap decreases. By linearization of this function around the equilibrium position, we obtain

$$f_m = k_m z_1 \tag{3}$$

We assume the state vector as $x = (\ z_0 \quad z_1 \quad \dot{z}_0 \quad \dot{z}_1\ )^t$ and output is z_0. From Equations (1), (2), and (3), the state space model is represented as

$$\dot{x} = Ax + bu, \quad y = cx \tag{4}$$

where,

$$, \quad A = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -k_1/m_0 & k_1/m_0 & -\xi/m_0 & \xi/m_0 \\ k_1/m_1 & (k_m - k_1)/m_1 & \xi/m_1 & -\xi/m_1 \end{pmatrix}, \quad b = \begin{pmatrix} 0 \\ 0 \\ -1/m_0 \\ 1/m_0 \end{pmatrix}, \quad c = (1 \quad 0 \quad 0 \quad 0'$$

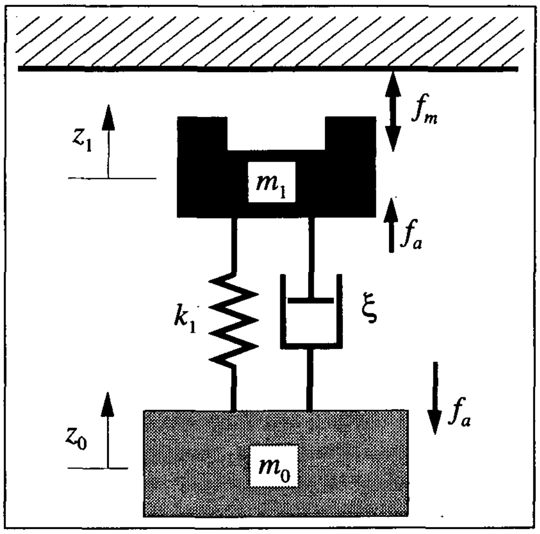

Figure 7. Model of levitation system

The determinants of the controllability matrix and the observability matrix are respectively,

$$\det C = -\frac{k_m^2}{m_0^2 m_1^4}, \quad \det O = \frac{k_m \xi^2 - k_1^2 m}{m_0^2 m_1} \qquad (5).$$

As Equations (5) are both non-zero, the experimental system is controllable and observable.

As the control method is using the z_0 PD feedback loop. the above feasibility check is insufficient. We examine the stability by another method of the Routh-Hurwitz stability criterion. When PD feedback control is used, the system input u is represented by proportional gain k_p and deferential gain k_d as

$$u = k_p z_0 + k_d \dot{z}_0 \qquad (6).$$

Substituting Equation (6) to (4), we obtain an autonomy system. The eigen-polynomial of the A matrix is

$$s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a \qquad (7)$$

where,

$$\begin{aligned} a_3 &= \xi(m_0 + m_1)/m_0 m_1 + k_t k_d / m_0 \\ a_2 &= (k_1 + k_t k_p)/m_0 + (k_1 - k_m)/m_1 \\ a_1 &= -k_m(\xi + k_t k_d)/m_0 m_1 \\ a_0 &= -k_m(k_1 + k_t k_p)/m_0 m_1 \end{aligned}$$

In Equation (7), we can solve as all roots locate in left half plane. So the system can be stable.

EXPERIMENTAL EXAMINATION

The experimental examination was carried out to verify that the object can be levitated. The photograph of the levitated object during levitation is shown in Figure 8. The sensor signals and input voltage during levitation were recorded and are shown in Figure 9. The feedback gains are $k_p = 1.2 \times 10^6$ V/m, $k_d = 40 \times 10^3$ Vs/m. It is seen that the object levitates with a precision better than 2 μm.

