REPULSIVE MAGNETIC BEARING USING A PIEZOELECTRIC ACTUATOR FOR STABILIZATION

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ABSTRACT

A magnetic bearing system was developed in which support for radial direction was provided with repusive forces between reing-shape permanent magnets and support for axial direction was achieved by the motion control of the permanent magnets. A piezoelectric actuator was used for the motion control. The characteristics of the magnetic bearing were studied both theoretically and experimentally.

INTRODUCTION

The levitation systems using forces of repulsion between permanent magnets are inherently stable in the levitation direction(s) but unstable in the lateral direction(s). The authors have proposed to stabilize the system by using the motion control of a permanent magnet of support in the lateral direction(s) [1]. This stabilization technique is similar to that for an inverted pendulum; the levitated object, which would slide in the lateral directions without control, is kept at a position by controlling the movement of the support composed of permanent magnet(s).

The authors have developed repulsive magnetic bearing systems using this levitation mechanism [2, 3]. In the developed system, the four-degree-of-freedom motions in the radial direction are passively supported by 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 the motion control of the magnets with a pair of voice coil motors.

This paper investigates the applicability of piezoelectric actuators to the repulsive magnetic bearing system instead of voice coil motors. Piezoelectric actuators have several advantages:

- high-speed response,
- small heat dissipation,
- no necessity of winding coil.

These characteristics are distinguishable from those of electromagnets that are ordinarily used in active magnetic bearings [4]. The third feature is advantageous in the fields where simplicity of structure is of primary importance such as micro machines.

In this research a magnetic bearing system using a piezoelectric actuator for motion control is developed. Its characteristics are studied both theoretically and experimentally.

MODEL

Basic Configuration

Figure 1 shows a basic configuration of magnetic bearings treated in this research. Support for radial direction was provided with repulsive forces between permanent magnets of ring shape. The single-degree-of-freedom motion in the axial direction is actively controlled by moving the ring-shape permanent magnets for radial support. For this motion control, a piezoelectric actuator is used in this work.

Modeling

Figure 2 shows a physical model of the system illustrated by Fig.1. It is assumed for simplicity that the rotor m_a moves only in the axial direction. The gravitational force acting on the rotor and the lateral forces between the permanent magnets are balanced in the equilibrium states. The effects of lateral force are modeled by a vertual spring that has a negative stiffness. For small deviations from the equilibrium, the equation of motion becomes

$$m_a\ddot{x}_a(t)=k_l(x_a(t)-x_b(t)),\tag{1}$$

where

m_a : mass of the levitated object,
k_l :stiffness of the vertual spring,
x_a : displacement of the rotor,
x_b : displacement of the magnets for radial support.

It is assumed that the actuator is controlled to follow a signal inputted to the driver circuit so that

$$x_b(t)=k_e u(t),\tag{2}$$

where

u : input voltage to the driver circuit,
k_e : gain of the driver circuit.

Substituting (2) into (1) gives

$$m_a\ddot{x}_a(t)=k_l x_a(t)-k_l k_e u(t).\tag{3}$$

Equation (3) indicates that the system is unstable without control ($u(t)=0$).

CONTROL SYSTEM DESIGN

PD Control

The PD control is a fundamental control scheme for the stabilization of most magnetic suspension systems. The control input is represented by

$$u(t)=K_P x_a(t)+K_D\dot{x}_a(t)+v(t),\tag{4}$$

where

K_P : gain of displacement feedback,
K_D : gain of velocity feedback,
$v(t)$: auxiliary input.

From (3) and (4), the transfer function of the closed-loop system is obtained as

$$\frac{X_a(s)}{V(s)}=\frac{-k_l k_e}{m_a s^2+k_l k_e K_D s+k_l(k_e K_P-1)}.\tag{5}$$

The pole assignment method is used to design the PD controller in this paper. Let the desired characteristic polynomial denoted by

$$\Delta(s)=s^2+2\varsigma_1\omega_1 s+\omega_1^2.\tag{6}$$

From (5) and (8), the feedback gains are determined as

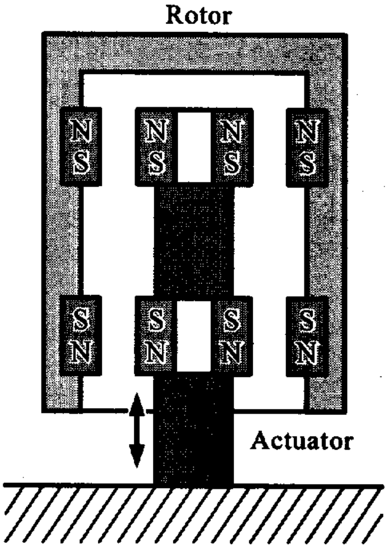


FIGURE 1: Repulsive-type magnetic bearing using the motion control of the magnet for support

