Repulsive Magnetic Bearing Using a Piezoelectric Actuator for Stabilization*

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A repulsive magnetic bearing system equipped with a piezoelectric actuator for the motion control of permanent magnets is studied experimentally. In this system, the radial motions of the rotor are passively supported by repulsive forces between permanent magnets. The motion in the axial direction is stabilized by moving the permanent magnets for radial suspension with a piezoelectric actuator. In the experiments, a piezoelectric actuator with a stroke of 200 μm was installed first. PD and I-PD controllers were applied to achieve levitation without any mechanical contact. It was experimentally shown that the dynamic characteristics of the levitation system could be adjusted by pole assignment. Next the actuator was replaced by an actuator with a stoke of 90 μm. Experimental results demonstrated that the rotor can follow stepwise command signal whose magnitude was within ±20 μm.

Key Words: Magnetic Bearing, Piezo-Element, Positioning, Mchatronics, Servo Mechanism, Motion Control, Permanent Magnet

1. Introduction

The levitation systems using forces of repulsion between permanent magnets are inherently stable in the normal direction but unstable in the lateral direction. The authors have proposed to stabilize the system by using the motion control of a permanent magnet of support in the lateral direction[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. This behavior was experimentally confirmed with an instrument simulating an inverted pendulum[2].

The authors have been investigating repulsive magnetic bearing systems using this levitation mechanism in which 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 for radial support[3)-(6]. In this system, the selection of actuator for the motion control of magnets is important. A pair of voice coil motors was used in the previous works[3],[4] mainly because the main aim of them was to show the feasibility of levitation in the proposed system. The authors have also tried to use a piezoelectric actuator for the motion control of the magnets[5],[6] because it has such characteristics as

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

The third feature is an advantage over electromagnetic actuators especially in the fields where simplicity of structure is of primary importance such as micro machines. However, limitation in stroke causes difficulty in achieving levitation[5]. The authors have developed a magnetic bearing apparatus equipped with a piezoelectric actuator whose stroke is 200 μm and succeeded in levitating the rotor without any mechanical contact[6]. This paper presents a brief description of the developed apparatus and several

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experimental results carried out in this system. It is also demonstrated that levitation is achieved with a piezoelectric actuator whose stroke is 90 μm.

2. Model

2.1 Controlled object

Figure 1 shows a schematic diagram of the developed magnetic bearing apparatus with a piezoelectric actuator[6]. It is outer-rotor type. Support for the radial directions is 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 by the piezoelectric actuator.

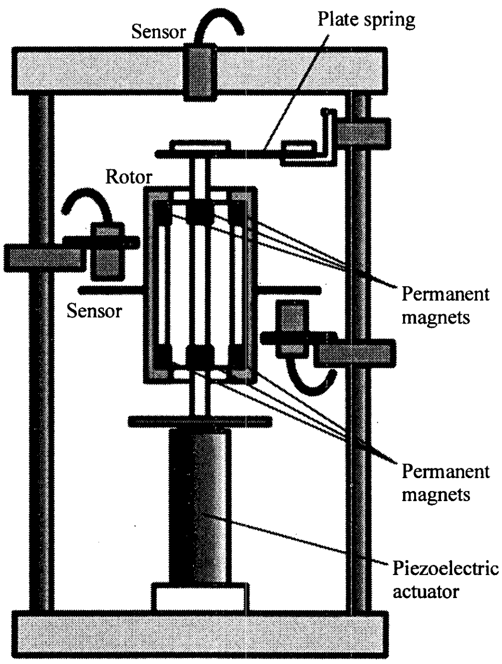


Fig. 1 Schematic diagram of the repulsive magnetic bearing system

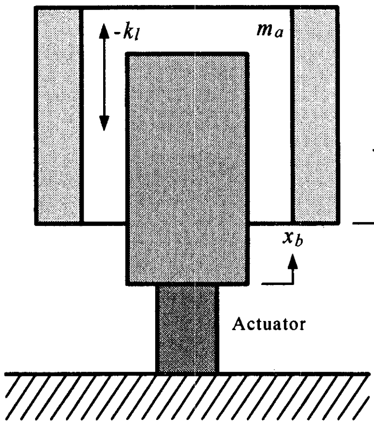


Fig. 2 Basic model

2.2 Basic model

Figure 2 shows a physical model of the apparatus shown by Fig. 1. The motion in the axial (vertical) direction is treated here. 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 virtual spring that has a negative stiffness k_l. For small deviations from the equilibrium, the equation of motion becomes

