Three-Dimensional Force Measurement and Control of a Flux-Path Control Magnetic Suspension*

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Abstract
In the flux-path control magnetic suspension system, the force acting on a floator is controlled by moving a control plate made of ferromagnetic material, which is located between the permanent magnet and the floator. In this paper, the three-dimensional attractive forces acting on the floator were measured with a manufactured force sensor. The force actuating in the vertical direction is measured with the load cell built in the sensor. The force actuating in the horizontal direction is measured with the plate springs with strain gauges. These measurements clarify the relations between the positions of the control plates and the three-dimensional attractive forces. In addition, stable suspension and three-dimensional positioning were achieved by applying PD control. Several dynamic characteristics were measured in both the vertical and horizontal directions.

Key words: Magnetic Suspension System, Variable Flux-Path, Load Cell, Ferromagnetic Material

1. Introduction
Magnetic suspension is a technology that supports an object (floator) by using magnetic force. There are various methods that are classified according to materials used for the object and the magnet [1],[2]. Being most widely used in these is a method that uses the attractive force of an electromagnet for a ferromagnetic floator. In this method, the current flowing through the coil is controlled according to the motion of the floator for achieving stable suspension. Reluctance-control magnetic suspension has been proposed, in which a reluctance in a magnetic circuit is varied. It is subdivided into two types:

1. changing gap by moving the permanent magnet [3],[4].
2. inserting a variable reluctance mechanism into the magnetic circuit [5].

The authors have proposed flux-path control magnetic suspension [6]. In the flux-path control magnetic suspension system, the force acting on the floator is controlled by moving a control plate made of ferromagnetic material, which is located between the permanent magnet and the floator.

Firstly, complete contactless suspension and positioning in the vertical and horizontal directions have been realized in an apparatus with a floator of 0.1 [kg] [7]. It has four flux-path control modules that use a pair of electromagnets as an actuator and a mechanical amplifier of displacement. Secondly, more damped positioning has been achieved in an apparatus which has three modules using a voice coil motor (VCM) as an actuator [8]. However, their fundamental properties have not been studied sufficiently. Mathematical
models for designing control system have not been derived. Moreover, it is not clear whether contactless suspension and 3-dimensional positioning are possible when the floator has much more mass. In this paper, a new apparatus with a floator of 1 [kg] is fabricated and the three-dimensional attractive forces acting on the floator are measured. In addition, complete contactless suspension and stable three-dimensional positioning are achieved by applying PD control. Several dynamic characteristics in each direction are also studied experimentally.

2. Principle of Flux-Path Control Magnetic Suspension

Figure 1 shows the principle of flux-path control magnetic suspension \[7,8\]. The narrower the distance between the control plates is, the more flux passes through the control plates so that the attractive force acting on the floator is reduced (Fig. 1(a)). In contrast, the wider the distance is, the stronger attractive force acts on the floator (Fig. 1(b)). Stable suspension in vertical direction can be realized by moving the control plates. In addition, control in the horizontal direction also can be realized by moving the control plates in the
same direction as shown in Fig. 1(c).

3. Apparatus

Figure 2 shows a fabricated experimental apparatus. The size is approximately $300 \times 300 \times 300$ [mm]. It has three flux-path control modules for achieving three-dimensional positions.

In each module, a control plate is attached at the top of the lever. The plate is made of ferromagnetic material and the size is $4 \times 70 \times 25$ [mm]. It controls the flux from the permanent magnet to the floator. The motion of the lever is controlled by a pair of electromagnets located at the bottom of the lever. A gap sensors $T_k$ ($k=1, 2, 3$) detects the position of the lever.

The diameter and the mass of the floator are 63 [mm] and 1 [kg] respectively. The three dimensional position of the floator is detected by $S_x$, $S_y$ and $S_z$. Figure 3 shows the Photograph of the apparatus.

4. Force Measurement

4.1 Two-axis Force Sensor

Figure 4 shows a manufactured two-axis force sensor for measuring attractive forces acting on the floator. It can measure attractive forces in the vertical and horizontal directions at the same time. The vertical force is measured with the load cell built in the sensor. The horizontal force is measured with the plate springs with strain gauges.
Figure 5 shows the definition of coordinate axes and variables. Three control plates are arranged in a concentric way at every 120 degrees. $W$ is the distance of the control plate from center axis of the floator. $G$ is the gap between the permanent magnet and the floator.

4.2 Experimental Method

First, the attractive forces $F_x$ and $F_z$ in the $x$ and $z$-directions are measured with the two-axis force sensor for the following variables:

$W$: 15 - 22 [mm] and $G$: 17.4 - 26.4 [mm].

Next, the two-axis force sensor is rotated by 90 degrees and the attractive forces $F_y$ in the $y$-axis and $F_z$ are measured in the same way. The three components of attractive force are calculated by combining both the measurement results.

