Flux Path Control Magnetic Suspension

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ABSTRACT

A new magnetic suspension system equipped with flux path control mechanisms was proposed in this paper. The mechanism consists of a ferromagnetic plate and an actuator for driving the plate. The lateral position of the plate, which is inserted into the gap between a permanent magnet and a suspended object (floator), is changed by the actuator. The flux from the permanent magnet to the floator and resultantly the attractive force acting on the floator are controlled with the mechanism. An experimental apparatus was fabricated which has two pairs of flux path control mechanisms. Stable suspension was realized in the apparatus. It was demonstrated that three-dimensional positioning is possible by the proposed magnetic suspension method.

INTRODUCTION

There are several electromagnetic methods of supporting moving or rotating masses [1]. Suspension using the force of attraction between magnetized bodies mostly utilizes controlled DC electromagnets; the attractive force is adjusted by changing current in the electromagnets. Another way of adjusting the attractive force is to change the gap between the magnetized bodies; Oka and Higuchi have proposed a suspension system with permanent magnet and linear actuator in which the permanent magnet is driven by the actuator for changing the gap between the magnet and the suspended object [2]. One of the problems of this system is that the actuator must suspend the whole weight of the suspended object.

This paper proposes a new suspension system using the force of attraction between a permanent magnet and a ferromagnetic body (floator). The attractive force is adjusted by means of flux path control mechanisms. The mechanism consists of a ferromagnetic plate and an actuator for driving the plate. The plate is inserted into the gap between the permanent magnet and the floator. The lateral position of the plate is controlled with the actuator. Since the flux from the permanent magnet to the floator a function of the lateral position of the plate, the flux from the permanent magnet to the floator and resultantly the attractive force acting on the floator can be adjusted by using the motion control of the plate. One of the advantages of this principle is that the actuator need not suspend the whole weight of the suspended object.

This paper is organized as follows. First, the principles of the proposed magnetic suspension system are described. Second, the outline of a manufactured experimental apparatus is shown. Third, several experiments carried out with the apparatus are presented. They will demonstrate that stable suspension and positioning in both the normal and lateral directions are possible by the proposed suspension mechanism.

PRINCIPLES OF THE FLUX PATH CONTROL MAGNETIC SUSPENSION

Figure 1 shows a basic system configuration and the operations of the proposed magnetic suspension method. A permanent magnet is fixed over a floator to produce magnetic force for suspending the weight of the floator. The attractive force acting on the floator is adjusted by a pair of flux path control mechanisms. The mechanism consists of a ferromagnetic plate and an actuator for driving the plate. The plate is inserted into the gap between the permanent magnet and the floator. The lateral position of the plate is controlled with the actuator.

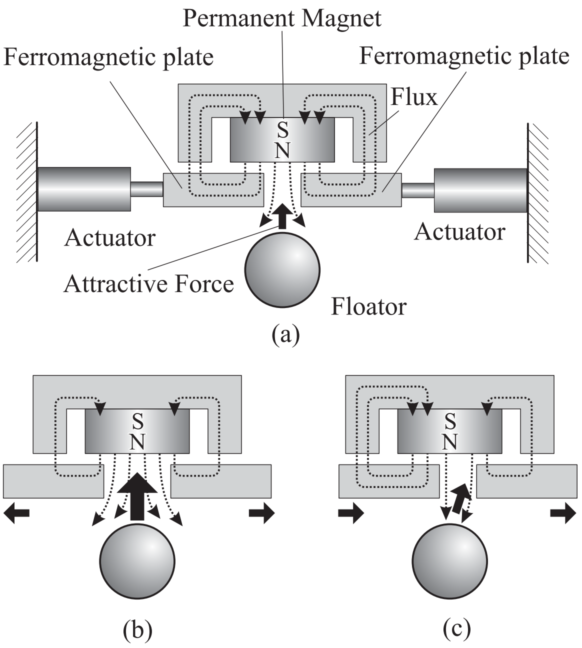


FIGURE 1: Principles of magnetic suspension

The flux path control mechanisms are located to face each other across the permanent magnet and the floator. For stabilization, they are operated in the reversed-phase mode; when the gap between the two ferromagnetic plates becomes wider, the flux from the permanent magnet to the floator increases so that the attractive force also increases (Fig.1b), and *vice versa*. Positioning in the vertical direction is also possible in this mode.