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

where m_a : mass of the levitated object, x_a : displacement of the rotor, and x_b : displacement of the magnets for radial support[6]. The displacement of the actuator is controlled with a driver circuit to follow the inputted signal:

$$x_b(t)=k_e u(t), \qquad (2)$$

where u : input voltage to the driver circuit, and k_e : gain of the driver circuit. Substituting (2) into (1) leads to

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

3. Controller Design

3.1 PD controller

When PD control is applied, the control input is represented by

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

where K_P : gain of displacement feedback, K_D : gain of velocity feedback, and $v(t)$: auxiliary input. From Eqs. (3) and (4), we obtain

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

Let the desired characteristic polynomial denoted by

$$\Delta(s)=s^2+2\zeta_1\omega_1 s+\omega_1^2. \qquad (6)$$

From Eqs. (5) and (6), the feedback gains are determined as[6]

$$K_P=\frac{k_l+\omega_1^2}{b_0}, \qquad (7)$$

$$K_D=\frac{2\zeta\omega_1}{b_0}, \qquad (8)$$

where

$$b_0=\frac{k_l k_e}{m_a}. \qquad (9)$$

3.2 I-PD controller

Integral action should be added for the rotor to follow a command signal precisely. The control is represented by

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

where x_r : command signal, and K_I : gain of integral feedback. This control law is called as I-PD control. It is pointed out that I-PD type control systems are superior in low sensitivity and good disturbance attenuation by small control input to PID type control systems[7]. From Eqs. (3) and (10), we get

$$G_r(s)=\frac{X_a(s)}{X_r(s)}$$
$$=\frac{k_t k_e K_I}{m_a s^3+k_t k_e K_D s^2+k_t(k_e K_P-1)s+k_t k_e K_I} \qquad (11)$$

Let the desired characteristic polynomial denoted by

$$\Delta(s)=(s^2+2\zeta\omega_1 s+\omega_1^2)(s+\omega_2). \qquad (12)$$

From Eqs. (11) and (12), the feedback gains are determined as[6]

$$K_I=\frac{\omega_1^2\omega_2}{b_0}, \qquad (13)$$

$$K_P=\frac{\omega_1^2+2\zeta\omega_1\omega_2+k_t}{b_0}, \qquad (14)$$

$$K_D=\frac{2\zeta\omega_1+\omega_2}{b_0}. \qquad (15)$$

4. Experiments

4.1 Experimental apparatus

Figure 3 shows the first magnetic bearing apparatus equipped with a piezoelectric actuator for the motion control of permanent magnets[5]. The stroke of the actuator was 46 μm. The height and outer and inner diameters of the rotor was 51 mm, 51 mm and 32 mm, respectively. The weight is about 300 g. The rotor has two ring-shape permanents at its top and bottom whose distance could be adjusted. Although contactless levitation was tried under various conditions, it could not be achieved in this apparatus. One of the difficulties was to set the levitated object in an appropriate position at the start of levitation control. Another was to stabilize the tiling motions because the distance of the two magnets was not large.

Figures 4 shows a photo of the second apparatus whose schematic diagram was presented in section 2.1. The following modifications were carried out in designing.

1) Piezoelectric actuators with larger stroke are used.

2) The shape of rotor is similar to that used in the previous works where contactless levitation was achieved[3],[4].

3) The initial position of the rotor can be adjusted precisely with a single-axis (vertical direction) positioning stage (which was omitted in Fig. 1).