4.3 Experimental Results

Figures 6 and 7 show the three components of attractive force when one actuator is operated. They show that the smaller $G$, stronger the attractive force. It also shows that $F_x$, $F_y$ and $F_z$ are approximately proportional to $W$. The force can be controlled from 2.1 to 11.3 [N] in the $z$-direction, and from 0 to 0.35 [N] in the $x$- and $y$-directions. Figure 8 shows the three components of attractive force when $G$ is set to be 20.4 [mm] and one actuator is operated. The results are magnified in Fig. 9. The relations expression of $F_x$, $F_y$ and $F_z$ to $W$ are obtained as

\[
F_x = 0.02(W - 15) \quad \text{[N]}, \quad \text{(1)}
\]
\[
F_y = 0.03(W - 15) \quad \text{[N]}, \quad \text{(2)}
\]
\[
F_z = 0.19(W - 15) + 4.4 \quad \text{[N]}. \quad \text{(3)}
\]

Figures 10 and 11 show the three components of attractive force when two actuators are operated. The relations of $F_x$, $F_y$ and $F_z$ to $W$ when $G = 20.4$ [mm] are obtained as

\[
F_x = 0.06(W - 15) \quad \text{[N]}, \quad \text{(4)}
\]
\[
F_y = 0.01(W - 15) \quad \text{[N]}, \quad \text{(5)}
\]
\[
F_z = 0.43(W - 15) + 4.4 \quad \text{[N]}. \quad \text{(6)}
\]

Comparing Fig. 6 with Fig. 10, we find that the attractive force and its ratio to gap are greater when two actuators are operated. The attractive force constant matrix $K_q$ is defined by

\[
F = K_q w,
\]

where
\[ \mathbf{F} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}, \quad \mathbf{w} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}, \]

\(w_i\) : displacement of control plate \(i\) (\(i=1, 2, 3\)),

Fig. 6 Three components of attractive force when one actuator is operated

Fig. 7 Horizontal components of attractive force when one actuator is operated

Fig. 8 Three components of attractive force at \(G=20.4[\text{mm}]\) when one actuator is operated

Fig. 9 Horizontal components of attractive force at \(G=20.4[\text{mm}]\) when one actuator is operated

Fig. 10 Three components of attractive force acting on the floator when two actuators are operated

Fig. 11 Horizontal components of attractive force when two actuators are operated
From the measurement results, \( K_q \) is obtained as given by
\[
K_q = \begin{bmatrix}
0.20 & 0.20 & 0.24 \\
0.02 & 0.02 & -0.03 \\
-0.03 & 0.04 & 0.01 \\
\end{bmatrix} \text{ [N/mm].}
\] (8)

5. Suspension Control in the Vertical Direction

5.1 Structure of Control System

In this research, 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 displacement of floator in the z-direction 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 suspension system.

5.2 Inner loop

An equation of motion in each flux-path control module is given by
\[
m \ddot{w}_k - k_s w_k = k_i k_i \quad (k = 1, 2, 3)
\] (9)
where \( m \): mass of the control plate with the lever, \( k_s \): force-displacement factor \( k_i \): force-current factor and \( i_k \): control current. When PD control is applied, the control current is given by
\[
i_k = -(p_d + p_v \frac{d}{dt}) w_k + e_k,
\] (10)
where \( p_d \): proportion gain, \( p_v \): derivative gain and \( e_k \): command signal. The transfer function from \( e_k \) to the displacement is obtained as
\[
G_k(s) = \frac{b_s}{s^2 + a_1 s + a_0},
\] (11)

Fig. 12 Local feedback control

Fig. 13 Outline of the control system
where
\[ a_t = \frac{k_i p_r}{m}, \quad (12) \]
\[ a_s = \frac{k_i p_d - k_s}{m}, \quad (13) \]
\[ b_s = \frac{k_i}{m}. \quad (14) \]

The block diagram of the local feedback is shown by Fig. 12.

5.3 Outer loop

The motion of the floator in the z-direction is given by
\[ M\ddot{z} = F(w_1, w_2, w_3, z) - mg, \quad (15) \]
where \( z \) : displacement of the floator in the z-direction, \( M \) : mass of the floator and \( F \) : attractive force acting on the floator. Considering the symmetry in structure of the system, we get an equation linearized about the equilibrium state where the gravitation force \( mg \) equals the steady magnetic force as
\[ M\ddot{z} = K_z z + K_{qz} w, \quad (16) \]
where
\[ K_z : \text{force-displacement factor,} \]
\[ K_{qz} = \begin{bmatrix} K_{qz1} & K_{qz2} & K_{qz3} \end{bmatrix} \]
\[ = \begin{bmatrix} 0.2 & 0.2 & 0.24 \end{bmatrix} \text{[N/mm].} \quad (17) \]

Control system in the vertical direction of the actual experiment is shown in Fig. 13 where \( q_d \) and \( q_v \) are proportional and derivative gains in the outer loop.

