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A control method to suppress the rotational oscillation of a magnetic levitating system

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Abstract: A magnetic levitation technique has a potential to realize a non-contact object manipulation. As a result, it is expected that a lot of problems caused by contacts can be evaded. Then, the authors developed a magnetic levitation system that was able to manipulate a magnetically levitated hand by non-contact. In this system, four electromagnets are assigned on a horizontal plane for 3-D positioning of the hand. However, it had been examined only about the movement of three directions so far.

In this paper, a new controller was presented which was developed to suppress the rotation around z axis, and its effectiveness was conformed through magnetic levitating experiments.

Keywords: Magnetic levitation, Adaptive Control, Positioning, Manipulation, Sensor

1 INTRODUCTION

Problems sometimes occur from the contacts between actuators and objects. Among various actuator systems, a magnetic levitation technique that levitates a hand by an electromagnetic force with no contact has a potential ability of achieving non-contact object manipulations. Therefore, the non-contact object manipulations would be a solution for the above described problems.

Thus, the magnetic levitation technologies have been in practical uses in some fields [1, 2, 3, 4] such as in a wind-tunnel test [5], and have been studied by applying various control theories such as the model reference adaptive control system (MRACS), H-infinity control [6, 7, 8, 9] to improve control characteristics. As for the multidegree-of-freedom systems, Fulford et al. [10] and Kim et al. [11] have studied on the magnetic levitation control where the air gap to the levitated object were very thin and the work spaces were restricted in very small range: the work spaces of translation was from nanometer to several millimeters, and that of rotation was from micro-radian to milliradian. Although Craig et al. [12] employed a magnetic levitation system that have as much wide work-spaces of several centimeters as our system, they studied only on the three-DOF positional control technique, but didn’t take up the rotational control.

The authors have also developed a magnetic levitation system. In the system, four electromagnets are assigned on a horizontal plane for 3 dimensional (3-D) positioning of the hand as well as the work by Khamesee [13]. Yet we have also developed various 3-D positional control schemes such as the model reference adaptive control system (MRACS) heretofore [14], there has been remaining a problem of controlling orientations. Especially, unexpected rotational oscillation occurred around the vertical axis, which was a pressing issue for the system. Thus, we have studied on the oscillation-suppressing controller. The detail of the study for developing the controller was presented in this paper. Experimental apparatus including a sensor system to measure the rotational angle is described in Chapter2. Next, after showing a finding that the magnetic flux sum value has a dominant effect on the rotational oscillation, we present a way of designing oscillation-suppressing controller, i.e., a controller for stabilizing the magnetic-flux sum, in Chapter 3. Then, the effectiveness of the proposed method is confirmed by magnetic levitation experiments using a trial controller in Chapter 4. Finally, Chapter 5 concludes this paper.

2 EXPERIMENTAL APPARATUS

2.1 Magnetic levitation system

Schematic view of a magnetic levitation system used in this work is shown in Fig. 1and Fig. 2. In the system, as shown Fig. 3 and Fig. 4, four electromagnets are assigned on a horizontal plane for 3 dimensional (3-D) hand positioning. The electric circuits for the four electromagnets are independently controlled by FET amplifier circuits. The hand is levitated at an arbitrary position by controlling the currents flowing into the four electromagnets where the hand position is utilized as feedback information (Fig. 5). Fig. 6 shows an appearance of the levitated hand that is carrying a transistor. The permanent magnet in the driving unit is used to achieve the zero-power control: the zero-power control decreases the necessary power for the electromagnetic by compensating the hand gravity. As for the hand, the mass is approximately 6 g, and the weight capacity is approximately 1 g in the space of 20 mm × 20 mm × 20 mm cubic, and the spacing between the hand and the electromagnets is approximately 50 mm. The magnetic fluxes below the electromagnets are measured with the hall elements (THS119, Toshiba Corporation) that are attached at the electromagnets one-by-one.

