Active Repulsive Magnetic Bearing Using a Three-Segment Permanent Magnet

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***Abstract*– This paper proposes a noble three-axis repulsive-type magnetic bearing that uses the motion control of permanent magnets. It has a three-segment permanent magnet of support. The motion of each segment is independently controlled with an actuator. This configuration enables the bearing to control the three-dimensional motion of the rotor. An apparatus is fabricated for experimental study on the proposed magnetic bearing. The dynamics characteristics of the motion control system for the permanent magnets of support were measured. It was demonstrated that the proposed magnetic bearing system can achieve three-dimensional motion control.**

***Index Terms* – Magnetic suspension, Magnetic bearing, Motion control, Permanent Magnet, Repulsion.**

I. INTRODUCTION

The levitation system using forces of repulsion between permanent magnets is inherently stable in the levitation 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 direction without control, is kept at a position by controlling the movement of the support composed of permanent magnets.

The authors have developed repulsive magnetic bearing systems using this levitation mechanism [1-4]. In the previous works, 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. Voice coil motor [1, 2], piezoelectric actuator [3] and solenoid [4] were used as an actuator for the motion control of a permanent magnet. A problem of the previous systems is that force for suspending the weight of the rotor is produced by the lateral force that is rather lower than the repulsive force.

This paper proposes a new three-axis repulsive-type magnetic bearing. It has a three-segment permanent magnet of support. The motion of each segment is independently controlled with an actuator. This configuration enables the bearing to control the three-dimensional motion, that is an axial motion and two radial motions of the rotor.

II. PRINCIPLES

The levitation system using forces of repulsion between permanent magnets is inherently unstable in the lateral direction. This can be stabilized by moving a permanent magnet of support in the lateral direction like an inverted pendulum as shown in Fig.1; the levitated object, which would slide in the lateral directions without control, is kept at a position stably by controlling the movements of the support (permanent magnet).

For achieving actual levitation, the levitation system shown by Fig.1 needs planar motion as shown by Fig.2. Since rather long stroke and speedy motion are required to this motion control system, its actualization may be a challenging task worth being investigated, but it is still difficult at the present stage of technology.

This paper proposes another configuration of magnetic levitation system for achieving two-dimensional motion control of magnet for support. Figure 3 shows a schematic diagram of the proposed levitation system. The permanent magnet of support is divided into three segments. The motion of each segment is controlled with a linear actuator. The lateral motions of the rotor can be stabilized by using the motion control of the segment magnets according to the similar principle of the stabilization of an inverted

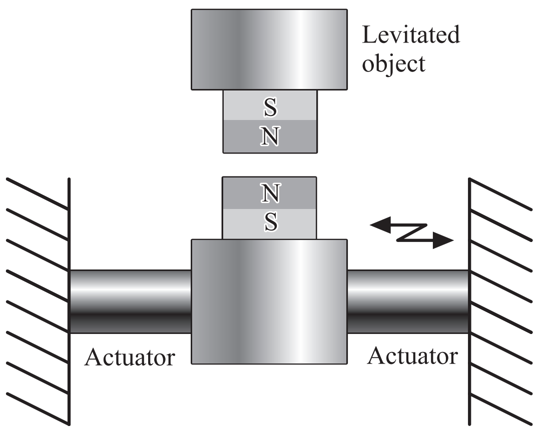


Fig.1 Concept of magnetic levitation system using the motion control of permanent magnet of support

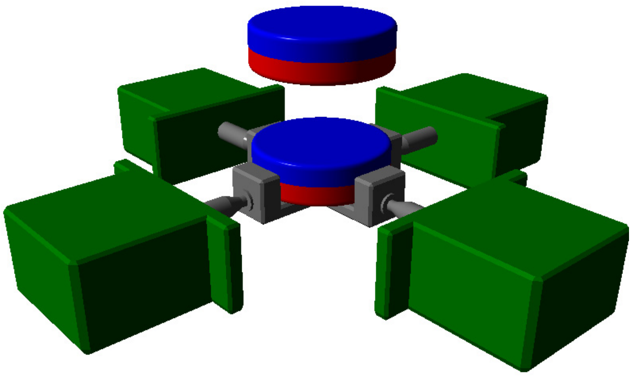


Fig.2 Schematic diagram of a levitation system with a single permanent magnet of support for two-dimensional motion control.

