Proposal of Flux-Path Control Magnetic Suspension using Flux Concentration

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Abstract

The concept of flux concentration was applied to the flux-path control magnetic suspension to increase suspension force. In the proposed system, control plates made of permanent magnet were used instead of ferromagnetic control plates in the conventional flux-interrupted type. The magnets were arranged to concentrate the flux from the magnetic source to the floator. Such effects were confirmed by magnetic field analysis. An experimental study shows that the suspension force achieved by the flux-concentrated type was approximately 2.5 times that achieved by the flux-interrupted type with the same size. In addition, contactless suspension was achieved by applying PD control in the flux-concentrated type suspension system.

1 Introduction

Magnetic levitation technique has been used in various applications because it can realize noncontact support. There are various combinations of material in supporting magnet and suspended body to achieve magnetic suspension (Jayawant, 1981; Schweitzer and Maslen, 2009). Most magnetic suspension systems use electromagnet. In such system, the suspension force is supplied only by electromagnet, and it requires steady current in the electromagnet. It causes energy consumption and heating up of the electromagnet. An effective way of solving such a problem is zero-power magnetic suspension using hybrid magnet (Sabnis *et al.*, 1975; Morishita *et al.*, 1989; Mizuno and Takemori, 2002). Another approach is to control flux path mechanically (Higuch and Oka, 1993). In this method, the amount of flux reaching the floator from the permanent magnet is controlled with a mechanism, and the attractive force acting on the floator can be adjusted. There are several methods of controlling flux path:

1. adjusting the reluctance in the magnetic circuit (Higuch and Oka, 1993)
2. changing the flux path with a rotary actuator (Oka *et al.*, 2004)
3. using a variable flux path mechanism (Mizuno *et al.*, 2006)

This paper treats the third method.

In the conventional flux-path control magnetic suspension, ferromagnetic control plates are inserted into the gap between the magnetic source (permanent magnet) and the floator (ferromagnetic body). The distance between the plates is controlled with a pair of actuators (Mizuno *et al.*, 2006) or a single actuator (Mizuno *et al.*, 2012). Since the flux from the permanent magnet to the floator is a function of the distance, the attractive force acting on the floator can be controlled with the actuator(s).

Contactless suspension and positioning in the vertical and horizontal directions were achieved (Mizuno *et al.*, 2007; Nishimura *et al.*, 2012).

An advantage of the proposed suspension system is that the direction of the attractive force generated by the magnetic source is perpendicular to the direction of driving the control plate so that the actuator does not need to suspend the weight of the floator. It is expected that even a low-power actuator may control large force acting on the floator. It may be adapted to support a heavy floator.

However, the suspension force produced in the actual systems was not so large (Furutachi *et al.*, 2008). One of the reasons is that the flux flowing into the control plate and the leakage flux are rather large and resultantly the flux reaching the floator is not so large as expected.

In this work, a new flux-path control magnetic suspension using flux concentration is proposed to overcome this problem. In the modified system, ferromagnetic control plates are replaced by plates made of permanent magnet. The flux from the magnetic source to the floator is concentrated by the control plates so that the increase of attractive force can be expected.

2 Principles

2.1 Flux-Interrupted Type

Figure 1 shows a basic configuration of the original flux-path control suspension system. A pair of ferromagnetic control plates are inserted into the gap between the magnetic source and the floator. When the distance between the control plates becomes wider, more flux reaches the floator from the magnetic source, and the attractive force acting on the floator becomes stronger (Fig.1(b)), and *vice versa* (Fig.1(c)). The suspension system with such configuration is called as flux-interrupted type because the control plates interrupt the flux path from the magnetic source to the floator.

One of the advantages of this principle is that the actuator does not need to suspend the whole weight of the suspended object; the direction of attractive force generated by the permanent magnet is perpendicular to the direction driving the plates. It enables, therefore, the suspension of a heavy floator with a small-output actuator.