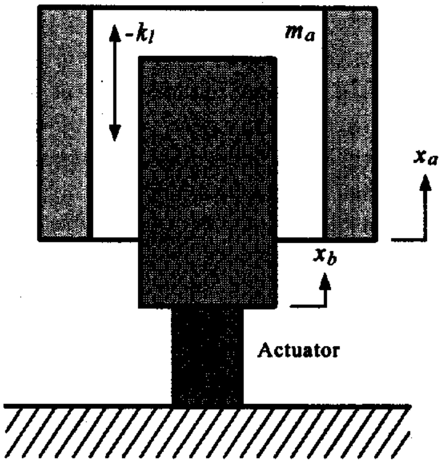


FIGURE 2: Basic model

$$K_P=\frac{k_l+\omega_1^2}{b_0},\tag{7}$$

$$K_D=\frac{2\zeta\omega_1}{b_0},\tag{8}$$

where

$$b_0=\frac{k_l k_e}{m_a}.\tag{9}$$

I-PD Control

For precise position control, an integral action should be incorporated into the feedback loop. The I-PD controller as well as the PID controller is widely used. This controller is represented by

$$u = K_I \int (x_a - x_r)dt + K_P x_a + K_D \dot{x}_a, \tag{10}$$

where

x_r : command signal,

K_I : gain of integral feedback.

From (3) and (10), we get

$$G_r(s) = \frac{X_a(s)}{X_r(s)}$$

$$= \frac{k_l k_e K_I}{m_a s^3 + k_l k_e K_D s^2 + k_l(k_e K_P - 1)s + k_l k_e K_I} \tag{11}$$

The pole assignment method is applied for designing the I-PD controller as well. Let the desired characteristic polynomial denoted by

$$\Delta(s) = (s^2 + 2\zeta\omega_1 s + \omega_1^2)(s + \omega_2). \tag{12}$$

From (11) and (12), the feedback gains are determined as

$$K_I = \frac{\omega_1^2 \omega_2}{b_0}, \tag{13}$$

$$K_P = \frac{\omega_1^2 + 2\zeta\omega_1\omega_2 + k_l}{b_0}, \tag{14}$$

$$K_D = \frac{2\zeta\omega_1 + \omega_2}{b_0}. \tag{15}$$

EXPERIMENTS

Experimental Setup

Figures 3 and 4 show a schematic diagram and a photo of the developed magnetic bearing apparatus with a piezoelectric actuator.

The outer rotor has two ring-shape permanents at its top and bottom. The inner and outer diameters of each magnet are 20 mm and 26 mm, respectively; the height is 5mm. The mass of the rotor, m_a is about 215g.

Two types of piezoelectric actuators are prepared whose strokes are 200μm and 90μm, respectively. One of them is fixed to the base of the apparatus. It moves the stator shaft inside the rotor. A pair of ring-shape permanent magnets for radial support are attached to the sahft. The inner and outer diameters and height of the magnets are 6mm, 9mm and 5mm, respectively. All the