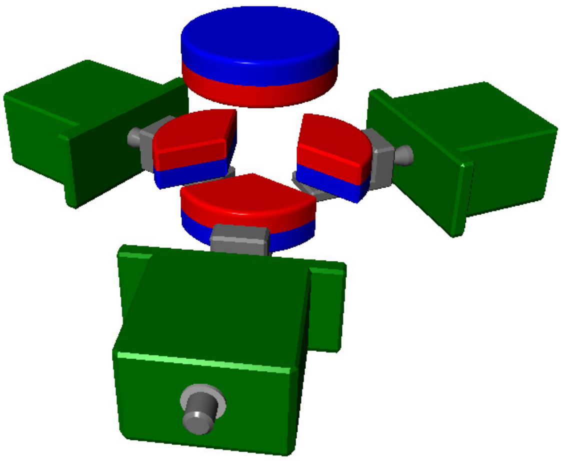


Fig.3 Schematic diagram of a levitation system with a three-segment permanent magnet of support for three-dimensional motion control.

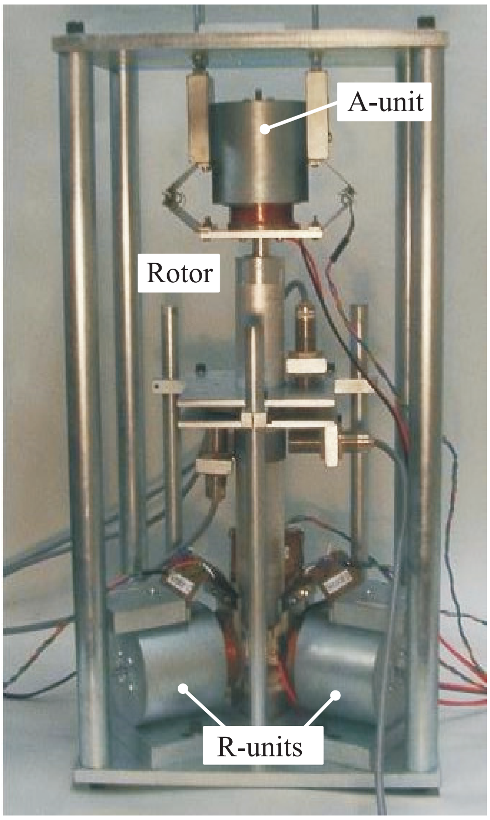
pendulum as shown in Fig.1. In addition, the levitation force can be also adjusted by using the motion control of the segment magnets. The levitation force is reduced by increasing the distance between the segment magnets and vice versa. Therefore, this system can control the three-dimensional motion of the rotor.

III. Experimental Apparatus

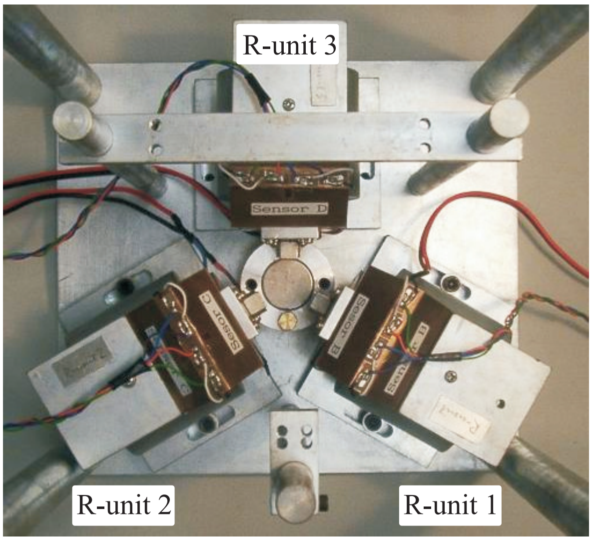
Figure 4 shows photographs of the manufactured experimental apparatus. It consists of a rotor with permanent magnets, three actuator units located under the rotor (R-units), and an actuator unit at the top of the rotor (A-unit).

The three R-units are located at the vertices of an equilateral triangle for achieving three-dimensional positioning of the rotor as shown by Fig.4b. Figure 5 shows a photo and a schematic drawing of the R-unit. A permanent magnet is directly driven by a VCM with a stoke of 15mm and a maximum force of 25N. The position of the plate is detected with a fabricated displacement sensor that is comprised of a V-shape plate spring and four strain gauges pasted on it. The VCM is energized by a power amplifier with current output.