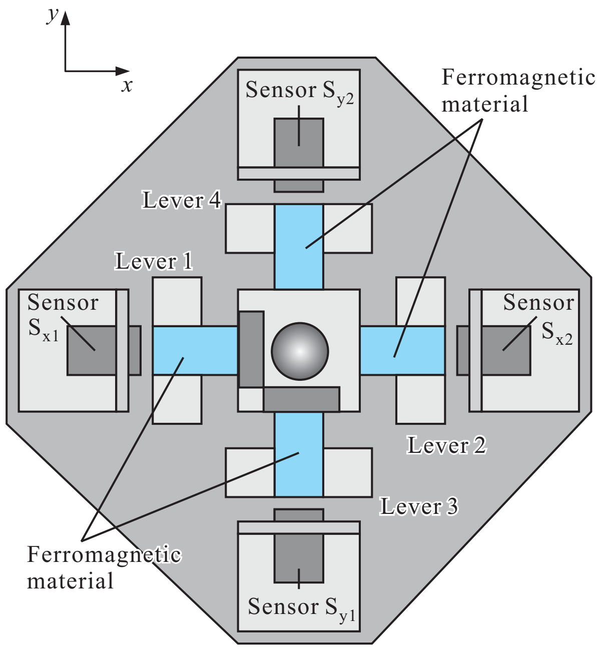
In addition, positioning in the lateral direction can be achieved by operating them in the in-phase mode (Fig.1c); when the two ferromagnetic plates are moved in the same direction, the lateral position of the flux path moves in the same direction so that the lateral position of the suspended object can also be changed.

EXPERIMENTAL SYSTEM

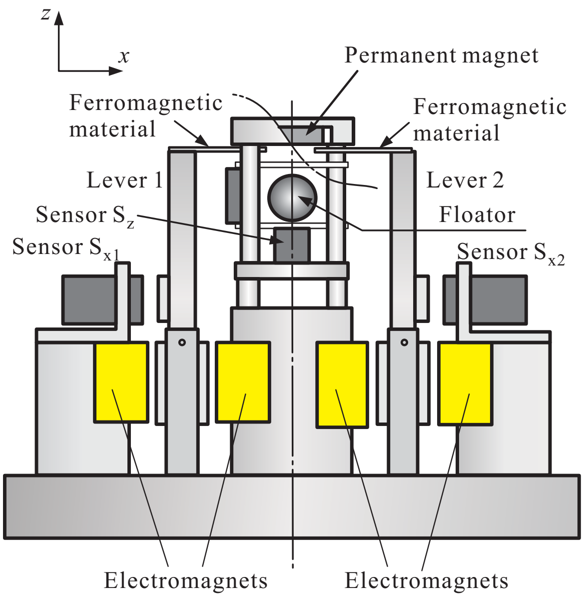
Experimental Apparatus

Figures 2 and 3 show a schematic drawing and a photograph of the fabricated experimental apparatus. It has two pairs of flux path control mechanisms that are located to be right angles to each other for achieving three-dimensional positioning of the suspension object. One of them is set in the x-axis direction and the other is set in the y-axis direction.

In the fabricated flux path control mechanism, a ferromagnetic plate is fixed to the top of a lever. The lever is suspended by a ball bearing to rotate about a horizontal axis. A pair of electromagnets is placed at the bottom of the lever to face each other across the



(a) Top view



(b) Front view

FIGURE 2: Schematic drawing of experimental apparatus

lever. They control the rotational motion of the lever. The motion of the lever at the electromagnets is mechanically amplified about six times at the top of the lever. Each magnet is energized by a fabricated PWM amplifier.

The suspended object is a sphere of steel with a diameter of 30 mm and a mass of 110g. The permanent magnet is made of NeFeB and has a ring shape. The vertical and horizontal displacements of the sphere and the angular displacement of each lever are detected with eddy-current-type displacement sensors.

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 the eight PWM amplifiers through D/A converters.