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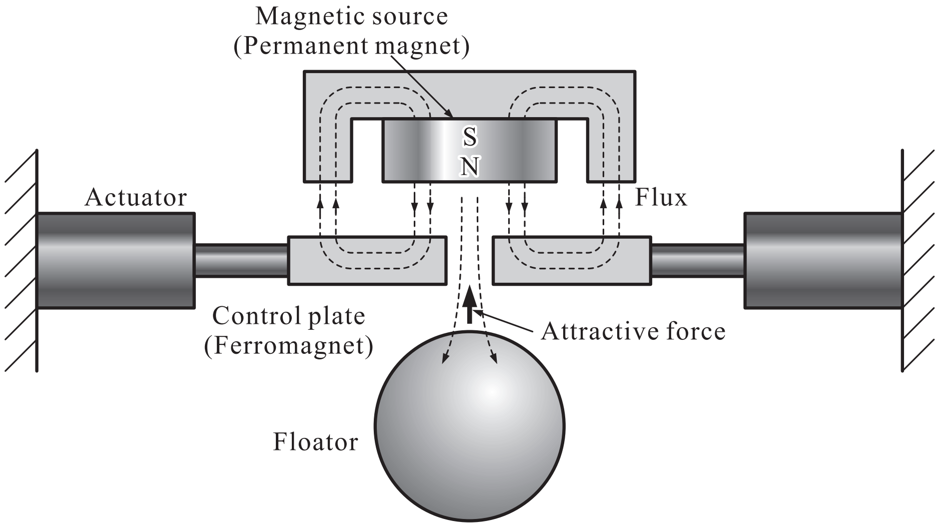
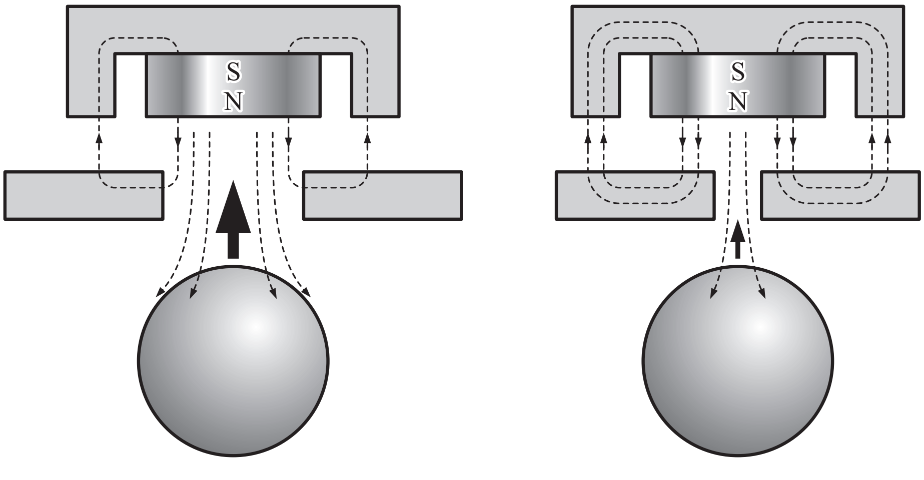
2.2 Flux-Concentrated Type

The suspension force increases by intensifying the magnetic flux reaching the floator. The magnetic-flux-concentrated permanent magnetic array has been proposed to obtain a high flux density (Murakami *et al.*, 2011; Shiota *et al.*, 2013). In this work, this concept is applied to the flux-control magnetic suspension. Figure 2 shows a basic configuration of the modified flux-path control suspension system. The control plates are made of permanent magnet instead of ferromagnetic materials. Because the flux from the magnetic source is centered by the control plates, the suspension system with such configuration is called as flux-concentrated type. It is expected that this type is superior in producing intensive force to the conventional type. In addtion, the responses to the motion of the control plates are different. When the distance between the control plates becomes smaller, more flux is concentrated in the gap so that the attractive force acting on the floator becomes stronger (Fig.2(c)), and *vice versa* (Fig.2(b)).



