REPULSIVE MAGNETIC BEARING STABILIZED BY THE MOTION CONTROL OF PERMANENT MAGNETS FOR SUSPENSION

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ABSTRACT

A magnetic bearing system using forces of repulsion between permanent magnets is developed. In the developed magnetic bearing, radial motions of the rotor are passively supported by repulsive forces. For supporting the axial motion of the rotor, active control is necessary because of inherent instability in this direction. Stabilization is achieved by using the motion control of the permanent magnets for passive radial suspension; these magnets are driven by voice coil motors in the axial direction. The characteristics of the system are studied both theoretically and experimentally.

INTRODUCTION

Magnetic bearings support rotating mass (rotor) without any mechanical contact. There are several methods of magnetic suspension (Jayawant, 1981). Most magnetic bearings use DC electromagnets and the force of attraction between magnetized bodies. Another principal method of achieving contact free suspension uses forces of repulsion between permanent magnets. However, it is usually combined with either some mechanical bearings or controlled DC electromagnets for stable action because static stable levitation is impossible in a system composed solely of permanent magnets. Another problem is poor damping in the levitation direction(s). In consequence of these problems, this type of levitation system has not been used so widely as the suspension using controlled DC electromagnets. However, magnetic materials have been recently improved significantly. Moreover, it is an advantage that no energy is required to generate levitation force. The possibility of new levitation systems using permanent magnets is worth being investigated.

The authors have proposed to introduce the motion control of magnets into repulsive magnetic levitation systems to improve their performance (Mizuno *et al.*, 1994, 1995, 1996). The introduction of such mechanism brings out three new types of levitation systems. In the first type, the levitation magnets are driven in the direction of repulsive force to control the

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position and vibration of the levitated object. In the second type, a magnet of support is moved in the lateral directions to stabilize the system like an inverted pendulum. In the third type, the lateral motions are stabilized by vibrating the magnet of support in the direction of repulsive force. The principles and basic model of each system have been studied in the previous works (Mizuno *et al.*, 1994, 1995, 1996).

This paper applies the second type to realize a magnetic bearing system. The developed system is passive in the radial directions and active in the axial direction; the motion of permanent magnets for passive radial support is controlled by voice coil motors for active stabilization in the axial direction. The characteristics of the system are studied both theoretically and experimentally.

STABILIZATION OF LATERAL MOTION BY ACTIVE CONTROL

The levitation system using forces of repulsion between permanent magnets is inherently stable in the levitation direction but unstable in the lateral directions as shown in **Fig.1**. These lateral motions of the levitated object can be controlled by using the motion control of a permanent magnet of support in the lateral directions (**Fig.2** (a)). This stabilization technique is similar to that for an inverted pendulum (**Fig.2** (b)); the levitated object, which would slide in the lateral directions without control, is kept at a position by controlling the movements of the support composed of permanent magnet.

This active stabilization method enables repulsive levitation systems to have various configurations. **Figure 3** shows a basic configuration of magnetic bearings using this levitation mechanism. The four-degree-of-freedom motions in the radial directions of the rotor are passively supported by using repulsive forces between permanent magnets of ring shape; the single-degree-of-freedom motion in the axial direction, which corresponds to the lateral direction, is actively controlled by moving the ring-shape permanent magnets for radial support.

In the proposed magnetic bearings, suspension characteristics in the axial direction depend much on the selection of an actuator for moving magnets. In the following experiment, voice coil motors are used to drive permanent magnets because they have enough moving ranges for stabilization. Piezoelectric actuators have another advantage of no necessity of winding coils. It will make the manufacture of small magnetic bearings easier so that this configuration may be suitable for micro machines.

