Repulsive Magnetic Levitation Systems Using Motion Control of Magnets

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Abstract: Motion control of magnets is introduced to repulsive magnetic levitation systems to improve their performance in this research. This makes them have the ability of controlling the position and vibration in the levitation direction and stabilizing the motion(s) in the lateral direction(s).

1 Introduction

There are many methods of supporting moving or rotating mass by using electromagnetic forces without any contact [1]. The suspension using DC electromagnets and the force of attraction between magnetized bodies needs active control for achieving complete contact free suspension. Although it leads to rather high cost, the number of its industrial application is growing. One of the main reasons is because the fact of being actively controlled gives an advantage over conventional mechanical bearings. For example, stiffness and damping can be easily adjusted; a disturbance force acting on the suspended object is effectively canceled.

Another method of magnetic levitation uses forces of repulsion between permanent magnets. It follows from Earnshaw's theorem that static stable levitation is impossible in a system composed solely of permanent magnets. Since at least one direction remains unstable, it is usually combined with either some mechanical guidance or controlled DC electromagnets for stable action. Another problem is poor damping in the levitation directions. In consequence of these problems, this type of levitation system has not been used so widely as the suspension using controlled DC electromagnets. However, magnetic materials have been recently improved significantly. Moreover, it is an advantage that no energy is required to generate levitation force. The possibility of new levitation systems using permanent magnets should be investigated.

In this research, motion control of magnets is introduced to repulsive magnetic levitation systems to improve their performance. Three types of levitation systems are discussed. In the first type, the levitation magnets are driven in the direction of repulsive force to control the position and vibration of the levitated object. In the second type, a magnet of support is moved in the lateral directions to stabilize the system like an inverted pendulum. In the third type, the lateral motions are stabilized by vibrating the magnet of support in the direction of repulsive force. The principles and basic model of each system are described. Several experimental studies are also presented.

2. Control of Levitation Position and Vibration

2.1 Principles

A schematic diagram of the first-type levitation system is shown in Fig.1(a). A levitation magnet in the stator-side is driven by an actuator in the direction of repulsive force for controlling the position and vibration of the levitated object. Another configuration is shown in Fig.1(b) where an actuator is arranged between the permanent magnet and the levitated object. The actuator should be carefully selected to suit the applications of the mechanism from available actuators. For example, we can avoid wiring to the levitated object even in the system of the configuration (b) by using a magnetostrictive actuator because this actuator can be controlled by the magnetic field supplied from the stator-side.

These mechanisms are also applied to levitation systems using superconductors as shown in Fig.2. Although superconductive levitation systems are inherently stable, precise position and vibration control will be necessary for some applications. Piezoelectric actuators are suitable for this system because of small heat dissipation.

2.2 Basic Model

The levitation system shown in Fig.1(a) is treated here. A physical model of this system is shown in Fig.3. The

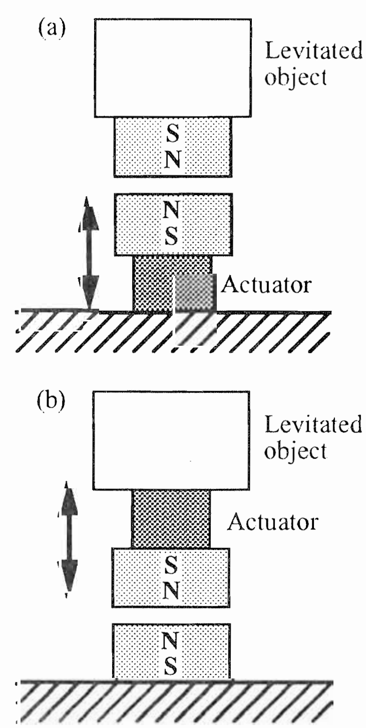

Fig.1 Two basic configurations of active repulsive magnetic levitation system

repulsive force between the permanent magnet is modeled as a spring without damping. Then the equation of motion of the levitated object is given by

$$m\ddot{z}_a = k_z(z_b - z_a) + p_z(t) \tag{1}$$

z_a : displacement of the levitated object
z_b : displacement of the magnet driven by an actuator
m: mass of the levitated object
k_z : spring stiffness in the levitating direction
p_z : disturbance force acting on the levitated object