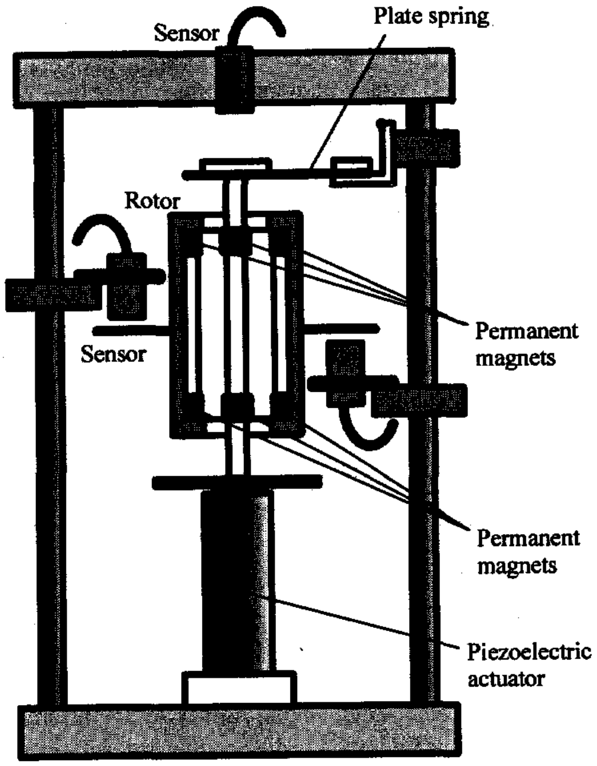


FIGURE 3: Schematic drawing of the manufactured experimental apparatus

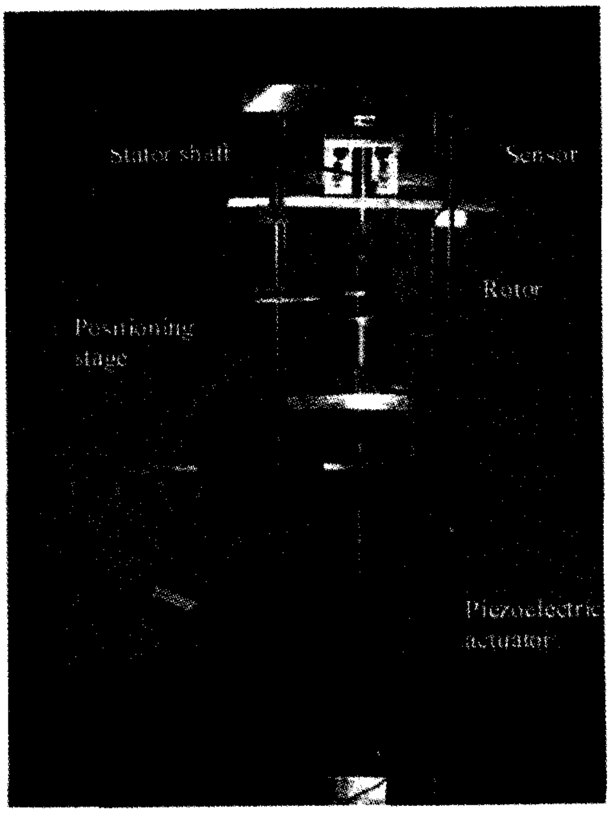
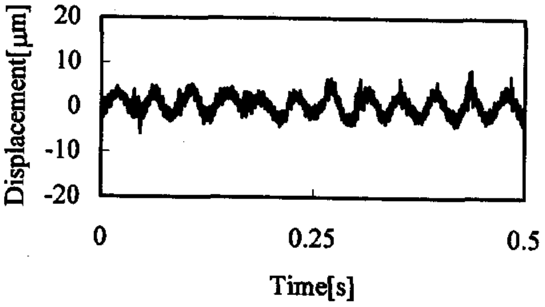
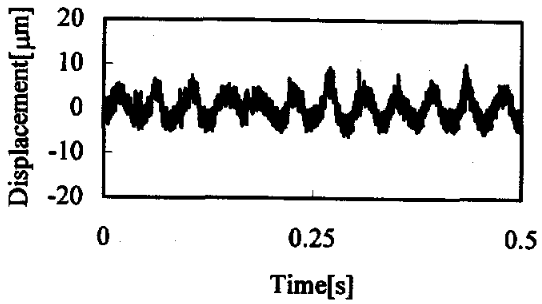