Two types of piezoelectric actuators are prepared whose strokes are 200 μm and 90 μm. 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 is attached to the shaft. The height and outer and inner diameters of the rotor was 100 mm, 40 mm and 20 mm, respectively. The weight m_a is 215 g. The rotor has two ring-shape permanents at its top and bottom. All the permanent magnets are made of NdFeB materials. The dimensions of the magnets are listed in Table 1.

The axial motions of the rotor and stator shaft are detected with eddy-current gap sensors. These signals are inputted to a DSP-based digital controller. The controller calculates control input according to Eq. (4) or Eq. (10) and sends it to a driver circuit for piezoelectric actuator through a D/A converter.

4.2 Experimental results

4.2.1 Identification of lateral factor Force-displacement characteristics in the lateral direction were measured with a setup shown by Fig. 5. The rotor was fixed to the positioning stage and the stator

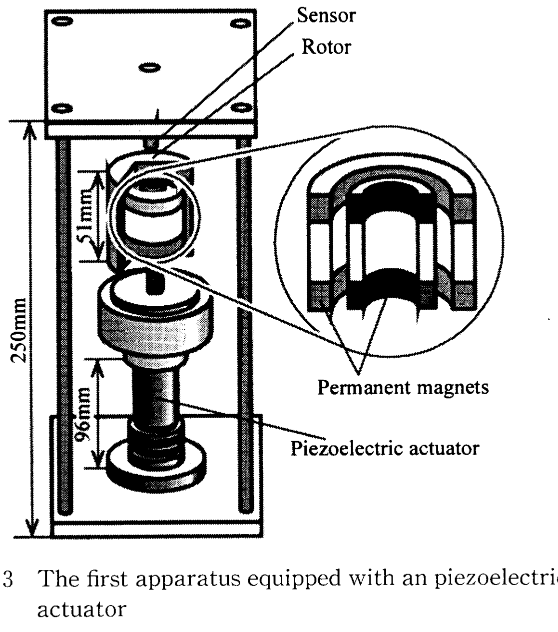


Fig. 3 The first apparatus equipped with an piezoelectric actuator

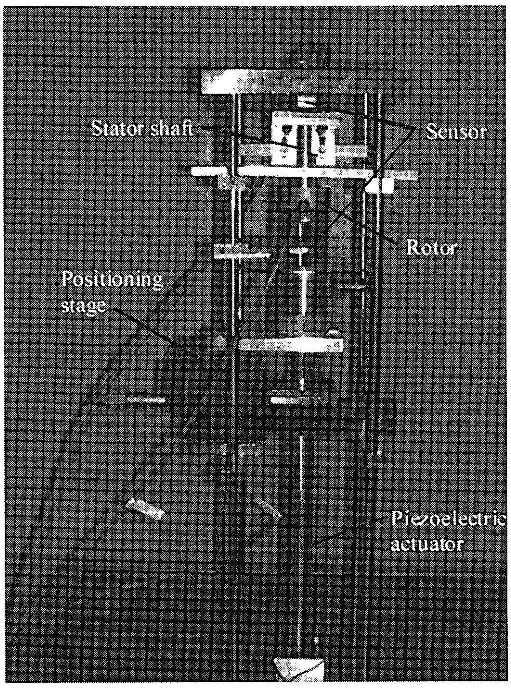


Fig. 4 Photo of the second apparatus

Table 1 Dimensions of the permanent magnets

	inner diameter	outer diameter	height
Rotor	20mm	26mm	5mm
Stator shaft	6mm	9mm	5mm

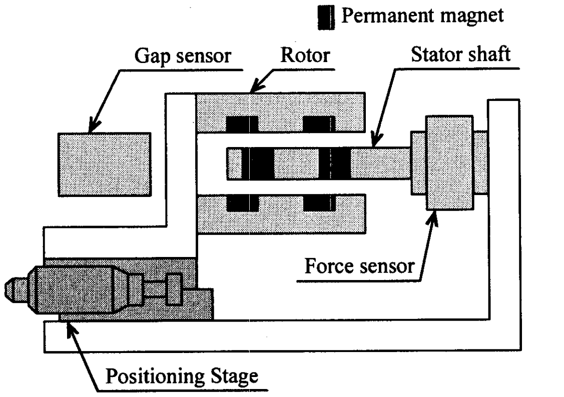


Fig. 5 Setup for measuring force-displacement charcteristics in the lateral direction