(a)Basic configuration

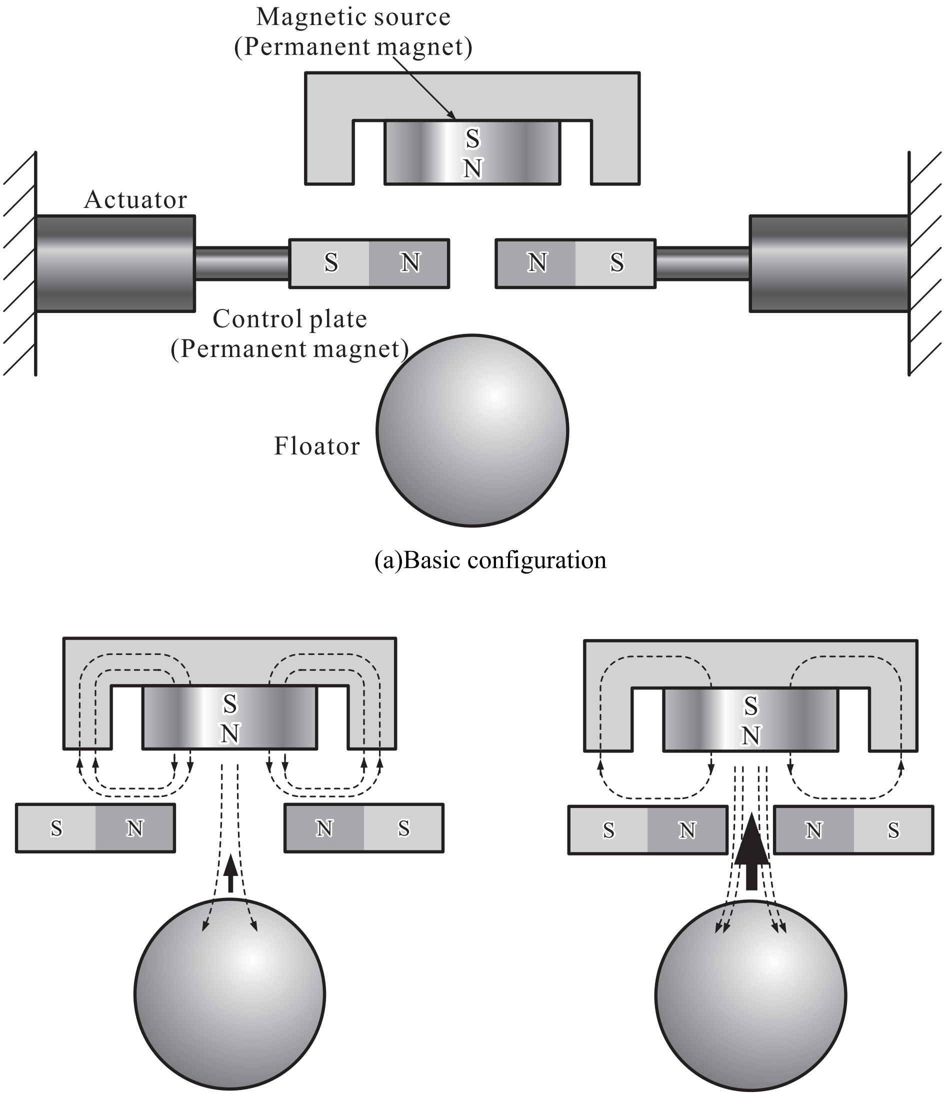


(b) Opened (c) Closed

Fig.1 Flux-interrupted magnetic suspension system

3 Magnetic Field Analysis

Magnetic field analyses are carried out to verify the expectation. Figures 3 and 4 show a model for the analysis and its section view, respectively. It consists of a stator including a magnetic source, a ferromagnetic floator and a pair of control plates. The stator is comprised of a permanent magnet (magnetic source) and a ferromagnetic yoke. The magnetic source is assumed to be a ring-shape



(a)Basic configuration

(b) Opened

(c) Closed

Fig.2 Flux-concentrated magnetic suspension system

Neodymium magnet. The control plates are assumed to be rectangular, and made of ferromagnetic material in the flux-interrupted type and *Ferrite* magnet in the flux-concentrated type, respectively.