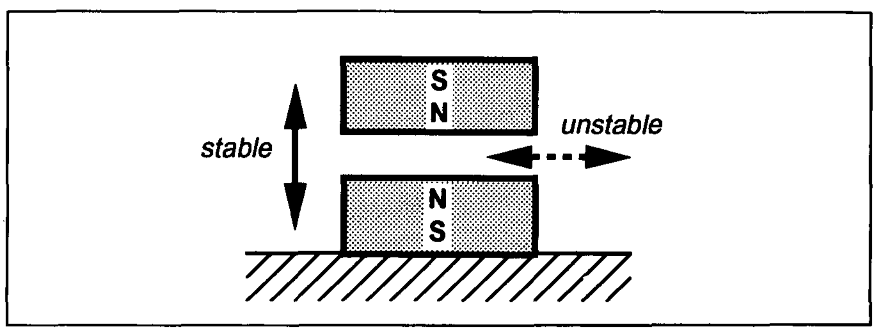

Figure 1. Levitation using repulsive forces between permanent magnets

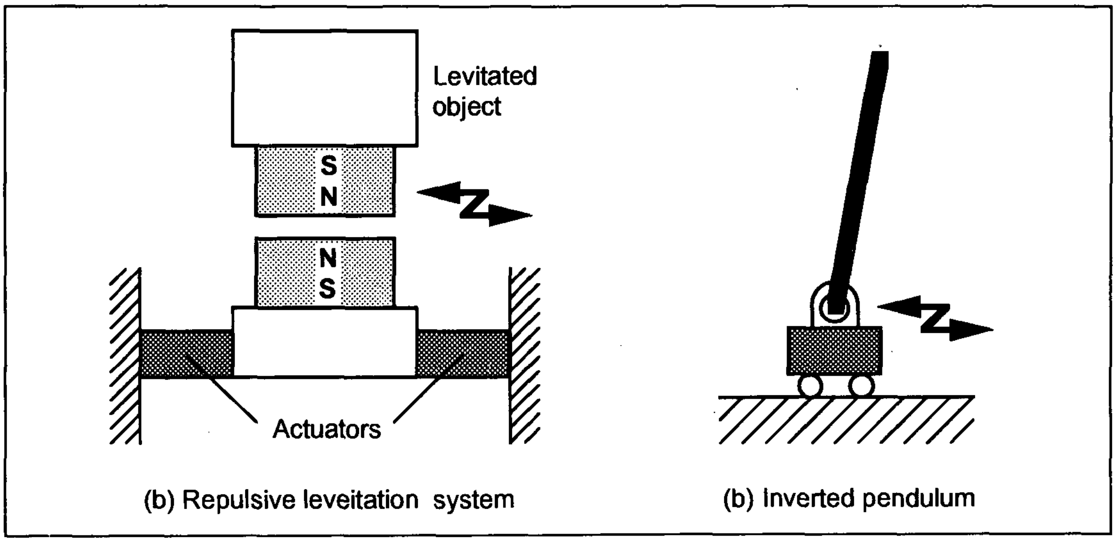

Figure 2. Stabilization using motion of the support

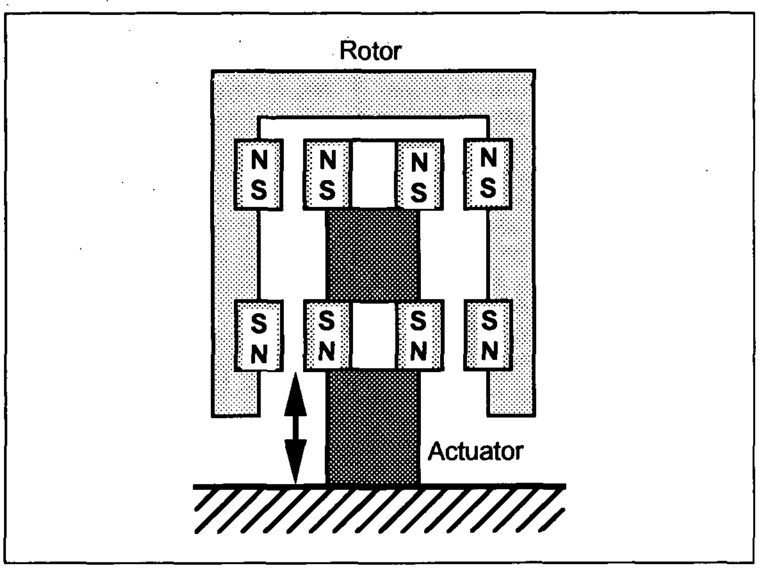

Figure 3. Stabilization of the axial motion using the motion control of magnets in a radially passive magnetic bearing

BASIC MODEL

Figure 4 shows a basic model of the system illustrated in **Fig.3**. It is assumed for simplicity in this section that the rotor moves only in the axial direction. The ring-shape permanents for support are connected to the base through spring and damping elements k_p and c_p, and are driven by an actuator. The actuator is modeled as a force generator whose output is denoted by $F_p(t)$. The gravitational force acting on the rotor m_a is balanced by the lateral forces between the permanent magnets in the equilibrium states. For small deviations from the equilibrium, the equation of motion becomes

$$m_a \ddot{z}_a(t) = k_l(z_a(t) - z_p(t)) \tag{1}$$

$$m_p \ddot{z}_p(t) = k_l(z_p(t) - z_a(t)) - c_p \dot{z}_p(t) - k_p z_p(t) + F_p(t) \tag{2}$$

where $z_a(t)$ is the displacement of the rotor, $z_p(t)$ is the displacement of the permanent magnets for support, k_l is the lateral factor between the permanent magnets, and m_p is the mass of the support including the permanent that is driven by the actuator.