FIGURE 4: Photograph of the apparatus

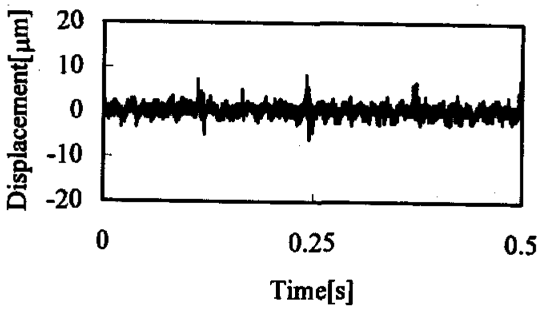


(a) Displacement of the rotor

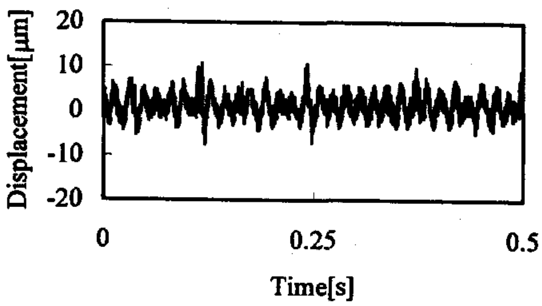


(a) Displacement of the stator shaft

FIGURE 5: Steady-state motion during levitation when PD control is applied.



(a) Displacement of the rotor



(a) Displacement of the stator shaft

FIGURE 6: Steady-state motion during levitation when I-PD control is applied.

permanent magnets are made of NdFeB materials. The initial position of the rotor can be adjusted precisely with a single-axis (vertical direction) positioning stage, which is omitted in Fig.3.

The axial motions of the rotor and stator shaft are sensed by eddy-current gap sensors. A DSP-based digital controller is used to produce a control input for stabilization from a signal produced by the sensor located in the axial direction. A voltage-output power amplifier drives the actuator according to the signal generated from the controller.

Experimental Results

First, the actuator whose maximum displacement is 200 μm is installed. Figure 5 shows the movements of the rotor and the magnets for support when the rotor levitates with a PD controller. The deviation of the rotor from the equilibrium position is kept within ±5μm .

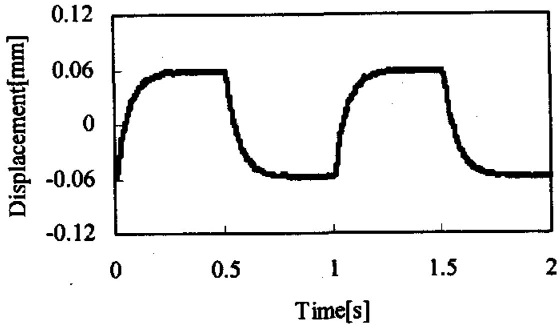
Figure 6 shows the movements of the rotor and the magnets for support when the rotor levitates with an I-PD controller. The deviation of the rotor from the equilibrium position is kept almost within ±3μm so hat the levitation accuracy is improved in comparison with that of the PD-controlled system.

A step response of the I-PD controlled system is shown in Fig.7. The closed-loop polynonimal $\Delta(s)$ is selected as

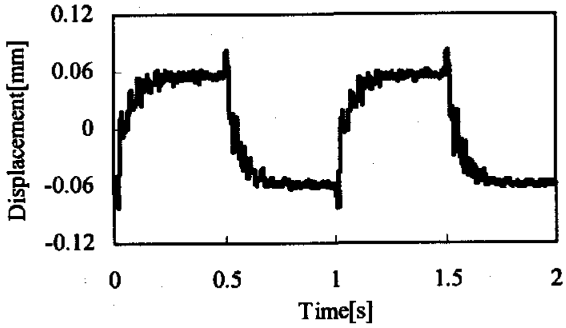
$$\omega_1 = 75.4 \text{ [rad/s]}, \quad \zeta = 0.7, \quad \omega_2 = 50.2 \text{ [rad/s]}.$$

The command signal x_r is changed from -60μm to +60μm and vice versa. It was the maximum value for the rotor to follow. Figure 7 shows that the system behaves in a simlar way to the conventional inverted pendulum. Just after the command signal changes to a new value, the magnets of support move in the direction opposite to the new stationary position (goal). Then it drives the magnet of the rotor in the direction of the goal. Finally it stops there.

The frequency response of the I-PD controlled system to command signal is shown in Fig.8 where the amplitude of the input signal is set to be 60μm in measurement. This result indicates that the system can follow the command signal up to about 7Hz.



(a) Displacement of the rotor



(a) Displacement of the stator shaft

FIGURE 7: Step response of the I-PD control system.

