STUDY OF 2 DOF MAGNETICALLY SUSPENDED MANIPULATION SYSTEM WITH AIR GAP CONTROL

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ABSTRACT
It is known that a magnetic suspension system can be made with a permanent magnet and a linear actuator. The linear actuator is used to control the air gap and makes a suspension system stable. To control supporting forces, system adjusts the air gap length by permanent magnet movements. Some applications using the suspension system have been developed.
This paper describes the first step of the 2 DOF system which aims the micromanipulation system. The suspension system is suitable for micromanipulation, because of no heat generation and little losses of the magnetic circuit. Stability of a 2 DOF magnetic suspension system is studied compared with a 1 DOF system. 2 DOF means that the suspension system controls an object in an $x-z$ (vertical) plane. First, the outline of the proposed 2 DOF system is introduced, and modeled. Two models are considered by the difference of the inputs of suspension system. The inputs of one model are the positions, and the inputs of the other model are the driving forces for the magnets. Two models are compared with 1 DOF systems by numerical simulations.

INTRODUCTION
Magnetic suspension system which controls the attractive force by adjusting the air gap has been developed [1]. The feature of this suspension mechanism is use of permanent magnets and linear actuators. To control supporting forces, system adjusts the air gap length by permanent magnet movements. There were some 1 DOF developments of this suspension system[2]-[4].
The suspension mechanism uses a permanent magnet not a electromagnet, so there is no heat generation, no need of volume for a coil, and no actuator installation near the object by using telecontrol of permanent magnet movement. So, this suspension mechanism may be suitable for micro manipulation. When this suspension mechanism is used for the operation of manipulation, the performance of a 1 DOF system is insufficient for the stability of passive control direction, countermeasures for various shape of the suspended object, controllable area, and so on, We need multi DOF suspension systems. Multi DOF suspension systems, however, may have the problem that it can not consider the system into multi individual subsystems along magnet movement directions. Because the suspension system does not make the magnetic path to be closed, the air gap length is large compared with normal magnetic bearings.
In this paper, we study the 2 DOF suspension system which manipulate the object in the vertical plane, as the first step of micromanipulation. Stability of a 2 DOF magnetic suspension system is studied compared with a 1 DOF system. First, the principle of suspension system is explained and A 2 DOF system is introduced, analyzed, and modeled. There are two models of suspension system. One is position input system, and the other is actuator force input system. These models are numerically simulated compared with 1 DOF systems.

PRICIPLE OF SUSPENSION SYSTEM
A suspension system with a permanent magnet and linear actuator is proposed as shown in FIGURE 1 [1]. A ferromagnetic body is suspended by the attractive force from a permanent magnet positioned above. The magnet is driven by an actuator. The direction of levitation is vertical, and the magnet and the object move only in this direction. The equilibrium position determined by a balance between the gravity force and the magnet force.