The actuator is controlled to follow a signal inputted to the driver circuit.

$$z_b = k_a u_z \tag{2}$$

u_z : input voltage to the driver circuit
k_a : gain of the driver circuit

Substituting (2) into (1) gives

$$m\ddot{z}_a + k_z z_a = k_z k_a u_z + p_z(t) \tag{3}$$

2.3 Control System Design

Stiffness and damping are commonly used to estimate the suspension characteristics. The PD control is adopted to modify these properties in the proposed levitation system. The control input is determined as follows.

$$u_z(t) = -(p_d z_a(t) + p_v \dot{z}_a(t)) \tag{4}$$

Substituting (4) to (3) gives

$$m\ddot{z}_a + k_z k_a p_v \dot{z}_a + k_z(1 + k_a p_d) z_a = p_z(t) \tag{5}$$

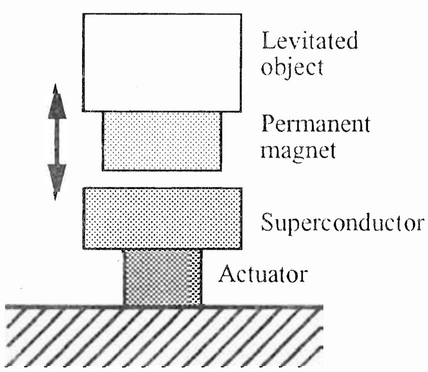

Fig.2 Active superconducting levitation

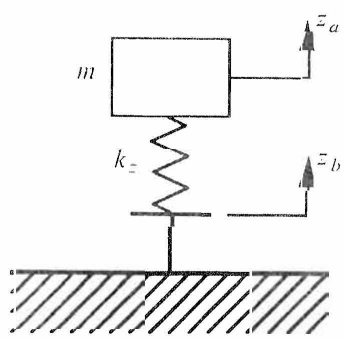

Fig.3 Basic model

The stiffness and damping characteristics are adjusted by displacement and velocity feedback as shown in (5).

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

$$u_z(t) = p_I \int (z_r - z_a)\, dt - (p_d z_a + p_v \dot{z}_a) \tag{6}$$

z_r : reference signal

Substituting (6) into (3) leads to

$$z_a(s) = \frac{k_z k_a p_I}{t(s)} z_r(s) + \frac{s}{t(s)} p_z(s) \tag{7}$$

where

$$t(s) = ms^3 + k_z k_a p_v s^2 + k_z(1 + k_a p_d)s + k_z k_a p_I \tag{8}$$

Equation (7) shows that there remains no error in position for a step reference signal under constant disturbances. For well-damped response, the coefficients are determined so as that the transfer function

$$\frac{z_a(s)}{z_r(s)} = \frac{k_z k_a p_I}{ms^3 + k_z k_a p_v s^2 + k_z(1 + k_a p_d)s + k_z k_a p_I} \tag{9}$$

matches a model having a desired response [2]:

$$G_m(s) = \frac{1}{1 + \sigma s + 0.5\sigma^2 s^2 + 0.15\sigma^3 s^3} \tag{10}$$