The actuator is controlled to follow a signal inputted to a driver circuit:

$$F_p(t) = k_a u(t) \tag{3}$$

where $u(t)$ is the input voltage to the driver circuit, and k_a is the gain of the driver circuit. From (1), (2) and (3), the transfer function from the input to the displacement of the rotor is obtained as

$$G_a(s) = \frac{Z_a(s)}{U(s)}$$

$$= -\frac{k_a k_l}{m_a m_p s^4 + m_a c_p s^3 + \{m_a k_p - (m_a + m_p)k_l\}s^2 - k_l c_p s - k_l k_p} \tag{4}$$

Equation (4) demonstrates that this system is unstable. Thereby, feedback control is necessary for stable contactless suspension.

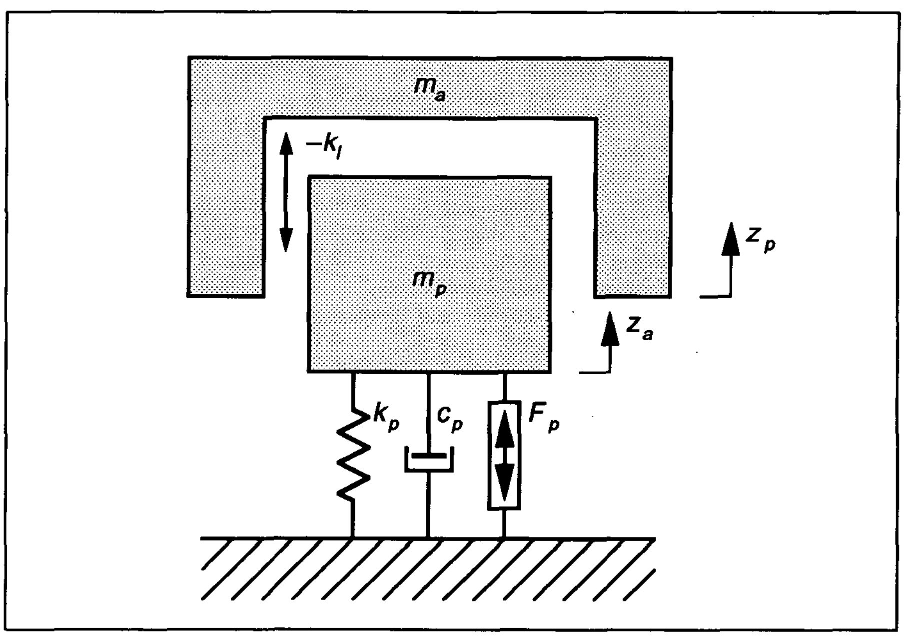

Figure 4. Basic model

CONTROL SYSTEM DESIGN

PD CONTROL

The PD control is a fundamental control scheme for stabilization. The control input is represented by

$$u(t) = p_d z_a(t) + p_v \dot{z}_a(t) + v(t) \tag{5}$$

where p_d and p_v is the gains of displacement and velocity feedback, and $v(t)$ is the auxiliary input. From (4) and (5), the following equation is obtained.

$$\frac{Z_a(s)}{V(s)} = -\frac{k_a k_l}{m_a m_p s^4 + m_a c_p s^3 + \{m_a k_p - (m_a + m_p)k_l\}s^2 + k_l(k_a p_v - c_p)s + k_l(k_a p_d - k_p)} \tag{6}$$

Thus, the characteristics polynomial of the closed-loop system becomes

$$t_c(s) = s^4 + \frac{c_p}{m_p}s^3 + \frac{m_a k_p - (m_a + m_p)k_l}{m_a m_p}s^2 + \frac{k_l(k_a p_v - c_p)}{m_a m_p}s + \frac{k_l(k_a p_d - k_p)}{m_a m_p} \tag{7}$$

Equation (7) shows that the spring and damping elements suspending the permanent magnets must be selected to satisfy

$$c_p > 0, \tag{8}$$

$$k_p > (1 + \frac{m_p}{m_a})k_l, \tag{9}$$

to achieve stable suspension by using PD control. It is shown that this system can be stabilized by adjusting the gains p_d and p_v appropriately when the conditions (8) and (9) are satisfied (Oka and Higuchi, 1993).