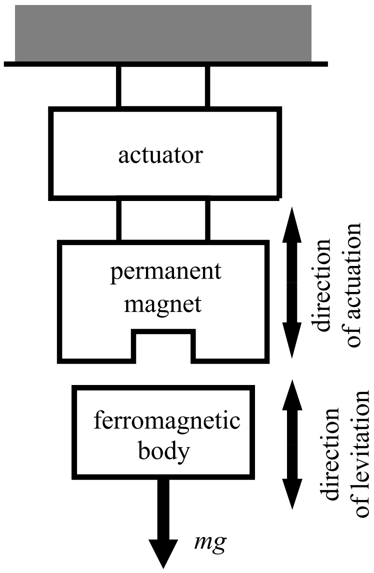

FIGURE 1: Outline of Magnetic Suspension System

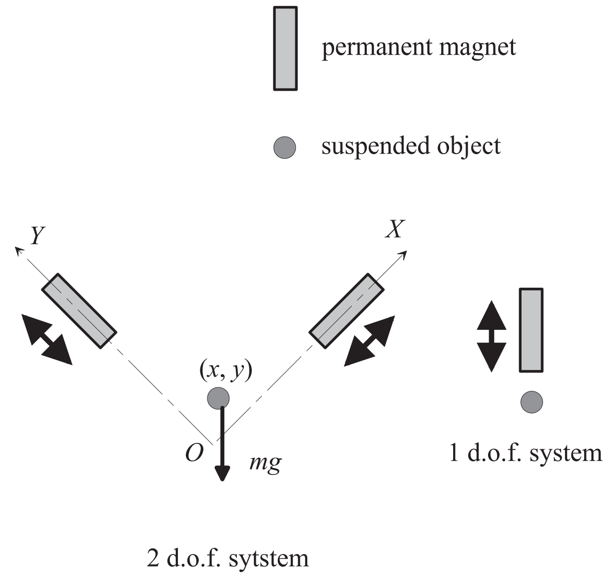

FIGURE 2: Outline of Two Types of Suspension System

If the actuator does not actively control the magnet's position, the levitated object will either fall or adhere to the magnet. However servo-control of the actuator can make this system stable. Because there is a smaller attractive force for a larger air gap between the permanent magnet and object, the actuator drives the magnet upwards in response to object movement from its equilibrium position towards the magnet. Similarly, the actuator drives the magnet downwards in response to object movement away from the magnet. In this way, the object can be stably suspended without contact. In comparison to the electrical control method of electromagnetic suspension systems, this system is a mechanical control maglev system

2 DOF SUSPENSION SYSTEM

The outlines of a 2 DOF suspension system and a 1 DOF suspension system are shown in Figure 2. In the 2 DOF suspension system, O is the origin of the coordinate frame and the circle indicated by (x, y) is the suspended object. The suspended object is acted on by the force of gravity in the vertical direction. The rectangles on the X and Y axes are permanent magnets, and each magnet can move along its own axis respectively. These two axis are perpendicular to each other and the gradients of two axes are both $\pi/4$.
The attractive forces of permanent magnets acting on the object has the direction from the center of the object to the near tip of the magnet and the strength which is inverse proportion to the length between the object and the tip. The size of the object can be neglected. The potential forces (lateral force) of the magnets are assumed to be same as the lateral component of the attractive force vectors.
In the 1 DOF suspension system, the magnet force and the gravity force are balanced in the equilibrium, and the permanent magnet is driven in the vertical direction to make system stable. The stability of the horizontal direction is controlled passively. We consider the movement of vertical direction in the 1 DOF system.

MODEL OF SUSPENSION SYSTEM

To analyze the stability of the 2 DOF suspension system, we have to make the model of the system. Here are symbols for modeling.
x, y : position of the suspended object
m : mass of the suspended object
x_m : position of the permanent magnet about X axis
y_m : position of the permanent magnet about Y axis
m_m : mass of the permanent magnet
f_x, f_y : attractive force between the object and the X axis magnet
f_{xx}, f_{xy}, f_{yx}, f_{yy} : component of the force whose direction is indicated by the second subscript letter
k : constant of the permanent magnet which defined as Eq. (1)
l_x, l_y : length between the object and the respective axis magnet
k_p : proportional feedback gain
k_d : deferential feedback gain
x_{m0}, y_{m0} : equilibrium positions for the permanent magnets

k_e : spring constant of the suspension of the magnet
k_c : dumping constant of the suspension of the magnet
F_x, F_y : driving force for respective magnet, input of force control system
l_0 : air gap length of equilibrium
g : gravity acceleration

Equation of Movement of Suspended Object
We assume that the attractive forces act on the direction from the magnet tip to the center of the object, and are inversely proportional to the square of the air gap lengths. The attractive forces are represented by

$$f_x = \frac{k}{l_x}\ , \quad f_y = \frac{k}{l_y} \tag{1}$$

And the each components of the X and Y axes direction of the forces are represented by

$$f_{xx} = k(x_m - x)/l_x^3 \tag{2}$$
$$f_{xy} = -ky/l_x^3 \tag{3}$$
$$f_{yx} = -kx/l_y^3 \tag{4}$$
$$f_{yy} = k(y_m - y)/l_y^3 \tag{5}$$

where,

$$l_x = \sqrt{(x_m - x)^2 + y^2}$$
$$l_y = \sqrt{x^2 + (y_m - y)^2}$$

When the viscous friction of the air can be neglected, the equations of the movement of the suspended object about X and Y axis are

$$m\ddot{x} = f_{xx} + f_{yx} - mg/\sqrt{2} \tag{6}$$

$$m\ddot{y} = f_{xy} + f_{yy} - mg/\sqrt{2} \tag{7}$$

The outputs of the system are x and y position of the object and we assume that these position could be sensed by sensors.