Figure 5 shows the analytical results of magnetic flux density with ispleth and flux lines. In the flux-interrupted type, shown in Fig.5(a), most of flux departing from the source magnet flows into the control plates and the flux reaching the floator is small. It indicates that the control plates work to *interrupt* the flux from the source to the floator.

In contrast, the density is made intensive in the gap between the control plates so that more flux reaches the floator in the flux-concentrated type as shown by Fig.5(b). It indicates that the control

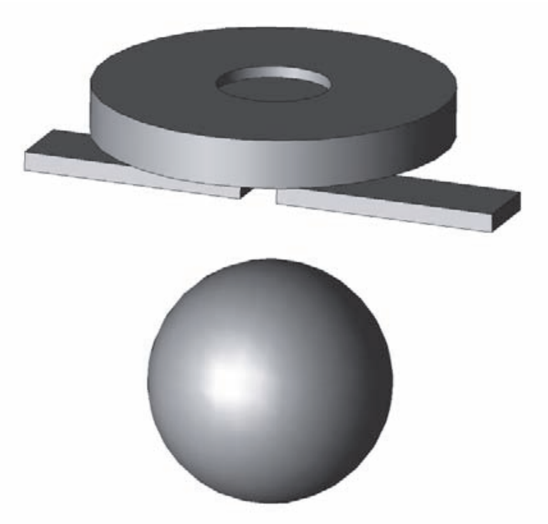


Fig.3 Model for magnetic field analysis

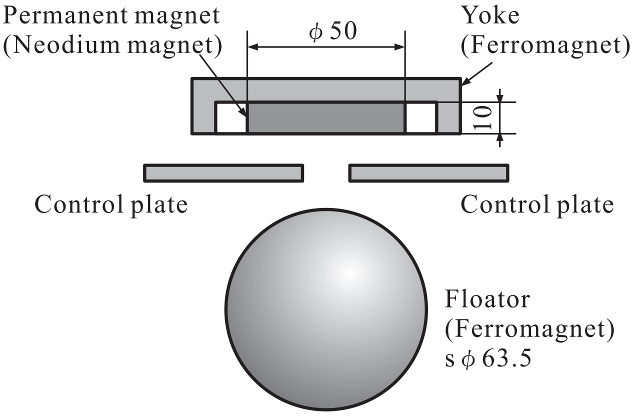


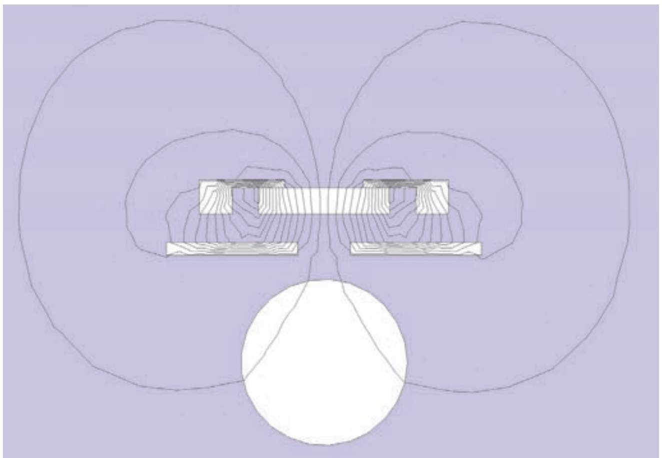
Fig.4 Section view of the model

plates work to *concentrate* the flux in a path to the floator, which leads to the increase of the suspension force.