I-PD CONTROL

For precise position control in the axial direction, an integral action should be incorporated into the feedback loop. The I-PD control as well as the PID control is widely used. When the I-PD control scheme is applied, the control input is represented by

$$u(t) = -p_i \int (z_r(t) - z_a(t))dt + p_d z_a(t) + p_v \dot{z}_a(t) \tag{10}$$

where $z_r(t)$ is the reference signal. Substituting (10) into (4) leads to

$$\frac{Z_a(s)}{Z_r(s)} = \frac{c_0}{s^5 + c_4 s^4 + c_3 s^3 + c_2 s^2 + c_1 s + c_0} \tag{11}$$

where

$$c_4 = \frac{c_p}{m_p}, \quad c_3 = \frac{m_a k_p - (m_a + m_p)k_l}{m_a m_p}, \quad c_2 = \frac{k_l(k_a p_v - c_p)}{m_a m_p},$$

$$c_1 = \frac{k_l(k_a p_d - k_p)}{m_a m_p}, \quad c_0 = \frac{k_a k_l p_i}{m_a m_p}.$$

This system can be also stabilized by adjusting the gains p_i, p_d and p_v appropriately when the conditions (8) and (9) are satisfied.

EXPERIMENT

EXPERIMENTAL APPARATUS

Figure 5 shows a schematic diagram of the developed magnetic bearing system using the proposed levitation mechanism. It is outer-rotor type. The rotor has two ring-shape permanents at its top and bottom. The inner and outer diameters of each magnet are 24 mm and 32 mm, respectively.

Two voice coil motors are fixed to the ceiling and the base of the apparatus. Each motor drives a ring-shape permanent magnet for support whose inner and outer diameters are 7 mm and 12 mm, respectively. All the permanent magnets are made of SmCoB materials. The length of stroke of the voice coil motors is 10 mm, and the maximum output force is 9.8 N. Each of the permanent magnets for support is connected to the base through a plate spring , which corresponds to k_p in Fig.4. In the following research, the length between the two permanent magnets is kept constant by constraining the movements of the two motors mechanically. Thus, this system can be treated as a scalar input system.

The radial and axial motions of the rotor are sensed by eddy-current gap sensors. An analog controller is used to produce a control input for stabilization from a signal produced by the sensor located in the axial direction. Two current-output amplifiers drives the voice coil motors according to the signal generated from the controller. The sensors located in the radial directions are used for monitoring.

The values of the parameters of the apparatus are listed in **Table 1**.

EXPERIMENTAL RESULTS

A step response of the system with an I-PD controller is shown in **Fig.6**. The reference signal $z_r(t)$ is changed from $-25\,\mu\text{m}$ to $25\,\mu\text{m}$, and *vise versa*. Just after the reference signal changes to a new value, the magnet of support moves in the opposite direction to the new stationary position (goal). Then it drives the magnet of the rotor in the direction of the

TABLE 1 PARAMETERS OF THE EXPERIMENTAL APPARATUS

Parameter	Value
m_a	0.353 kg
m_p	0.340 kg
k_p	7.23×10^4 N / m
c_p	15.2 Ns / m
k_l	2.92×10^3 N / m
k_a	9.80 N / A