The displacement signal in the z-direction of the floator is sent to the PD controller. The command signal generated from this controller sent to each module. The attractive forces \( F_{z1}, F_{z2}, \) and \( F_{z3} \) are changed by moving the control plates.

5.4 Digital Implementation

A DSP-based digital controller was used for implementing these controllers. The control period is 100 [µs]. Moreover, an approximation differentiation circuit with the transfer function given by Eq. (18) was built in the digital controller.
\[ G_d(s) = \frac{\omega_0^2 s}{s^2 + 2\zeta(\omega_0 + \omega_0^2) s + \omega_0^2 \omega_0^2}. \quad (18) \]

In the experiment described in the next section, each parameter of the approximation

Fig. 14 Adjustability of the z-direction position by the command signal \( e_z \)
differentiation circuit was set as follows.
\[ \omega_{n1} = 200 [1/s], \quad \omega_{n2} = 300 [1/s], \quad \zeta = 0.5. \]

5.5 Positioning

Figure 14 shows the \( z \)-direction displacement of the floator when the command signal \( e_z \) is set to be 0.01 to 0.12 [V]. It is found that the position is approximately proportional to the value of command.

Fig. 16 Frequency response of floator in the \( z \)-direction

5.6 Step Response

A rectangular wave with an amplitude of 1.4 [V] and a frequency of 0.2 [Hz] was inputted as a command signal. Figure 15 shows the displacement when \( q_d = 9.7 \times 10^2 [A/m] \) and \( q_v = 29.1 [As/m] \). The amplitude of the floator’s displacement is about 0.6 [mm].

5.7 Frequency Response

Figure 16 shows a frequency response in the \( z \)-direction when \( q_d = 9.7 \times 10^2 [A/m] \) and \( q_v = 29.1 [As/m] \). The input is \( e_z \) with an amplitude of 50 [mV] and the output is displacement \( z \). A resonance is observed at a frequency of 8.9 [Hz].

6. Motion Control in the Horizontal Directions

6.1 Structure of Control System

Figure 17 shows the block diagram of three-dimensional control system. The controller for the horizontal motions has a structure similar to that for the vertical motion. The values
of $K_q$ are given by Eq. (8). The horizontal displacements of the floator are detected by two sensors located in the horizontal directions as shown in Fig. 18. In this figure, $A_1$, $A_2$ and $A_3$ indicate the directions of the actuators. The mode control is applied because the directions of the actuators are different from those of the sensors. In Fig. 17, “Transformation” calculates the command signals ($e_1$, $e_2$, $e_3$) sent to the modules corresponding to the control signals in the $x$- and $y$- directions. They are given by

$$
\begin{bmatrix}
e_1 \\
e_2 \\
e_3
\end{bmatrix} = T
\begin{bmatrix}
p_q^x + p_v^x s & 0 \\
0 & p_q^y + p_v^y s
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix}.
$$

(19)

The transformation matrix $T$ is given by

$$
T = \begin{bmatrix}
-0.6 & -0.5 \\
0.3 & -0.5 \\
-0.09 & 1.0
\end{bmatrix}.
$$

(20)

6.2 Positioning

Figure 19 shows the $x$-direction displacement of the floator when the command signal $e_x$ is set to be 0 to 0.6 [V]. It is found that the position is approximately proportional to the value of command. A similar result has been obtained in the $y$-direction. It is confirmed that positioning can be realized in horizontal directions.
6.3 Step Response

A rectangular wave with an amplitude of 1.4 [V] and a frequency of 0.1 [Hz] was inputted as a command signal. Figure 20 shows the displacement when $q_d = 9.1 \times 10^5$ [A/m] and $q_v = 12.7$ [As/m]. The amplitude of the floator’s displacement is approximately 0.8 [mm]. It demonstrates that the displacements of the floator in the horizontal directions can be controlled by moving control plates. However, the transient response of the floator was not
damped well. It is mainly because attractive force in the \( x \)-direction was so small that higher velocity-feedback gains were impossible.

6.4 Frequency Response

Figure 21 shows a frequency response in the \( x \)-direction when \( q_d = 9.1 \times 10^2 \) [A/m] and \( q_v = 12.7 \) [As/m]. The input is \( e \), with an amplitude of 300 [mV] and is the output is displacement \( x \). A resonance is observed at a frequency of 1.7 [Hz]. The value is considerably lower than \( z \)-direction. It is mainly because attractive force in \( x \)-direction is smaller than in \( z \)-direction.

7. Conclusions

In flux-path control magnetic suspension system, the three-dimensional attractive forces acting on the floator were measured with two-axis force sensor. The modeling of control system for the vertical and horizontal motions of the floator was carried out based on these measurement results. In addition, contactless suspension and positioning in both the vertical and horizontal directions were achieved by using PD control.

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