where

σ: parameter that is a measure of the rise-time

Comparing (9) with (10), we get

$$p_I = \frac{m}{0.15\sigma^3 k_a k_z} \tag{11}$$

$$p_v = 0.5\sigma^2 p_I \tag{12}$$

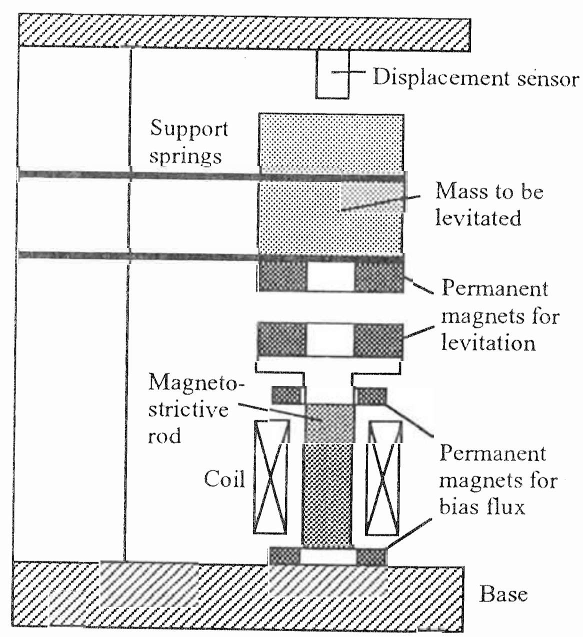

Fig.4 Schematic diagram of the experimental setup

$$p_d = \sigma p_I - \frac{1}{k_a} \tag{13}$$

2.3 Experiment

Figure 4 shows a schematic diagram of the experimental setup. It uses a magnetostrictive rod made of $Tb_x Dy_{1-x} Fe_y$ as an actuator [3]. A bias flux for the actuator is given by a permanent magnet.

The displacement of the levitated object is detected with a capacitive sensor. The detected signal is connected to an analog-type controller. The output of the controller is fed to a power amplifier. It drives current through the coil that is proportional to its input signal. The expansion from the equilibrium point of the actuator is, therefore, approximately proportional to the control input (see (2)).

The parameters of this instrument are given as follows.

$m = 0.61$ kg
$k_s = 2.5 \times 10^{-3}$ N/m
$k_a = 1.0 \times 10^{-6}$ m/V

The responses for a step disturbance are shown in Fig.5; (a)without control, and (b)with velocity feedback. The damping characteristic is modified dramatically by driving the actuator proportional to the velocity of the levitated object. The measured frequency responses shown in Fig.6 also support this result.

The step response of the system with I-PD control is shown in Fig.7. The parameter related to the rise-time is selected as

$\sigma = 45$msec

This results shows that the designed control system performs accurate levitation position control as well as active damping of vibration.

3 Stabilization of Lateral Motions by Active Control

3.1 Principles

The levitation system using forces of repulsion between permanent magnets is inherently unstable in the lateral directions. This can be stabilized by moving a permanent magnet of support in the lateral directions like an inverted pendulum as shown in Fig.8; 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).

Using this active stabilization method, we can construct a repulsive levitation system of various configurations. Figure 9 shows a levitation system which is passive in the radial directions and active in the axial direction. This is a rather practical system because only a single-degree-of-freedom motion is actively controlled. Using a PZT actuator, we can avoid winding coils, which will be suitable for micro machines.

3.2 Basic Model

Figure 10 shows a model of the system illustrated in Fig.8. The levitated object is assumed to move only in the lateral direction. The equation of motion is given by