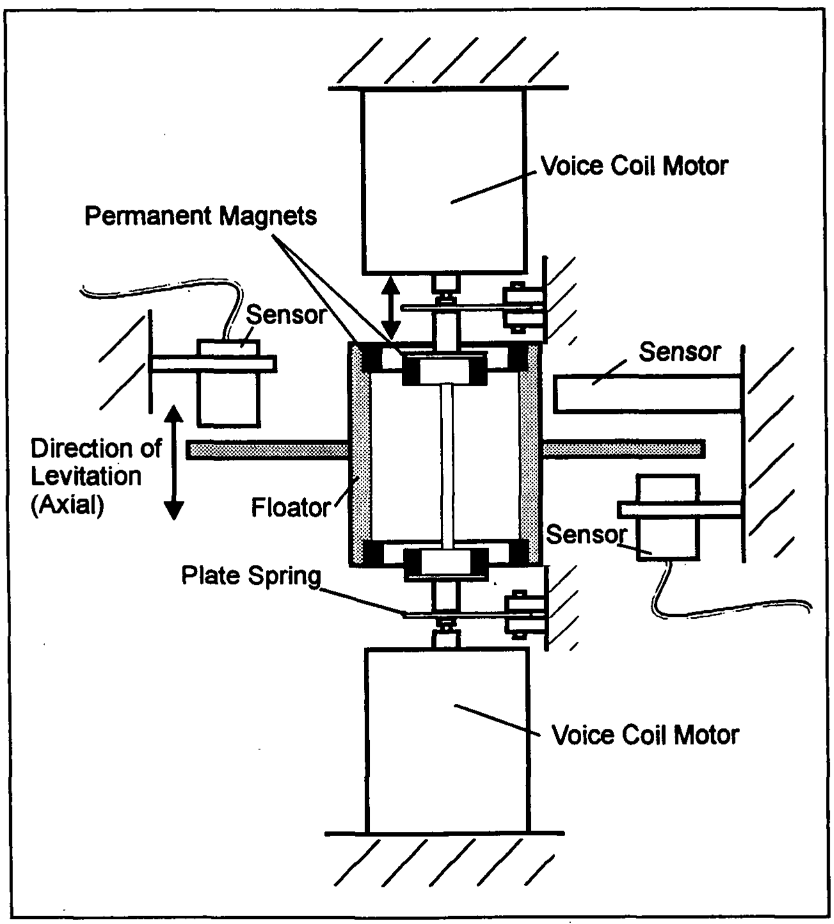

Figure 5. Experimental Apparatus

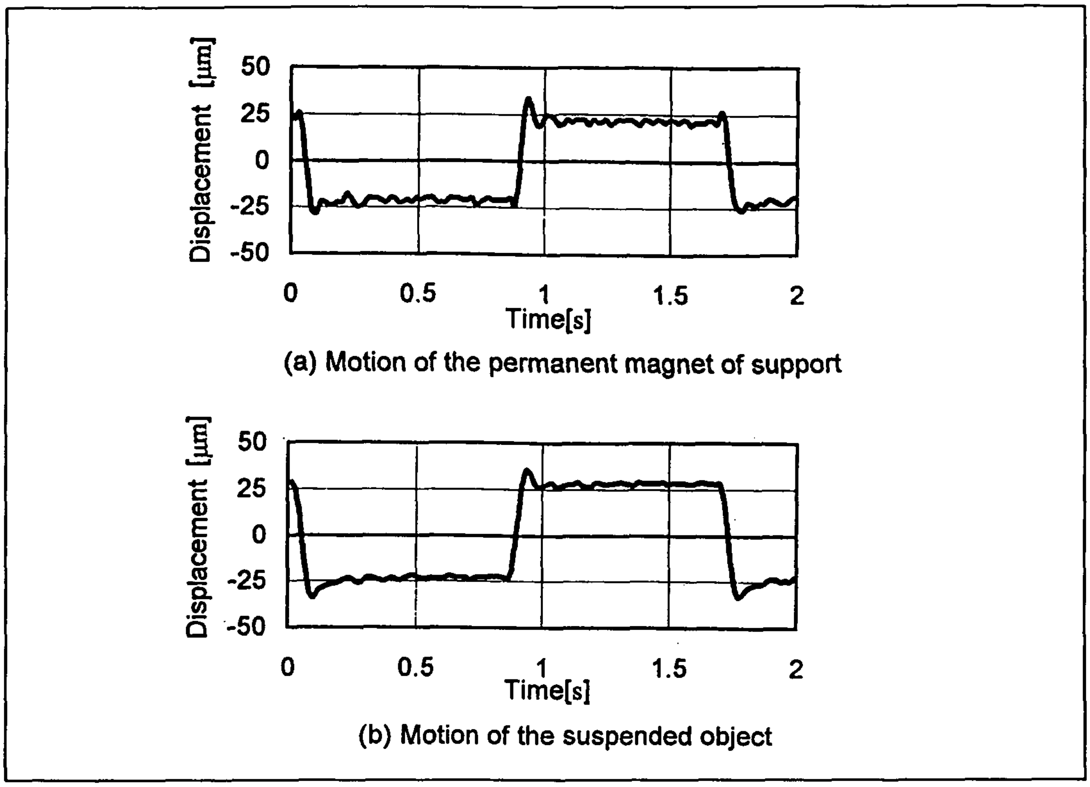

Figure 6. Step response of the magnetic bearing with a I-PD controller.