The structure of the A-unit is similar to that of the R-units. It is operated to achieve a single-axis active control in the axial direction and passive support in the radial directions as in the previous works [1-4]. Non-contact



(a) Side view



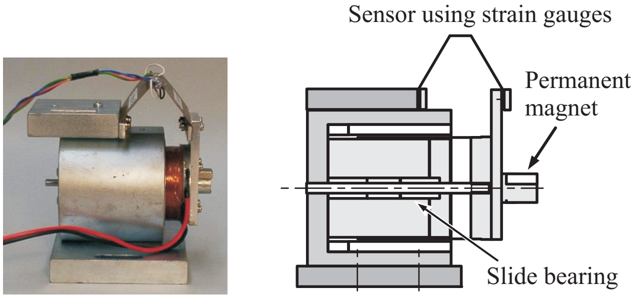
(b) Arrangement of the R-units

Fig.4 Photographs of the experimental apparatus levitation can be realized without the single-axis control theoretically so that it may be replaced by a passive repulsive magnetic bearing. For actual operation, however, such an active element is useful to achieving non-contact levitation for the first time.

Figure 6 shows the rotor. The mass and length of the rotor is 862 [g] and 270 [mm], respectively. The permanent magnet attached to the bottom is in the shape of a disk and made of NeFeB. The diameter and thickness are 30 and 10 [mm], respectively. The rough shape of the segment magnet is a trisected annual shape. The outer diameter, inner diameter and thickness of the magnet are 40, 30 and 5 [mm], respectively. It is also made of NeFeB.

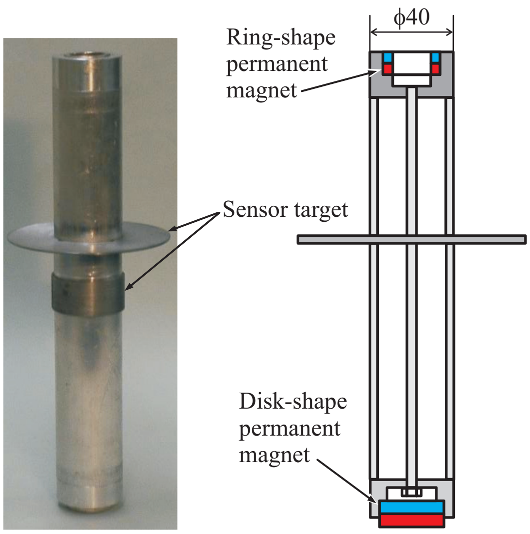
The radial displacements of the rotor are detected by four eddy-current-type displacement sensors. The displacements at the bottom are calculated from the four signals. The vertical displacement of the rotor is detected by a same-type sensor. Its target ring is attached to the middle of the rotor.

The outputs of the sensors are inputted into a DSP-based digital controller. The controller calculates control signals according to the algorithm described in the next section and send them to three power amplifiers for the VCM's through D/A converters.



(a) Photograph (b) Schematic drawing

Fig.5 R-unit



(a) Photograph (a) Schematic drawing

Fig.6 Rotor

IV DESIGN OF CONTROLLER

The control system for the three R-units is described in this section. The designed controller has a double-loop structure. In the inner loop, the displacement of the permanent magnet of support is locally fed back through a PD compensator. It can speed up the movement of the permanent magnet and increase damping.

In the outer loop, the displacements of the rotor are fed back. In the radial directions, the suspension system is unstable. For the stabilization, the command signals to the units are generated from the radial displacements at the bottom with a PD compensator. In addition, for positioning in the z-axis (vertical) direction, an auxiliary signal is added to the control input produced by a PD compensator.

V EXPERIMENTAL RESULTS

A. Dynamic Characteristics of the Actuator Units

First, the characteristics of the units were measured when PD control was applied. The control current i_k of the VCM in the R-unit k was given by

$$i_k = -(q_d x_k + q_v \frac{\mathrm{d}x_k}{\mathrm{d}t}) , \qquad (1)$$

where x_k is the displacement of the permanent magnet in the unit k ($k = 1, 2, 3$). Figure 6 shows the frequency responses of the R-unit 1. The input is command signal and the output is the displacement of the permanent magnet. The proportional gain q_d is changed from 0.43 to 2.58 [A/m] incrementally, and the derivative gain $q_v = 0$.

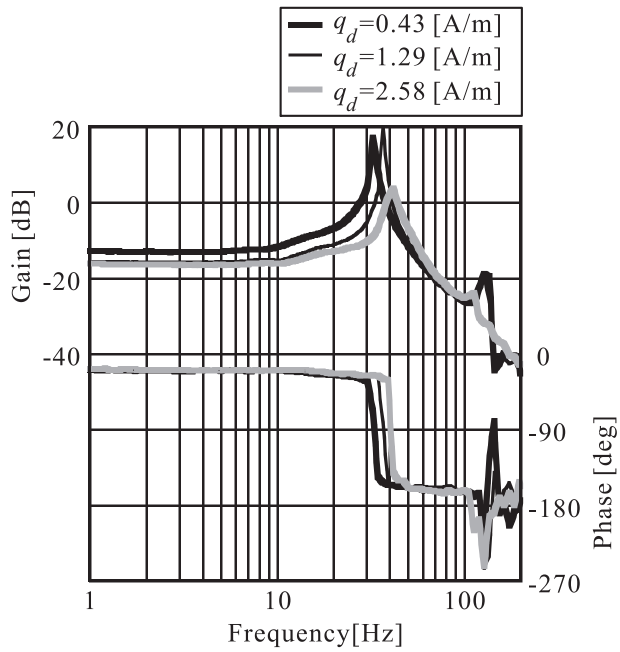


Fig.7 Frequency response of the R-unit 1.