$$m\ddot{y}_a = -k_y(y_b - y_a) \tag{14}$$

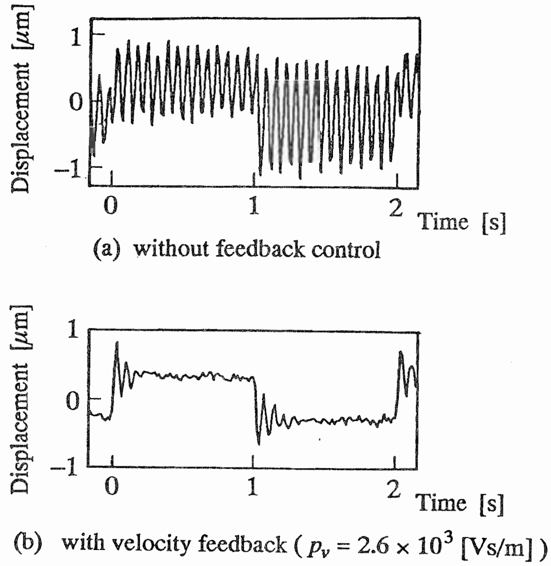

Fig.5 Step responses of the levitation system

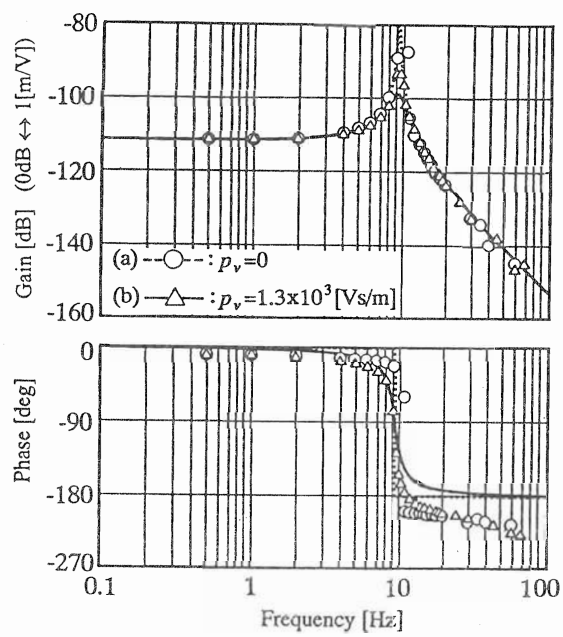

Fig.6 Frequency response of the displacement of the levitated object to disturbance ($p_d = 0$)

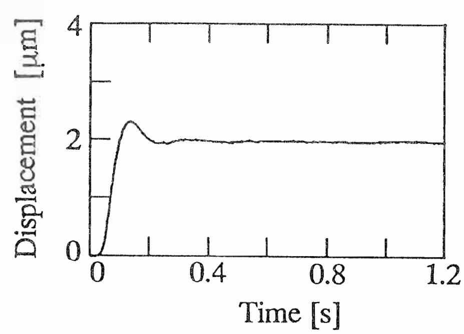

Fig.7 Step response of the levitation system with the I-PD controller

y_a : displacement of the levitated object
y_b : displacement of the magnet driven by an actuator
k_y: lateral factor

The actuator is controlled to follow a signal inputted to the driver circuit:

$$y_b = k_b\, u_y \tag{15}$$

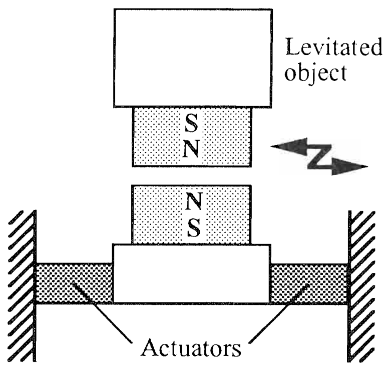

Fig.8 Stabilization of a repulsive levitation system by controlling the motion of a magnet of support

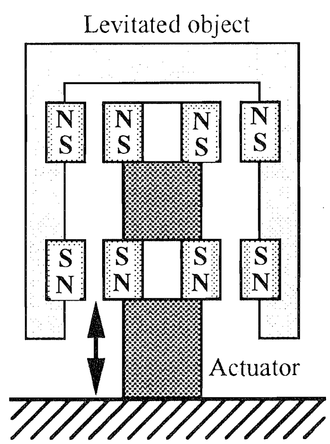

Fig.9 Stabilization of a radially passive repulsive levitation system by controlling the motion of the radial magnets