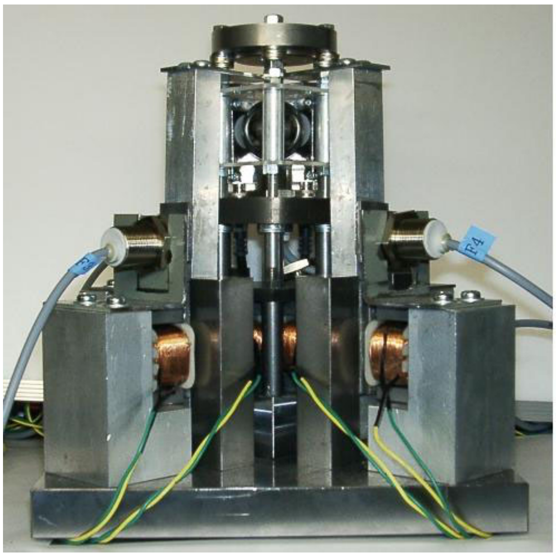


FIGURE 3: Photograph of the apparatus

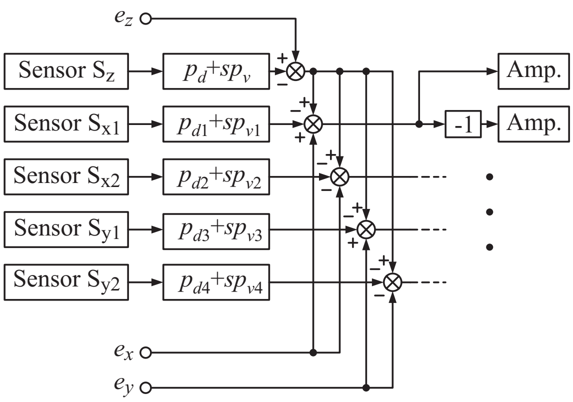


FIGURE 4: Block diagram of control system

p_d , p_{dk} : displacement feedback gains ($k = 1, \cdots, 4$),
p_v , p_{vk} : velocity feedback gains ($k = 1, \cdots, 4$).

Control Algorithm

Figure 4 shows a block diagram of the developed controller. For achieving stable suspension, PD control is applied in two stages. In the first stage, the displacement of a lever is locally fed back for the stabilization of the positioning control system of the lever. For example, the output of the sensor S_{x1} is fed back in the subsystem of the lever 1. In the second stage, a command signal to the positioning system is generated from the vertical displacement of the sphere through a PD compensator; the output of the sensor S_z is fed back. For example, when the sphere is lower than the desired position, the gap between the two plates is made wider, and *vice versa*.

In addition, for positioning in the z-axis (vertical) direction, an auxiliary signal e_z is added to the control input produced by the second-stage PD compensator. For positioning in the x-axis and y-axis (horizontal) directions, auxiliary signals e_x and e_y are superimposed on the control inputs produced by the first-stage PD compensators.

EXPERIMENTAL RESULTS

First, only a pair of flux path control mechanisms in the x-axis direction was operated for achieving stable suspension. Figure 5 shows the motions of the floater, the lever 1 and the lever 2 when the floater levitates without any mechanical contact. It demonstrates that

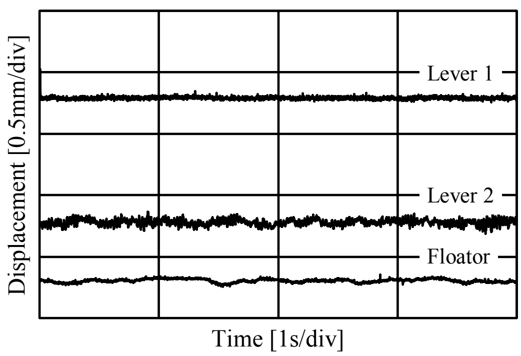


FIGURE 5: Motions of the floator and the levers when stable suspension is achieved

stable suspension was achieved by the proposed method. Figure 6 shows the responses of the suspension system when the signal e_z is rectangular. It indicates that the position in the vertical direction can be changed by e_z.

Next, positioning in the lateral direction was tried by moving the two plates in the in-phase mode. Figure 7 shows the response of the suspension system when the signal e_x is sinusoidal. The orbit in the *xz*-plane is also shown in Fig.8. They indicate that the position of the floator in one lateral direction can be controlled by the flux-path control mechanisms set in this direction.

Then, another pair of flux path control mechanisms set in the *y*-axis direction was operated. Figure 8 shows the orbit in the *yz*-plane when the signal e_y is sinusoidal. The position of the floator in the other lateral direction is changed by them.