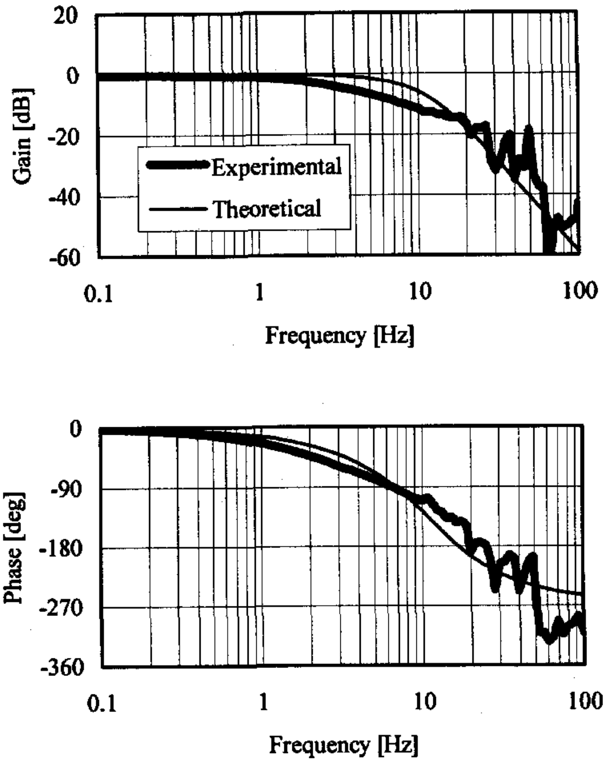


FIGURE 8: Frequency response of the I-PD control system.

Then, the actuator is replaced by the actuator whose maximum displacement is 90μm. When I-PD control is applied, the rotor can follow stepwise command signal whose magnitude is within ±20μm. Figure 9 shows a step response when The command signal x_r is changed from -20μm to +20μm and vice versa. The closed-loop polynonimal $\Delta(s)$ is selected as

$$\omega_1 = 132\,[\text{rad/s}],\quad \zeta=0.8,\quad \omega_2 = 50.2\,[\text{rad/s}].$$

These results show that the developed magnetic bearing system can suspend a rotor without any mechanical contact, and realize the positioning of the rotor in the axial direction.

CONCLUSIONS

A magnetic bearing system was developed in which support for radial direction was provided with repusive forces between reing-shape permanent magnets and support for axial direction was achieved by the motion control of the permanent magnets. A piezoelectric actuator was used for the motion control.

In the experiments, a piezoelectric actuator with a stroke of 200μm was used first. The rotor was successfully levitated without any mechanical contact in the developed magnetic bearing system. It was experimentally shown that the rotor could follow stepwise command signal whose magnitude was within ±60μm when I-PD control was applied. Then the actuator was replaced by the actuator with a stoke of 90μm. It was shown that the rotor could follow stepwise command signal whose magnitude was within ±20μm when I-PD control was applied.

Further works are under way in order to develope micro magnetic bearings using the proposed levitation mechanism.

ACKNOWLEDGMENT

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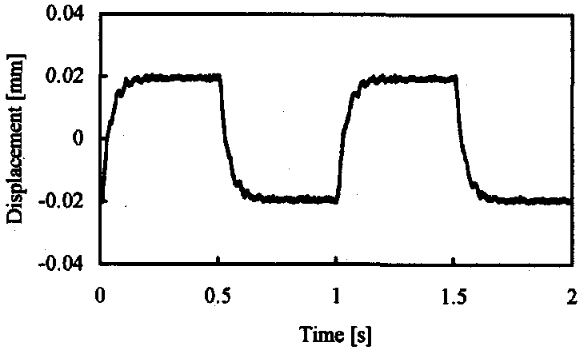
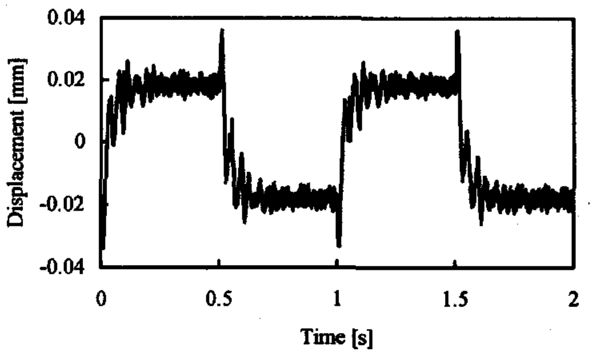


(a) Displacement of the rotor



(a) Displacement of the stator shaft

FIGURE 9: Step response of the I-PD control system using an actuator with a stroke of 90μm.

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