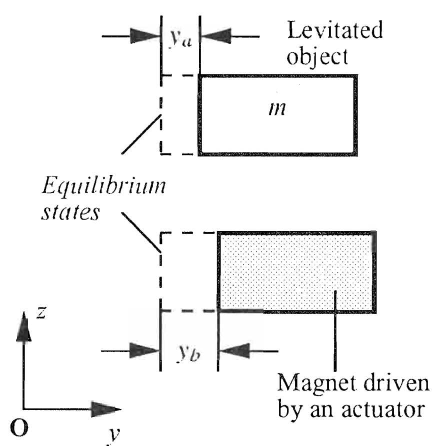

Fig.10 Definition of coordinates

u_y : input voltage to the driver circuit
k_b : gain of the driver circuit

3.3 Control System Design

The PD control is a fundamental control scheme for stabilization. The control input is represented by

$$u_y(t) = p_d\, y_a(t) + p_v\, \dot{y}_a(t) \tag{16}$$

From (14), (15), and (16), the following equation is obtained.

$$m\ddot{y}_a + k_b k_y p_v \dot{y}_a(t) + k_y(k_b p_d - 1)y_a = 0 \tag{17}$$

It is seen from (17) that the lateral motion can be stabilized by selecting the feedback coefficients to satisfy

$$p_d > \frac{1}{k_b}, \qquad p_v > 0 \tag{18}$$

When the I-PD control scheme is applied, the control input is represented by

$$u_y(t) = -q_I \int (y_r - y_a)\, dt + q_d y_a + q_v \dot{y}_a \tag{19}$$

From (14), (15), and (19), the following equation is obtained.

$$y_b(s) = \frac{k_y k_b q_I}{ms^3 + k_y k_b q_v s^2 + k_y(1 + k_b q_d)s + k_y k_b q_I}\, y_r(s) \tag{20}$$

The coefficients are determined so as that the transfer function matches the model given by (10).

$$q_I = \frac{m}{0.15\sigma^3 k_b k_z} \tag{21}$$

$$q_v = 0.5\sigma^2 q_I \tag{22}$$

$$q_d = \sigma q_I + \frac{1}{k_b} \tag{23}$$

3.4 Experiment

Fig.11 shows the schematic diagram of the experimental system that simulates an inverted pendulum with a repulsive levitation mechanism. It contains two levers, each of which has a permanent magnet for levitation. The motion of the lever 1 acting as a levitated object, is sensed by an eddy-current position sensor. The controller produces a control input for stabilization from the detected signal. The amplifier drives the piezoelectric actuator for moving the lever 2 according to the signal inputted from the controller.

The parameters of this instrument are given as follows.

m = 1.8 kg (equivalent mass).
$k_y = 1.2 \times 10^3$ N/m.
$k_b = 1.9 \times 10^{-6}$ m/V.

The step responses of the system with I-PD control is shown in Fig.12. The parameter related to the rise-time is selected as

σ = 100msec.

Just after the reference signal changes to a new value, the magnet of support moves in the opposite direction to the new stationary position (goal). Then it drives the magnet of the levitated object in the direction of the goal. Finally it stops there. This behavior is similar to that of a conventional inverted pendulum.

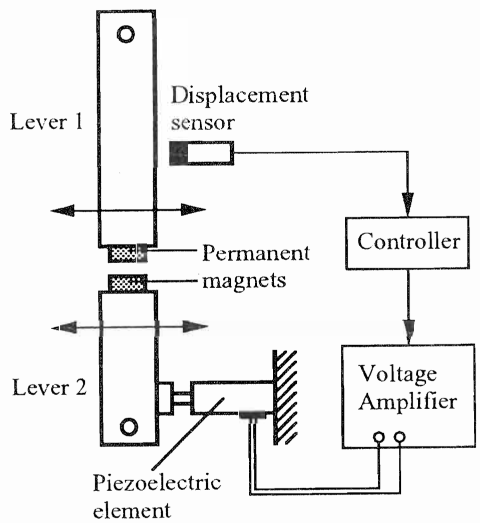

Fig.11 Schematic diagram of the experimental system

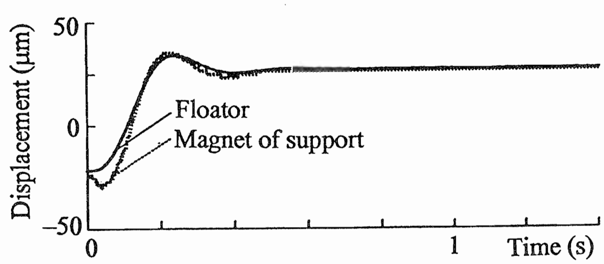

Fig.12 Responses to a step input of the lateral-motion system stabilized by the I-PD controller (The command input changes from -25mm to 25mm at $t = 0$).