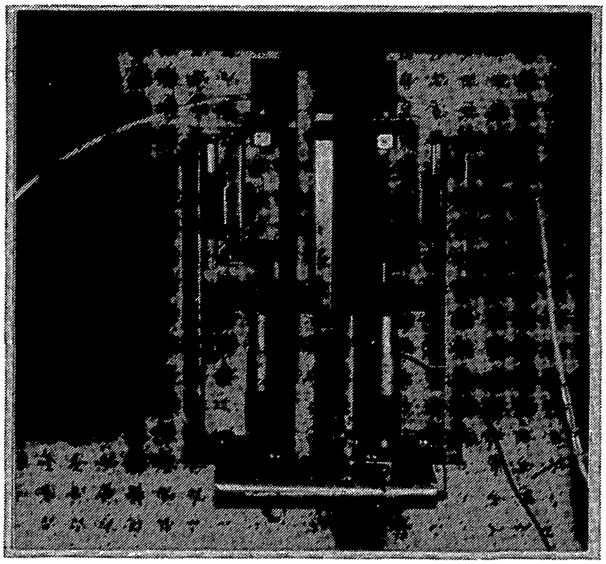

Figure 8. Photograph during levitation

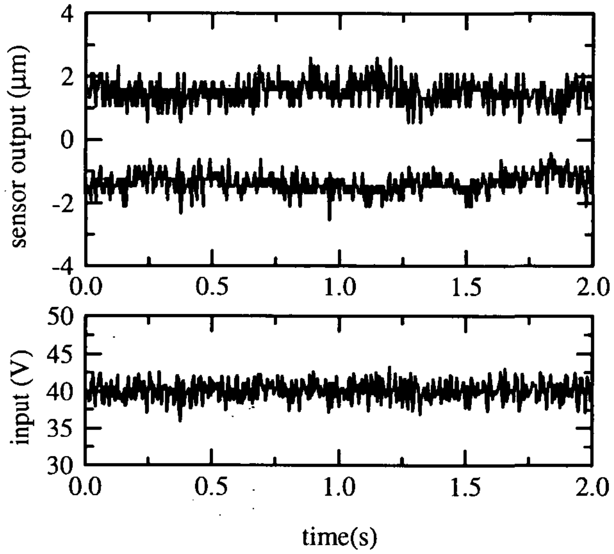

Figure 9. Sensor outputs and input voltage

The step disturbance response that a 25 g load put on the levitating object was measured. The results are shown in Figure 10. In the figure, two sensor output signals, the average of the two signals, and input voltage are shown. The vibrations of two sensor outputs remain for a long time. As the phase of these signals is 180 degrees different, we know that the object is swinging. The average of the two signals converges quickly. It is verified that the control scheme based on the average signal is effective against the object swinging.

The step amounts of two signals are different. This is caused by the location of the applied load. The load might not be located in the center of the levitated object.

When the load is applied, the object goes down, and correct servo action of the system is then observed as the object position converges towards the new desired reference point (attention that the object movement is inverse to the gap length). The new reference position