Equations of Movements of Permanent Magnets
We make two models of the suspension system. One is that the magnets are controlled by their positions. It means that the system inputs are the positions of the magnets. The other is the methods that the magnets are controlled by the actuator forces. In this case, the system inputs are forces.

When Input Is Magnet Position. When system inputs are the permanent magnet positions on X and Y axes, the magnet positions can be controlled by an operator without any delay. Open loop control can not make the system stable, feedback control is necessary. The controller senses the positions of the suspended object on both direction individually, and controls the position of each magnet based on the information of individual direction by PD control. The positions of magnets are calculated by

$$x_m = k_p x + k_d \dot{x} + x_{m0} \tag{8}$$
$$y_m = k_p y + k_d \dot{y} + y_{m0} \tag{9}$$

When Input Is Actuator Force. We consider when inputs of the suspension system are driving force of two magnets along X and Y axis, and the outputs are the positions of the object. In the case, we have to support the magnets by elastic elements and dampers [5], and control the driving forces on the base of the system outputs. We also use PD control method. The driving forces are calculated as

$$F_x = k_p x + k_d \dot{x} + F_{x0} \tag{10}$$
$$F_y = k_p y + k_d \dot{y} + F_{y0} \tag{11}$$

Suspension component constants and feedback gains are same on X and Y axes. The equations of the movements of the permanent magnets are

$$m_m \ddot{x}_m = F_x - f_{xx} - \frac{\sqrt{2}}{2} m_m g - k_e x_m - k_b \dot{x}_m \tag{12}$$
$$m_m \ddot{y}_m = F_y - f_{yy} - \frac{\sqrt{2}}{2} m_m g - k_e y_m - k_b \dot{y}_m \tag{13}$$

State Space Model
The state space model is often uses for system analysis or synthesis. This model is useful for multivariable system, and is usually a linear model. As the above equations have nonlinear terms, we have to linearize to make state space models. The system outputs are x and y, the positions of the suspended object.

Case of System Input of Magnet Position. When the system inputs are the X and Y axes magnet positions, the state variables are the positions and the velocities of the object. The state vector is represented by z_p and system input is u_p, and the state space equation is

$$\dot{z}_p = A_p z + B_p u_p \tag{14}$$

where,

$$z_p = (\,x \quad y \quad \dot{x} \quad \dot{y}\,)'$$
$$u_p = (\,\hat{x}_m \quad \hat{y}_m\,)'$$
$$A_p = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ k/x_m^3 & 0 & 0 & 0 \\ 0 & k/x_m^3 & 0 & 0 \end{pmatrix}$$

$$B_p = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ -2k/x_m^3 & 0 \\ 0 & -2k/x_m^3 \end{pmatrix}$$

and the symbol hat represents the displacement from the equilibrium.

Case of System Input of Actuator Force. When the system inputs are the driving forces of the X and Y axes magnet, the state variables are the positions and the velocities of the object and two magnets. The state vector is also represented by z_f and system input is u_f, and the state space equation is

$$\dot{z}_f = A_f z_f + B_f u_f \tag{15}$$

where,

$$\begin{aligned} z &= (x \quad y \quad x_m \quad y_m \dot{x} \quad \dot{y} \quad \dot{x}_m \quad \dot{y}_m)' \\ u &= (\hat{F}_x \quad \hat{F}_y)' \end{aligned}$$

NUMERICAL SIMULATION

As the aim of the numerical simulation is having the knowledge of the stability of the 2 DOF suspension system, the system constant can be normalized as

$$m = m_{mx} = m_{my} = k = k_b = l_0 = 1, \quad ke = 6 \tag{16}$$

When Input Is Magnet Position

Simulations start at the following conditions. In the 1 DOF system, the initial position of the object is 0.5 near to the magnet from the equilibrium. It means the simulation starts 0.5 upper positon. In the 2 DOF system, the initial position of the object is 0.5 near to the magnet along X axis from the equilibrium. It means the simulation starts at $(x,\ y) = (0.5, 0)$.