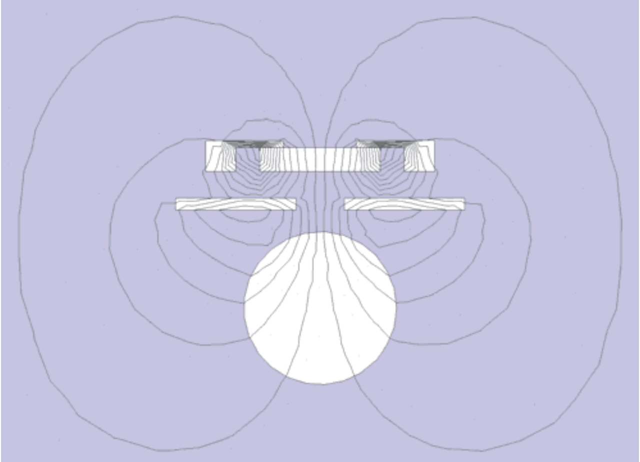
4 Experiment

4.1 Experimental Apparatus

Figures 6 and 7 shows a schematic drawing and a photo of the fabricated experimental apparatus. Its size is approximately 300×300×300 [mm]. A disk-shape Neodium magnet with a size of $\phi 50\times 10$



(a) Flux-interrupted type



(b) Flux-concentrated type

Fig.5 Analytical magnetic fields

[mm] is fixed at the top as a magnetic source. A pair of flux-path control modules are installed below the source. In each module, a control plate is attached at the top of a lever. The motion of the lever is controlled by a pair of electromagnets located at the bottom of the lever. The size of the control plate is $50 \times 20 \times 5$ [mm]. It is made of ferromagnetic material in the flux-interrupted type while it is comprised of two Ferrite magnets with a size of $25 \times 20 \times 5$ [mm] in the flux-concentrated type. Figure 8 shows a photo of the latter control plate. An eddy-current displacement sensor is used to detect the position of the lever. The diameter and mass of the floator are 63.5 [mm] and 1.04 [kg],

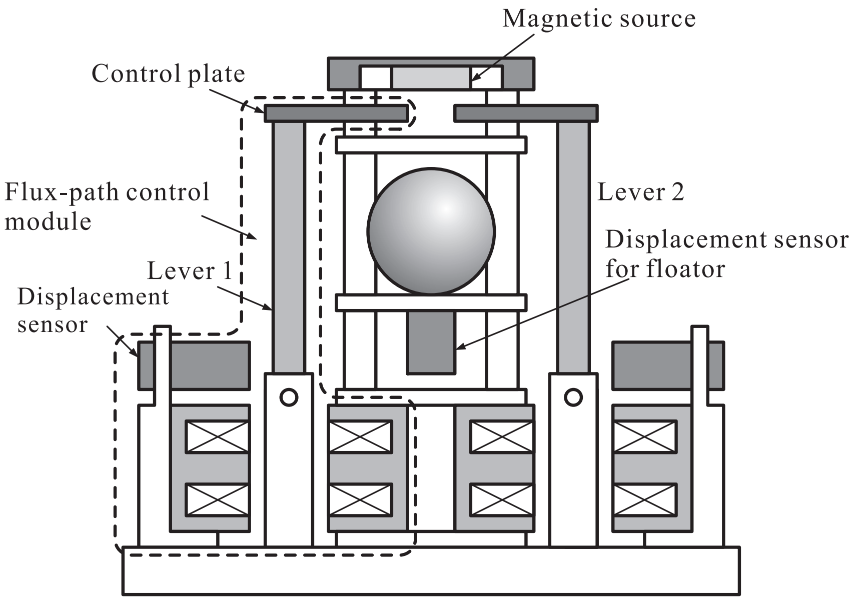


Fig.6 Schematic drawing of the experimental apparatus

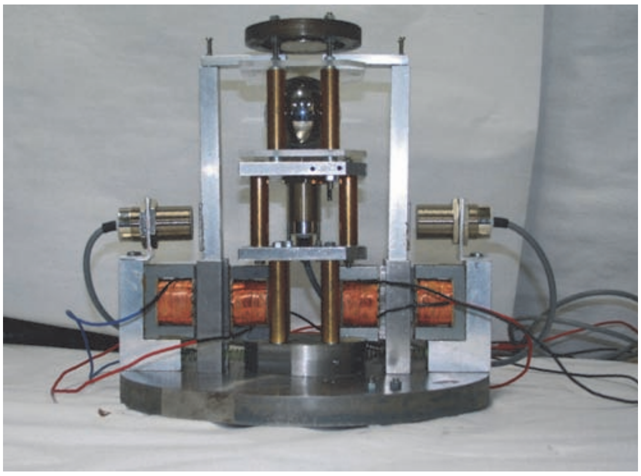


Fig.7 Photo of the experimetal apparatus

respectively. The vertical displacement of the floator is detected with another eddy-current displacement sensor.