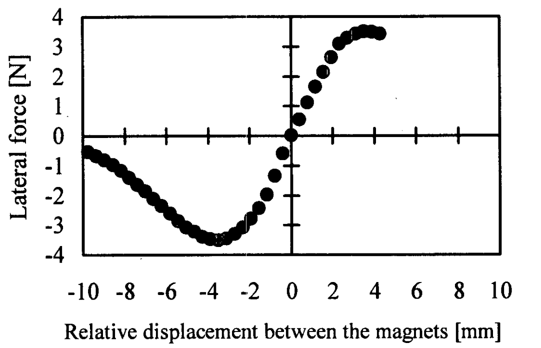
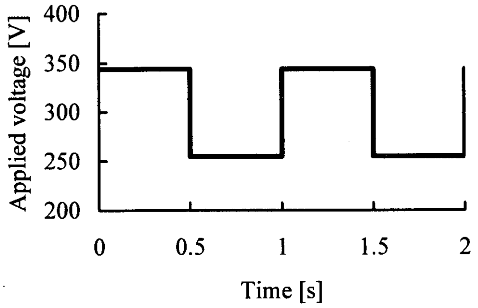
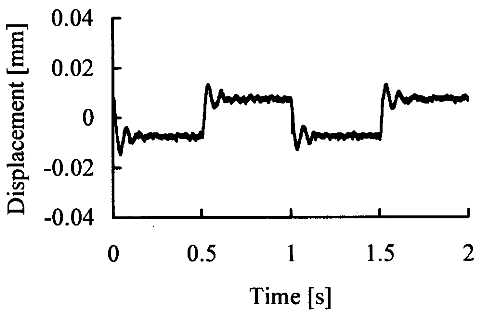


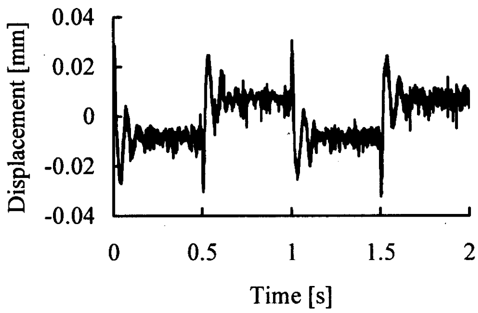
Fig. 6 Measured force-displacement characteristics



(a) Applied voltage



(b) Motion of the rotor



(c) Motion of the stator shaft

Fig. 7 Step response of the PD control system designed as $\omega_1=75.4$ [rad/s] and $\zeta=0.7$

shaft was fixed to the force sensor. The relative displacement of the rotor to the stator shaft was adjusted with the stage. The measurement results are plotted in Fig. 6. The lateral factor k_l was determined by linearizing the force-displacement relation in the region where the relative displacement is within ± 2 mm:

$k_l=1.4\times10^3$ [N/m].

4. 2. 2 Levitation using an actuator with a stroke of 200 μm The actuator with a stroke of 200 μm was installed in the apparatus shown by Fig. 1. The maximum displacement is obtained when the voltage applied to the actuator is 600 V. It means

$k_e=3.3\times10^{-7}$ [m/V].

The bias voltage was set to be 300 V for the actuator to achieve bi-directional movements.

Figures 7 and 8 show the step responses of PD control systems that are designed as

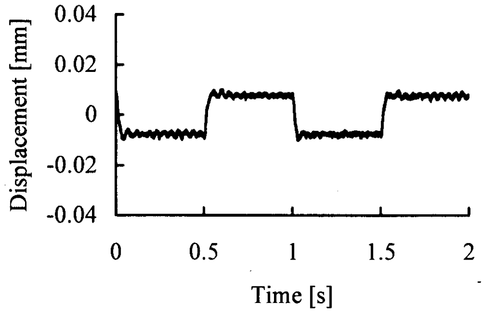
(a) $\omega_1=75.4$ [rad/s], $\zeta=0.7$, (Fig. 7),
(b) $\omega_1=75.4$ [rad/s], $\zeta=1.0$, (Fig. 8).