In case of Stable Gain. The feedback gains are set to $(k_p, k_d) = (2, 0.3)$. In the 1 DOF system, these gains make the system stable.
The response of the 1 DOF system is shown in the FIGURE 3. The horizontal axis is time from simulation start, and the vertical axis represents the displacement of the suspended object. As shown in the figure, the response converges with vibration, and it is shown that the system is stable.
The response of the 2 DOF system is shown in the FIGURE 4 In the figure, we record the locus of the suspended object in the X-Y plane. The horizontal axis represents the displacement of the X direction, and the vertical axis is the Y direction. The arrow shows the direction of the movement. As shown in the figure, the object converges with drawing ovals. It is very similar to the result of the 1 DOF suspension system.

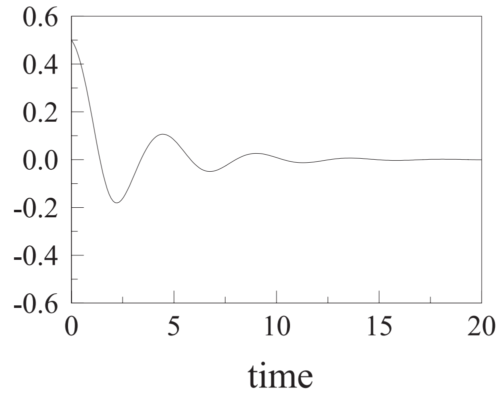

FIGURE 3: Simulation Result of 1 DOF System !! ! $(k_p,\ k_d)$=(2, 0.3)

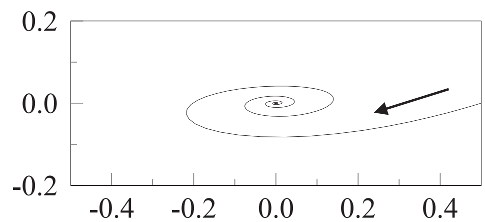

FIGURE 4: Simulation Result of 2 DOF System !! ! $(k_p,\ k_d)$=(2, 0.3)

In case of Critical Proportional Gain. The simulation is carried out when the feedback gains are set to $(k_p,\ k_d) = (1,\ 0.3)$. In this case, the proportional gain k_p is on the border between stable and unstable in the 1 DOF system. This proportional gain is called a critical proportional gain.
In the 1 DOF system, the result of simulation is shown in FIGURE 5. As the result is more clear, the initial velocity $\dot{x} = -0.1$ is given. As shown in the figure, the object does not converges, nor diverges. It is floating state.
In the 2 DOF system, however, the result of simulation is shown in FIGURE 6. An arrow in the figure indicates the movement direction of the object. As shown in the figure, we can see that the object stably converges to the origin. The reason is that the lateral force of the Y axis magnet increases the restoration force for the X axis movement of the object.

In case of Deferential Critical Gain. The feedback gains are set to $(k_p,\ k_d) = (2, 0)$, and simulation is carried out. This deferential gain k_d is the border gain of the stability in the 1 DOF system, and called deferential critical gain.

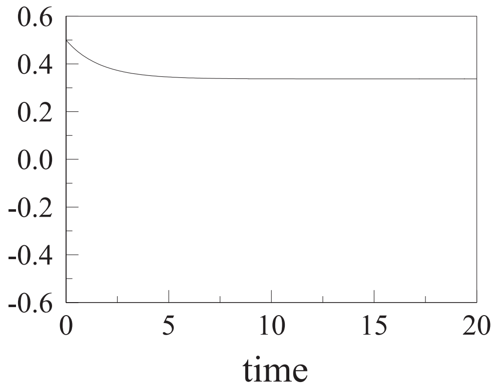

FIGURE 5: Simulation Result of 1 DOF System ! ! ! $(k_p,\ k_d)$=(1, 0.3)

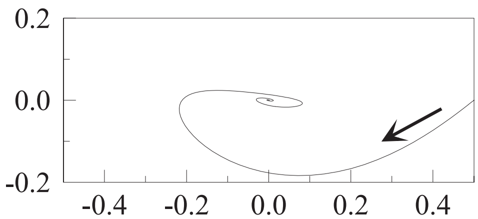

FIGURE 6: Simulation Result of 2 DOF System ! ! ! $(k_p,\ k_d)$=(1, 0.3)

In the 1 DOF system, the result of simulation is shown in FIGURE 7. If the system is linear, the vibration continues with same amplitude. The system, however, is nonlinear, the vibration becomes gradually larger. Although it can not be seen in the figure.

In the 2 DOF system, the result is shown in FIGURE 8. As shown in the figure, the amplitude of vibration becomes rapidly large. This shows the dumping factor of the 2 DOF system is inferior to the 1 DOF system. The reason my be because the object moves in the lateral direction.