4.2 Force Measurement

The attractive force acting on the floator were measured. In this experiment, the floator was fixed to a load cell for force measurement. Figure 9 shows the definition of parameters. The parameter *W* is

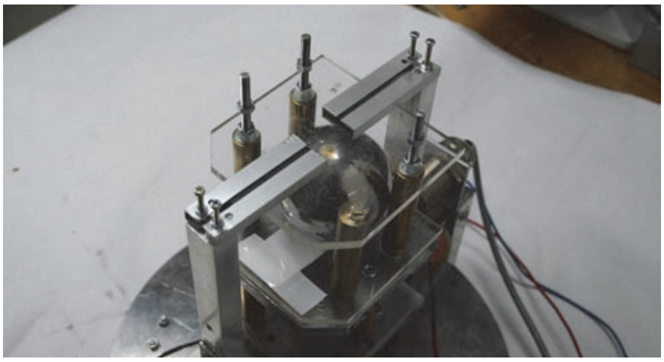


Fig.8 Photo of the control plates

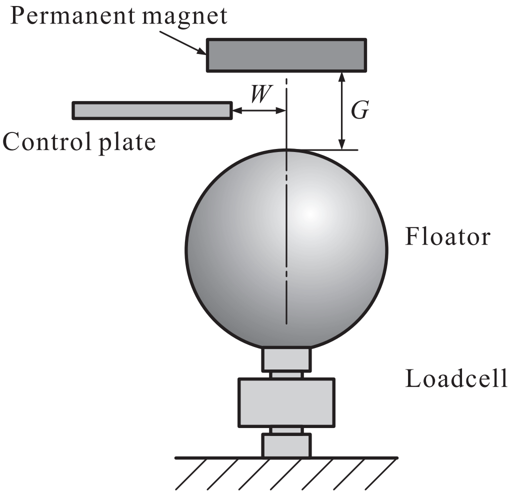
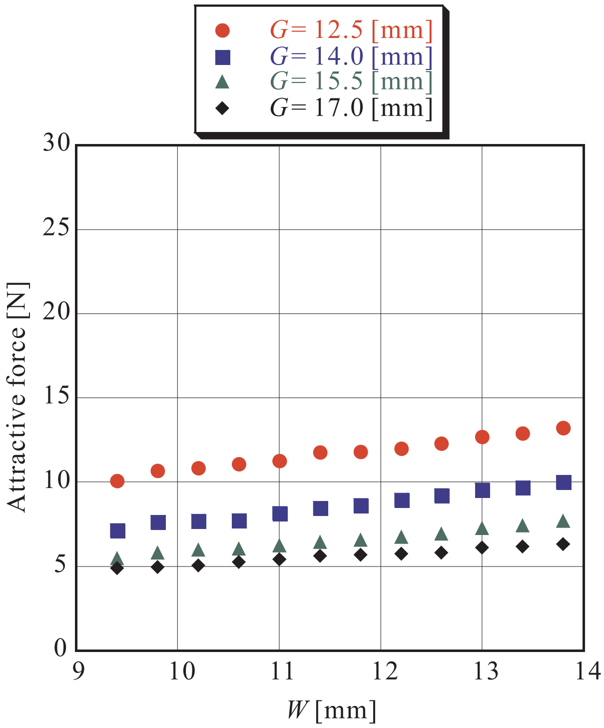