These results demonstrate that stable noncontact suspension and three-dimensional positioning can be achieved by the proposed magnetic suspension system.

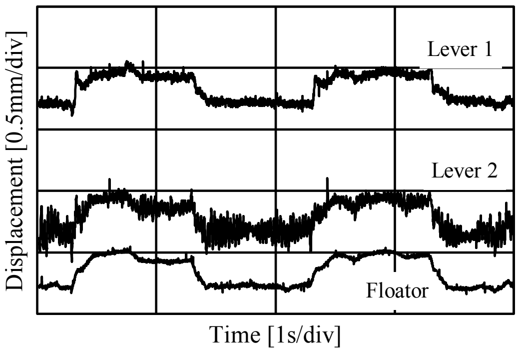


FIGURE 6: Step responses

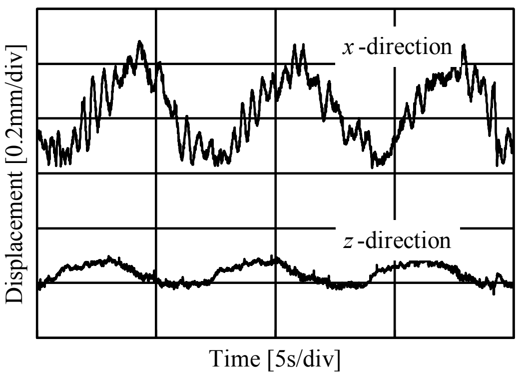


FIGURE 7: Response of the floator when sinusoidal signal is superimoposed on the position control system of the levers in the *x*-direction

CONCLUSION

A new magnetic suspension system equipped with flux path control mechanisms was proposed in this paper. The mechanism consists of a ferromagnetic plate and an actuator for driving the plate. The actuator changes the lateral position of the plate, which is inserted into the gap between a permanent magnet and

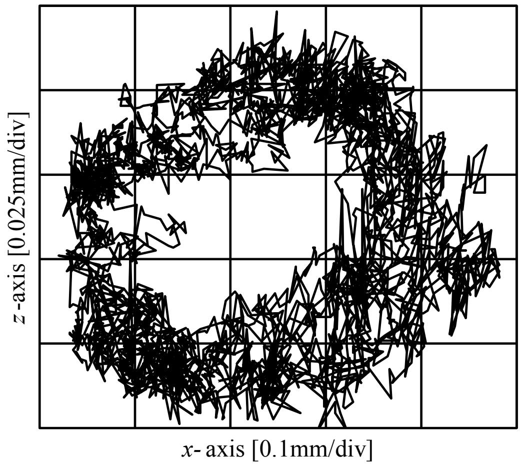


FIGURE 8: Motions of the floator when sinusoidal signal is superimoposed on the position control system of the levers in the *x*-direction

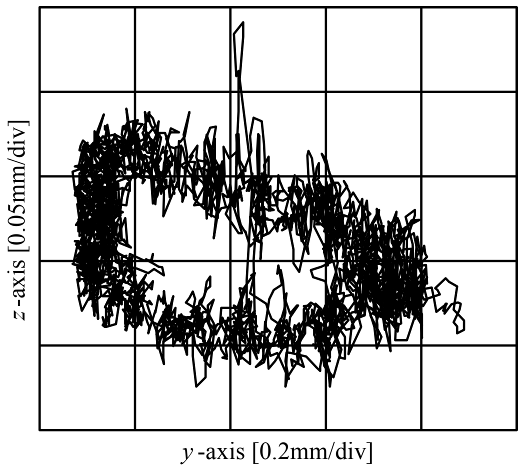


FIGURE 9: Motions of the floator when sinusoidal signal is added to the position control system of the levers in the *y*-direction

the floator. The flux from the permanent magnet to the floator and resultantly the attractive force acting on the floator are controlled by the mechanism.

An experimental apparatus was fabricated which has two pairs of flux path control mechanisms. The experimental results demonstrate that stable noncontact suspension and three-dimensional positioning were achieved by the developed magnetic suspension system.

A new apparatus has been developed which uses a voice coil motor as the actuator of a flux-path control mechanism; the performances of both suspension and positioning have been improved [3].

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