The auxiliary input is given by

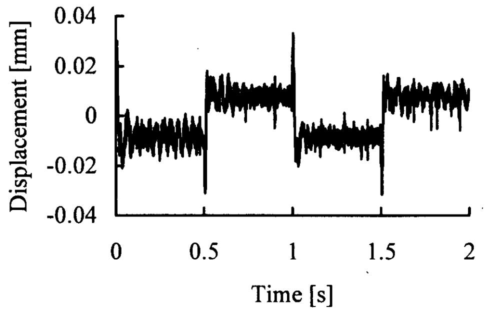
$v(t)=\pm45$ [V].

Just after $v(t)$ changes from 45 [V] to -45 [V], the stator shaft moves in the negative direction (see Fig. 7(c)). Then the rotor begins to move in the positive direction by lateral force. The stator shaft follows and then passes it. Finally they stop at new stationary positions. Such behavior is very similar to that an inverted pendulum. Comparing these figures, we find that the damping characteristic is improved by setting ζ larger. Figure 9 compares the frequency responses of the two systems. In the figure $-\angle G_p(j\omega)$ is plotted as phase. The maximum value of $|G_p(j\omega)|$ is reduced by setting ζ to be larger.

Figures 10 and 11 show the step response of I-PD control systems that are designed as

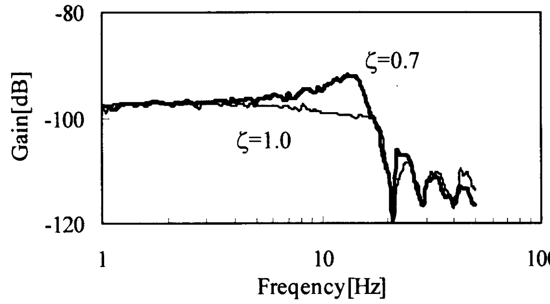


(a) Motion of the rotor

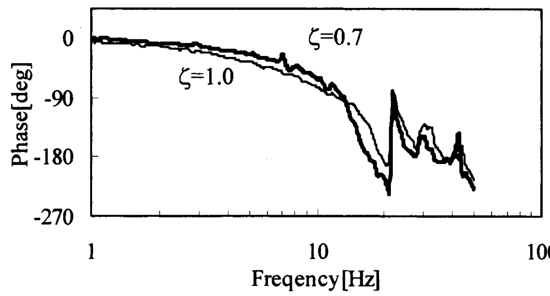


(b) Motion of the stator shaft

Fig. 8 Step response of the PD control system designed as $\omega_1=75.4$ [rad/s] and $\zeta=1.0$. (graph of the applied voltage is omitted)

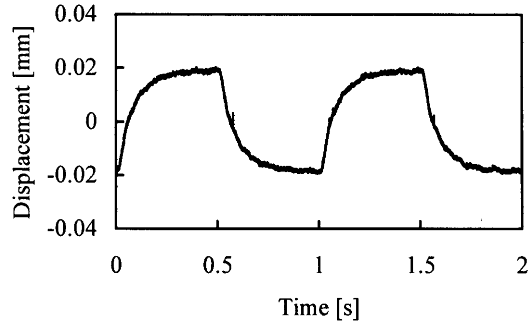


(a) Gain

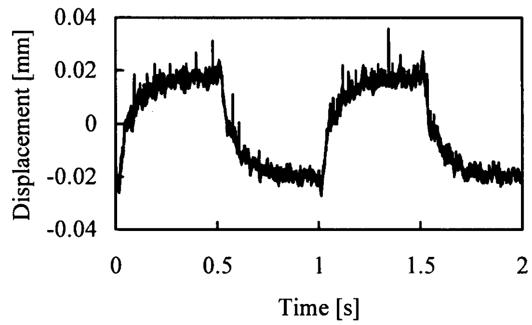


(b) Phase

Fig. 9 Frequency response of PD control systems



(a) Motion of the rotor



(b) Motion of the stator shaft

Fig. 10 Step response of the I-PD control system designed as $\omega_1=50.2$ [rad/s], $\zeta=0.7$ and $\omega_2=50.2$ [rad/s]