4 Stabilization of Lateral Motions Using Vibration

4.1 Principles

While an inverted pendulum is statically unstable, a pendulum with a harmonically moving point of support, shown in Fig.13, stands stably if the movement satisfies adequate conditions [4]. As repulsive levitation systems with permanent magnets behave like an inverted pendulum, there is a possibility of stabilizing them by vibrating the permanent magnet of support as shown in Fig.14.

4.2 Analysis

Figure 15 shows a model of the system illustrated in Fig.14. The lateral factor depends on the distance between the permanent magnets [5]. The equation describing the lateral motion becomes

$$m\ddot{y}_a = -k_y(d)\,(y_b - y_a) \tag{24}$$

$$d = d_0 + z_a - z_b$$

d_0: distance in the equilibrium states

The lateral factor is approximated by a linear relation

$$k_y(d) = k_y^0 + q(z_a - z_b) \tag{25}$$

$$k_y^0 = k_y(d_0), \qquad q = \left.\frac{\partial k_y}{\partial d}\right|_{d=d_0}$$

Let the permanent magnet of support vibrate with an amplitude of α and angular frequency of ω. When the frequency is selected far above the natural frequency of the levitation system, the displacement of levitated object is negligible. This leads to

$$m\ddot{y}_a - (k_y^0 - q\alpha\cos\omega t)\,y_a = 0 \tag{26}$$

This is equivalent to the Mathieu's equation

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2}w(t) + (\delta + \varepsilon\cos t)\,w(t) = 0 \tag{27}$$

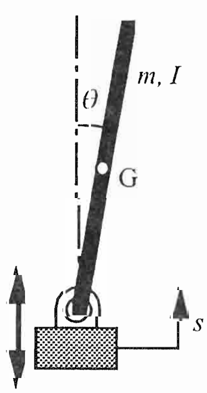

Fig.13 Inverted Pendulum on a moving support

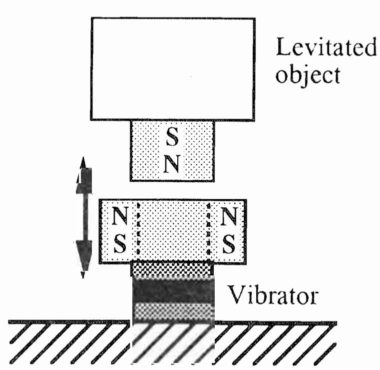

Fig.14 Repulsive magnetic levitation system with a vibrating magnet of support

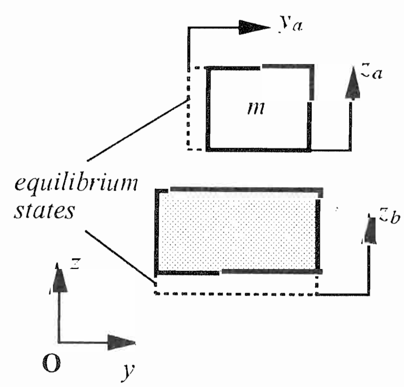

Fig.15 Definition of coordinates

Although its solution has not found in closed form, its stability has been studied in detail. It is shown that there are stable regions for negative values of δ; for small values of ε, the stable region is approximately given by [6]

$$-\frac{1}{2}\varepsilon^2 < \delta < \frac{1}{4} - \frac{\varepsilon}{2} \qquad (28)$$

This implies that a carefully designed levitation system has a possibility of being stabilized by vibrating the magnet of support with appropriate frequency and amplitude.