Fig.9 Definition of parameters

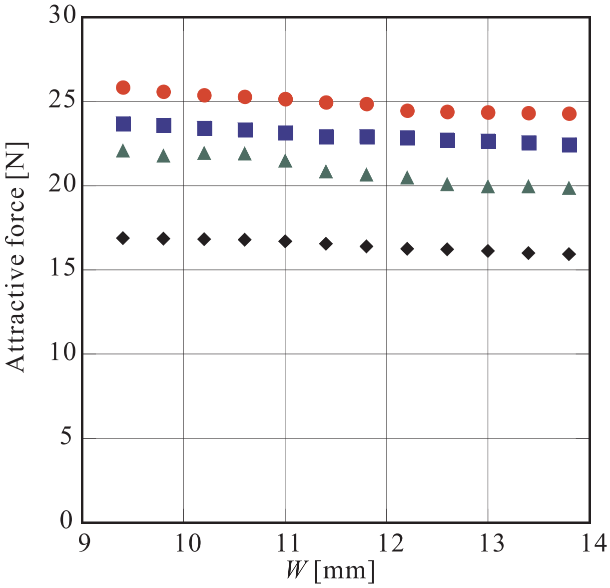
the distance of the control plate from center axis of the floator. The parameter *G* is the gap between the magnetic source and the floator. These parameters were varied in measuring. Figure 10 shows the measured results. It is observed that

1. The attractive force increases as the gap *G* decreases in both types.
2. The attractive force increases with the distance *W* in the interrupted type whereas it decreases with *W* in the concentrated type.
3. The concentrated type produces approximately 2.5 times attractive force than the interrupted type.

The third result demonstrates that the modified system can generate larger suspension force than the original system.



(a) Flux-interrupted type



(b) Flux-concentrated type

Fig.10 Measured suspension force

4.3 Levitation

Stable suspension was also achieved in the fabricated concentrated-type apparatus. The designed controller has a double-loop structure; in the inner loop, the motion of the flux-path control module is locally fed back; in the outer loop, the vertical displacement of floator is also fed back. In the inner loop, PD control is applied to provide the flux-path control modules sufficient stiffness and damping property to suspend the floator. In the outer loop, PD control is also applied to stabilize the levitation system.

Figure 11 shows the behavior of the floator and the levers. It demonstrates that stable levitation was achieved by the flux-concentrated type suspension.

5 Conclusions

A novel flux-path control magnetic suspension using flux concentration was proposed to increase suspension force. In the proposed system, control plates made of permanent magnet were used instead of ferromagnetic control plates in the flux-interrupted type. The magnets were arranged to concentrate the flux from the magnetic source to the floator. Such effects were confirmed by the magnetic field analyses. It was experimentally confirmed that the suspension force achieved by the flux-concentrated type was approximately 2.5 times that achieved by the flux-interrupted type with the same size. In addition, contactless suspension was achieved by applying PD control in the flux-concentrated type suspension system.

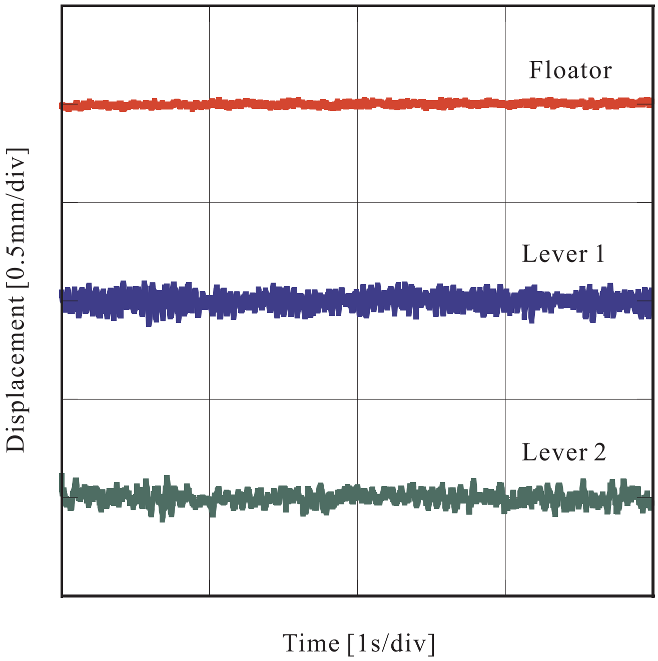


Fig.11 Behavior in levitation

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