(a) $\omega_1=50.2$ [rad/s], $\zeta=0.7$, $\omega_2=50.2$ [rad/s]. (Fig. 10),

(b) $\omega_1=75.4$ [rad/s], $\zeta=0.7$, $\omega_2=50.2$ [rad/s]. (Fig. 11).

The command signal x_r is changed from -20 μm to $+20$ μm and vice versa. Comparing the two systems, we find that increasing ω_1 leads to higher response but larger position deviation in the steady states. It is to be noted that the maximum amplitude of the command signal was ± 60 μm for the rotor to follow[6].

4. 2. 3 Levitation using an actuator with a stroke of 90 μm The actuator was replaced by the actuator whose maximum displacement was 90 μm. Figure 12 shows a step response of an I-PD control system that are designed as

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

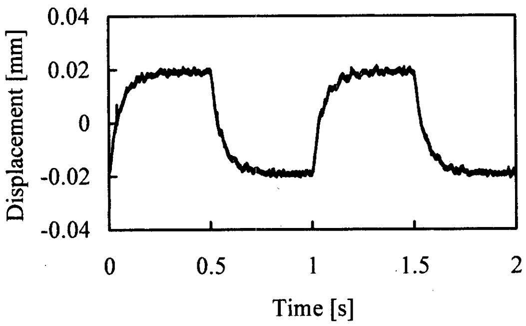
The command signal x_r is changed from -20 μm to $+20$ μm and vice versa, which was the maximum value for the rotor to follow. Figure 13 shows step responses when the command signal changes from 0 to (a) 6 μm and (b) 3 μm. This result indicates that the system has the ability of micron-order positioning.

The frequency response of I-PD control systems to command signal is shown in Fig. 14 where the amplitude of the input signal is set to be 20 μm in measurement. The closed-loop polynomial $\Delta(s)$ is selected as

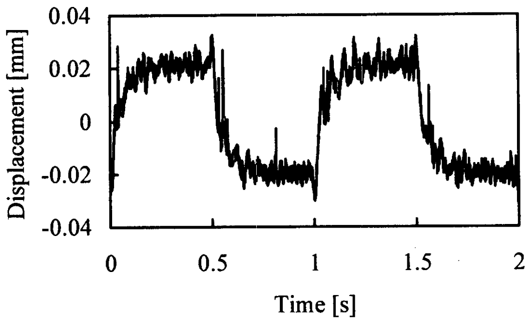
(a) $\omega_1=113$ [rad/s], $\zeta=0.6$, $\omega_2=50.2$ [rad/s] (thick line),

(b) $\omega_1=132$ [rad/s], $\zeta=0.6$, $\omega_2=50.2$ [rad/s] (thin line).

It indicates that the system can follow the command

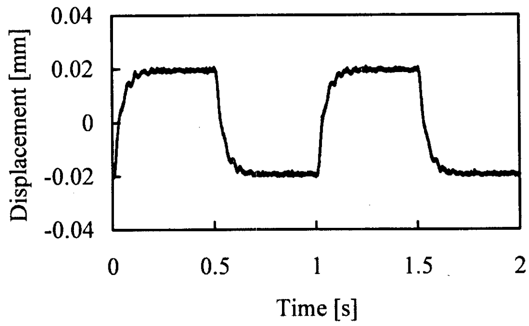


(a) Motion of the rotor

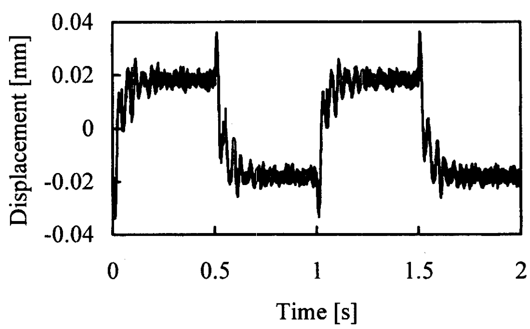


(b) Motion of the stator shaft

Fig. 11 Step response of the I-PD control system designed as $\omega_1=75.4$ [rad/s], $\zeta=0.7$ and $\omega_2=50.2$ [rad/s]