4.3 Experiment

Figure 16 shows a developed experimental setup for investigating stabilization by using vibration. Two voice coil motors are used to drive permanent magnets of support in the vertical direction. These magnets and the magnets attached to the levitated object are all ring-shaped. Since these magnets can be easily changed, we can also use this setup for study on stabilization by active control, which was discussed in the previous section.

The choice of magnets is critical in a repulsive levitation system. Looking into the stable regions of the Mathieu's equation [6], we find that for negative values of δ, $|\delta|<|\varepsilon|$ is necessary for the solution to be stable. This means that the lateral factor k_y must have both negative and positive values during a period of vibration. Figure 17 shows an example of a combination of magnets which satisfies such operating conditions.

Although we try several combinations of magnets, we have not yet succeeded in actual contact-free levitation by using vibration. The main reason is that the stable regions of the Mathieu's equation are very narrow for negative values of δ.

5. Conclusions

Motion control of magnets was introduced to repulsive magnetic levitation systems. The principles of controlling the position and vibration in the levitation direction and stabilizing the motion(s) in the lateral direction(s) were described based upon their basic models. Precise control of levitation position and vibration was realized in an experimental setup with a magnetostrictive actuator. The lateral motion was actively stabilized in the experimental system that simulated an inverted pendulum with a repulsive levitation mechanism. Although the contact-free levitation using vibration is possible theoretically, it was difficult to satisfy the stability conditions in an actual system.

Further experimental works are under way, in addition to the investigation of different aspects of the proposed levitation systems.

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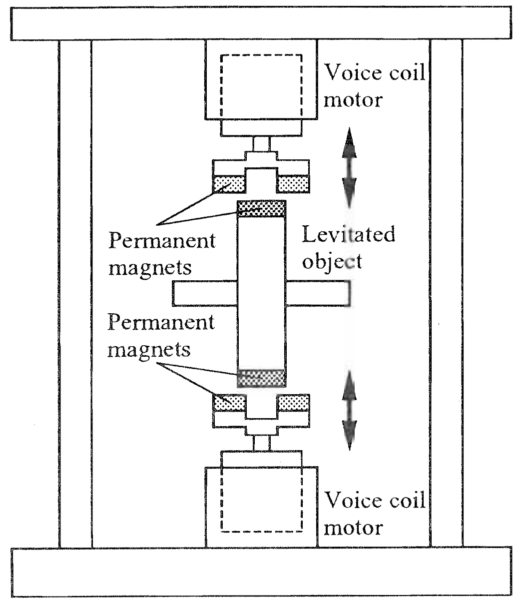

Fig.16 Schematic diagram of the experimental setup

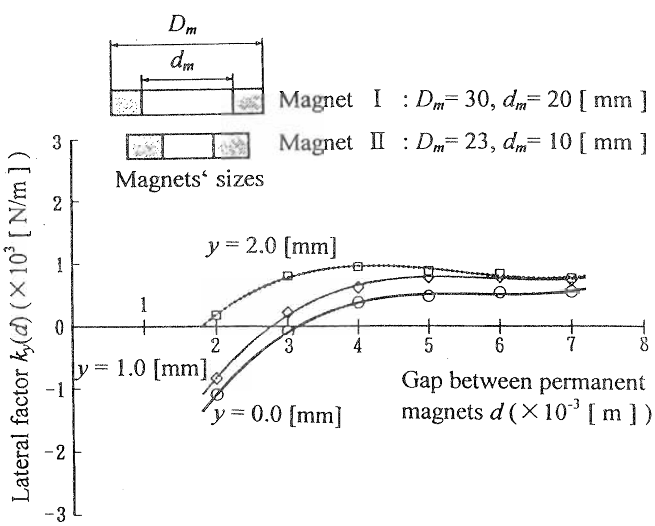

Fig.17 Measured lateral factor ($y = |y_a - y_b|$)