The resonant frequency increases from 30 to 40[Hz]. This result shows that the proportional action extends the frequency range up to 40Hz, in which the R-unit follows the command signal without significant phase delay. It is experimentally confirmed that the other R-units have similar characteristics. In the A-unit, the frequency can be extended up to 45 [Hz].

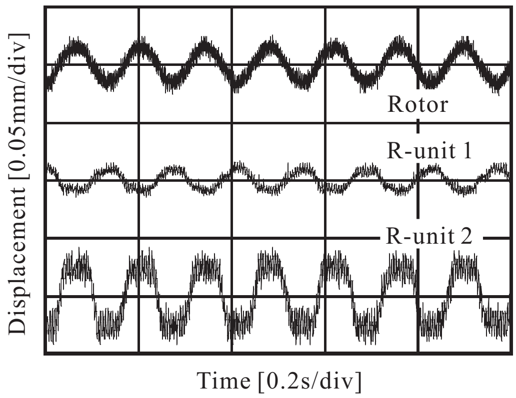
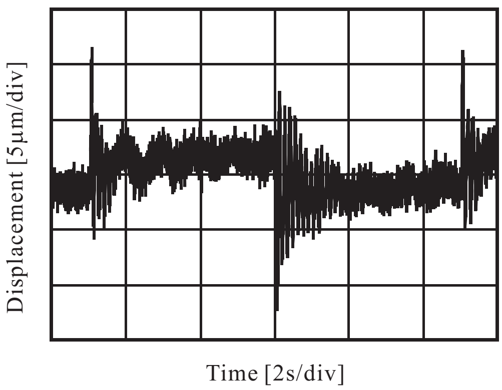
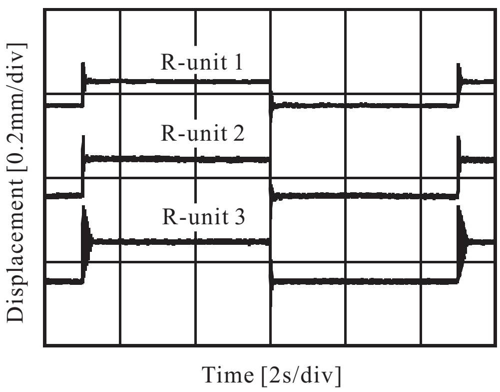


Fig.8 Movements of the rotor and the units when the lateral motion is stabilized



(a) Vertical displacement of the rotor



(b) Motions of the R-units

Fig.9 Positioning in the vertical direction during noncontact levitation

B. *Stabilization with R-units*

Second, to examine the stabilizability in the lateral direction by the R-unit, the apparatus was modified for the rotor to have a single degree of freedom of motion in the lateral (horizontal) direction. A plate spring suspends the rotor at the top from the ceiling of the apparatus. It constrains the motion of the rotor in the lateral direction. The R-units 1 and 2 are placed under the rotor to control this motion.

Figure 8 shows the movements of the rotor and the magnets for support of the R-units when the lateral motion of the rotor is stabilized by using PD control. The deviation of the rotor from the equilibrium position is kept within $\pm 25\mu m$.

C. *Noncontact Levitation*

Third, noncontact levitation was tried. However, the total levitation force, which consists of repulsive forces produced by the R-units and lateral force produced by the A-unit, was too small to counterbalance the weight of the rotor. To overcome this problem, the A-unit was replaced by an electromagnet and the rotor was modified to have a ferromagnetic part at the top. After the modification, noncontact levitation was achieved. Then, positioning in the vertical direction was tried by moving the three permanent magnets of support in the in-phase mode [5]. Figure 9 shows the response of the levitation system when a rectangular signal was superimposed on the control signal of each R-unit. It indicates that the position in the vertical direction can be changed by an integrated action of the three R-units.

VI CONCLUSION

A new three-axis repulsive-type magnetic bearing was proposed in this paper. It has a three-segment permanent magnet of support and the motion of each segment is controlled independently. It enables the system to control the three-dimensional motion of the rotor. This ability was confirmed experimentally by the fabricated apparatus.

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