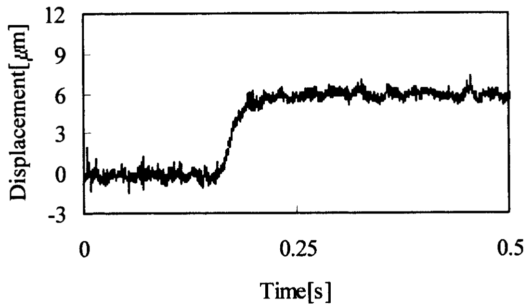


(a) Motion of the rotor

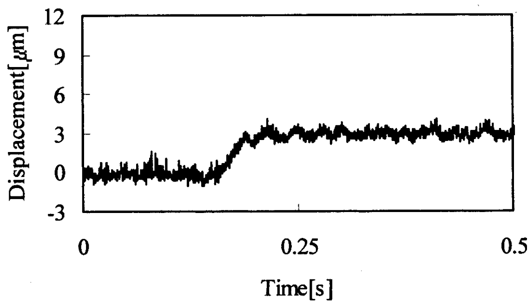


(b) Motion of the stator shaft

Fig. 12 Step response of the I-PD control system equipped with an actuator whose stoke of 90 μm

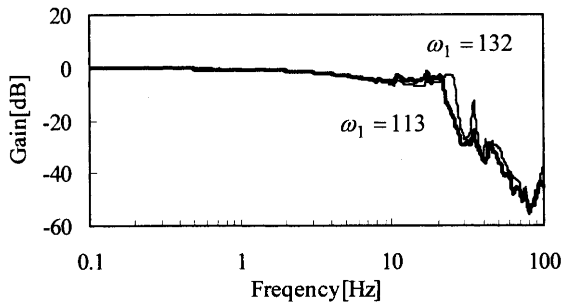


(a) Step size is 6 μm

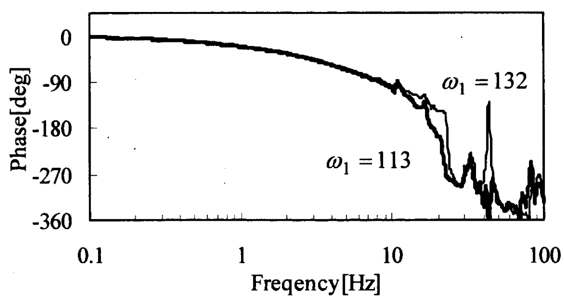


(b) Step size is 3 μm

Fig. 13 Step response of the I-PD control system when the step size is small



(a) Gain



(b) Phase

Fig. 14 Frequency response of I-PD control systems equipped with an actuator whose stroke is 90 μm signal up to about 10 Hz and this bandwidth can be extended by setting ω_1 to be larger.

5. Conclusions

The repulsive magnetic bearing system that was experimentally studied in this work is characterized by using a piezoelectric actuator for stabilization in the lateral direction, which corresponds to the axial direction in the developed apparatus. In the experiments of levitation, a piezoelectric actuator with a stroke of 200 μm was used first. PD and I-PD controllers were applied to achieve levitation without any mechanical contact. It was experimentally shown that the dynamic characteristics of the levitation system could be adjusted by pole assignment. Next the actuator was replaced by an actuator with a stoke of 90 μm. Experimental results demonstrated that the rotor can follow stepwise command signal whose magnitude is within ±20 μm when I-PD control is applied.

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

Acknowledgments

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