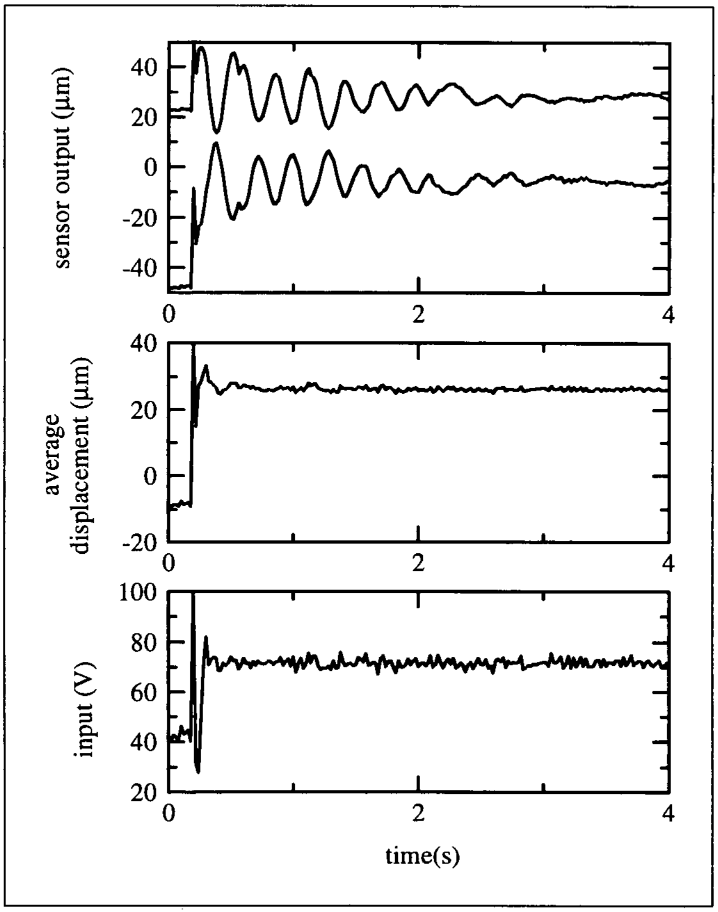

Figure 10 Response of step disturbance

is lower than the initial position as shown in the figure. However, as the mass of the object becomes heavier, the magnet position should be higher than the initial position. The PD controller shortens the air gap by lowering the object position.

These experimental results verify the feasibility of the proposed hanging type levitation system and show the possibility of the noncontact conveyance.

3 D.O.F. LEVITATION SYSTEM

EXPERIMENTAL SETUP

The 1 d.o.f. system has the problem that the object swings. A 3 d.o.f. levitation system, which can control the d.o.f.s of the rotation about two horizontal axes, is free of this problem. The levitation object of 3 d.o.f. system is illustrated in Figure 11. Three actuators and three magnets are installed on the object. They are arranged to be a regular triangles. Three displacement sensors are located under the permanent magnets respectively (they are not seen). Mass of the object is 2.06 kg. The controller has three independent PD feedback loops. Each magnet is controlled by the signal of the sensor below its magnet.