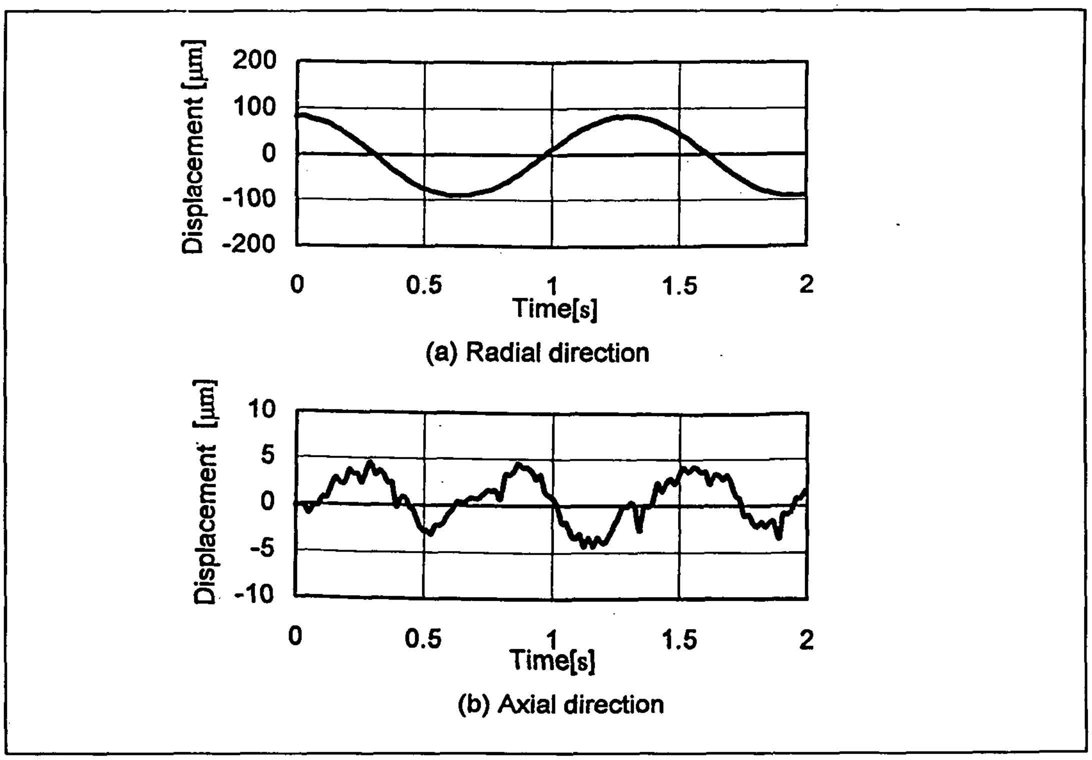

Figure 7. Motion of the rotor at a rotational speed of 36 rpm.

goal. When they overshoot the goal, the magnet of support outruns the magnet on the rotor to produce force restoring to the goal. Finally it stops there. This behavior is similar to that of an inverted pendulum.

Figure 7 shows the behavior of the rotor when it is rotating at a speed of 36 rpm. In the radial directions, whirling motion with an amplitude of about $60\,\mu m$ is observed. Since the procedure of balancing the rotor was omitted, whirl is rather large. This will be reduced if the rotor is balanced. Meanwhile, the deviation in the axial direction is within $\pm 5\,\mu m$.

These results show that the developed magnetic bearings can suspend a rotating mass without any mechanical contact, and adjust the position of the rotor in the axial direction.

CONCLUSIONS

A magnetic bearing system using forces of repulsion between permanent magnets was developed. In the developed magnetic bearing, the radial motions of the rotor were passively supported by repulsive forces between ring-shape permanent magnets; the axial motion was actively controlled by using the motion control of the permanent magnets for passive radial suspension.

A basic model for the dynamics in the axial direction was derived. Fundamental control methods such as PD and I-PD controls were discussed based on this model. In the experiments, voice coil motors were used to move the permanent magnets; the I-PD control was applied. The experimental results demonstrated that the developed magnetic bearing could suspend a rotating mass without any mechanical contact, and realize positioning control of the rotor in the axial direction.

Further experimental works are under way, in addition to manufacturing a small magnetic bearing using the proposed levitation mechanism.

ACKNOWLEDGMENT

This work is supported in part by Saneyoshi Scholarship Foundation, and a Grant-in-Aid for Exploratory Research from the Ministry of Education, Science, Sports and Culture of Japan.

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