The above 3 example show that the 2 DOF system is different from the 1 DOF system, if the feedback gains are same. So the 2 DOF system can not be divided as individual subsystems of X and Y. It must be investigate as a centralized system.

When Input Is Actuator Force

If the system inputs are the driving force of the permanent magnet, the movement of the magnets have to be considered. There are restrictions of the feedback gains[5]. And as the robustness is weak compared with the position input system, the initial position has to be near the origin. Here the feedback

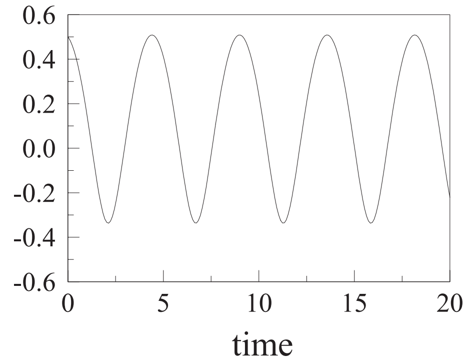

FIGURE 7: Simulation Result of 1 DOF System ! ! ! (k_p, k_d)=(2, 0.)

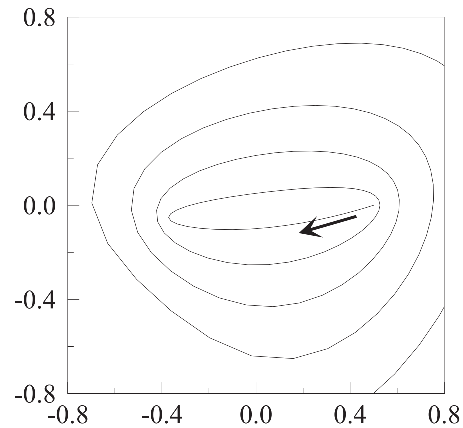

FIGURE 8: Simulation Result of 2 DOF System ! ! ! (k_p, k_d)=(2, 0.)

gains set to $(k_p,\ k_d)$ = (2.1, 1.2), and the initial position is $(x,\ y)$ = (0.1, 0), and simulation starts.

The response of the 1 DOF system are shown in FIGURE 9. It can be seen that the object converges the equilibrium. In the 2 DOF system, however, the system can not be made to be stable. Various gain sets are tried, but there is no stable feedback gain.

We can consider that the deference is large between the 1 DOF system and the 2 DOF system compared with position input system. We must calculate from the centralized 2 DOF system model for the gains which the system makes stable.

CONCLUSION

2 DOF magnetic suspension system which aims the micromanipulation function was proposed. The feature of the suspension system is that consist of permanent magnets and linear actuators. The proposed 2 DOF system was modeled, and numerical simulations were carried out compared with a 1 DOF sys-

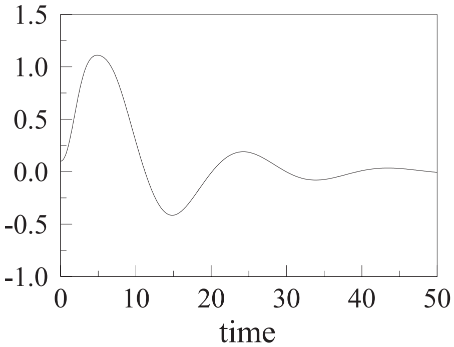

FIGURE 9: Simulation Result of 1 DOF System with Force Input

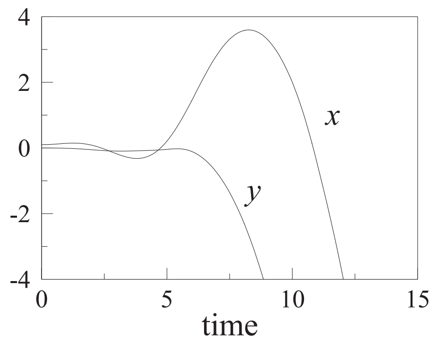

FIGURE 10: Simulation Result of 2 DOF System with Force Input

tem. The feedback gains which make the system stable is different between the 2 DOF system and the 1 DOF system.

As further study, the feedback gains are calculated from the centralized 2 DOF system when the system inputs are the driving force of the magnet. Experimental device will be made for an actual manipulation system, and verify the stability.

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