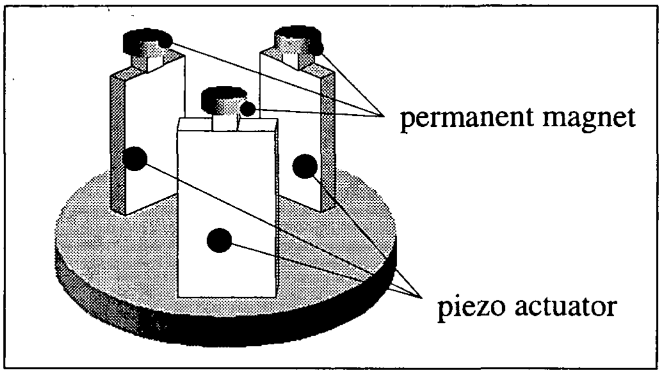

Fig. 11. Structure of levitated object

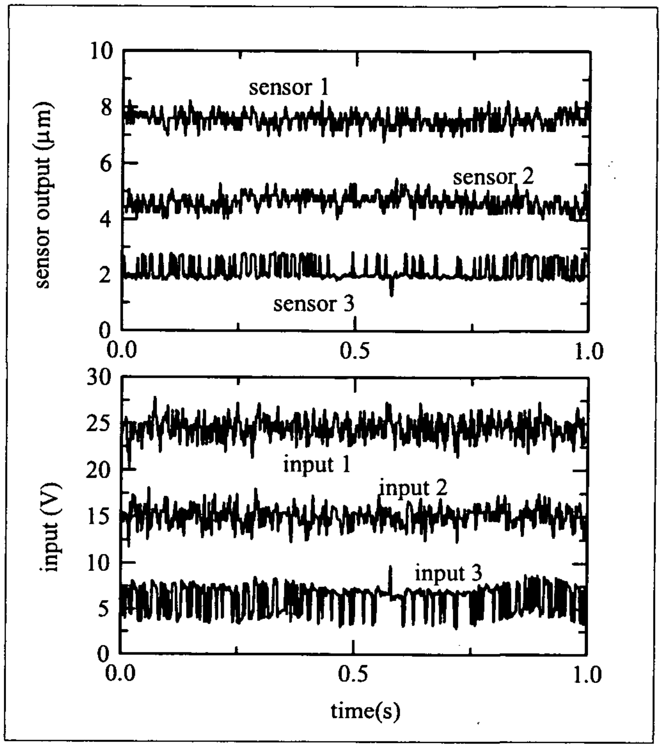

Figure 12. Sensor outputs and input voltage during levitation

EXPERIMENTAL EXAMINATION

Suspension of the system was carried out. Sensor signals and input voltages during levitation were recorded and are shown in Figure 12. The feedback gains are $k_p = 1.2 \times 10^6$ V/m, and $k_d = 3.3 \times 10^4$ Vs/m. The resolution of the A/D converter of sensor 3 is 12 bits, and the measurement range of the sensor is 4 mm. In this channel, 1 bit corresponds to 1 μm. As shown in the figure, the object levitated as good as the LSB resolution.

Next, a 10 V step input was added to the input voltage of actuator 2 with the results shown in Figure 13. In the figure, we found that the step input for a actuator mainly causes the variation of the output of only sensor 2. It means that if we arranged magnets and sensors symmetrically, it is possible to avoid the mutual interference between subsystems. However,

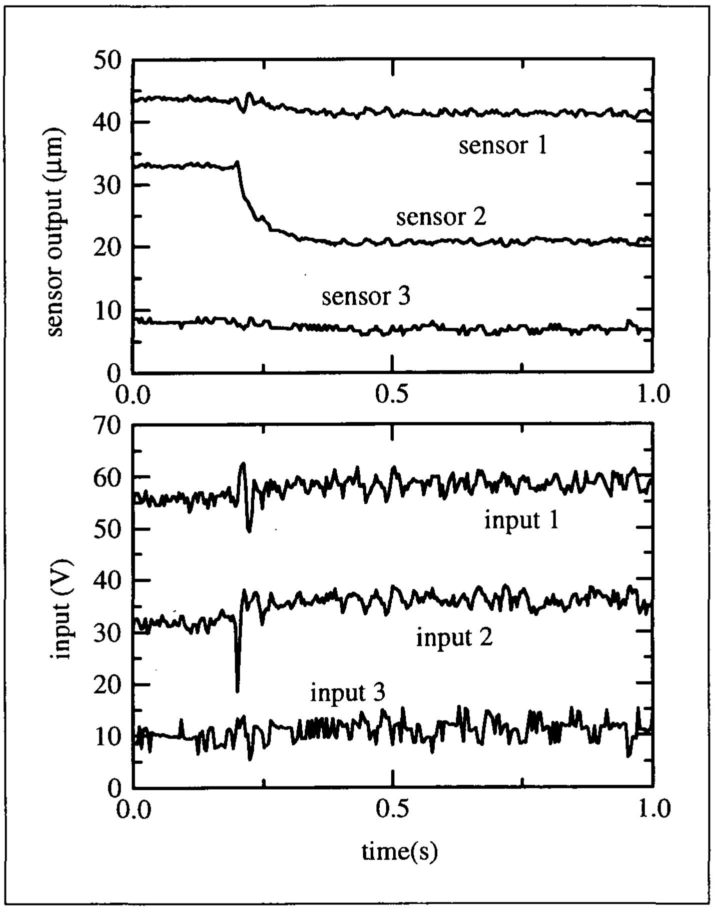

Figure 13. Step response when external disturbance is added

in case of needs of high stiffness of the rotational movement for stable conveyance, the centralized controller which controls about one translation and two rotations will be needed.

CONCLUSION

A hanging type active magnetic levitation system, featuring a bearing force control method, was designed. The aim of this levitation system is making noncontact conveyance system. Two experimental system were introduced and we succeeded in the levitation experiments.

The 1 d.o.f. experimental system was made and analyzed. On experimental examination, levitation accuracy is 2 μm and it was verified that symmetric two sensors are effective for the cancellation of the object swinging noise. It was possible that the object can be moved by catching the wind from a fan.

A 3 d.o.f. system was introduced, and we succeed in the experimental levitation of the system.

REFERENCE

Oka, K. and Higuchi, T. 1994. "Magnetic Suspension System with Permanent Magnet Motion Control," Proc. of Fourth Int. Symp. on Magnetic Bearings. 131-137.