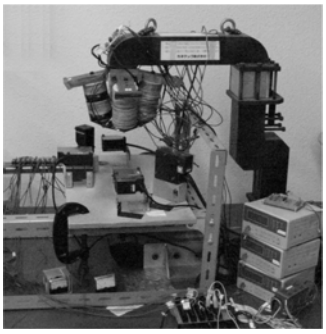

Fig. 1. Photograph of Magnetic levitation system

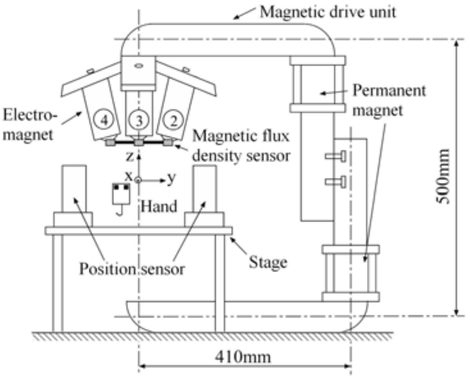

Fig. 2. Magnetic levitation system

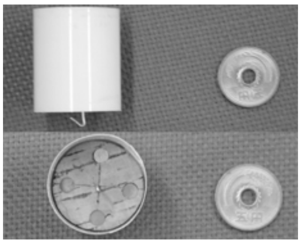

Fig. 3. Photograph of magnetically levitated hand

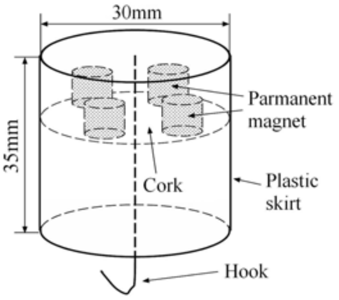

Fig. 4. Magnetically levitated hand

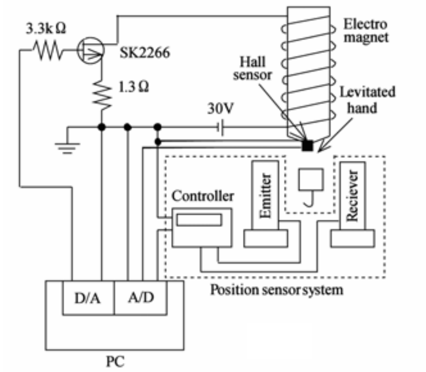

Fig. 5. Circuit diagram of magnetic levitation system

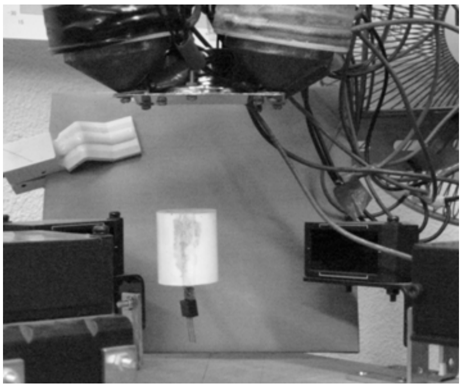

Fig. 6. Photograph of the levitated hand that is carrying a transistor

2.2 Rotation measurement system

This section describes a sensor system to measure the rotational angle around the axis in the longitudinal direction of the levitating hand.

As for a preparatory for developing the system, we had to examine the behavior of the levitated hand, and had to quantitatively evaluate the rotational oscillation. Here, since non-contact sensing system for measuring rotation to be applied to our levitation system was not available, we contrived a rotational measurement system. As shown in Fig. 8 and Fig. 9, by chipping off the lower part of the hand, we carved the bottom face into the spirally elevated slope. Then, the vertical distance between the slope and a distance sensor that was located down below varies with the rotation around the vertical axis as well as the 3-D positional change. As for the distance sensor, we employed a positional sensor (LB-040, Keyence): the measurable range is 35 to 45 mm, and the resolution is 2 μ m.

To confirm the effectiveness of the proposed rotation measurement system and to get an angle-distance conversion coefficient, rotational angle measurement experiments were carried out. While rotating the hand by a motor, the distance between the bottom of the hand and the positional sensor was measured.

Taking the medium height of the measured one as the origin, the averaged value of ten times of distance measurement is plotted along with the time in Fig. 10. While the hand rotating 360 ° in 0.8 seconds, the hand position decreased from 3.78 to -3.78. It gives the angle-to-distance conversion coefficient of 0.021mm/°. Here, note that, if the hand changes its 3-D position, the positional change causes an offset of the hand-sensor distance. Therefore, given the hand position, we should subtract the offset. Thus, the distance can be transformed into the rotation angle.

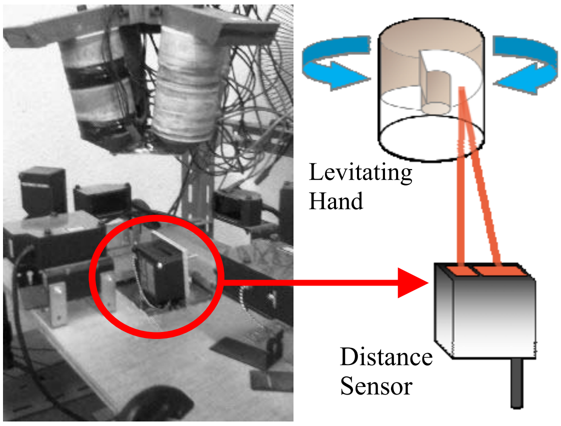

Fig. 7. Rotation measurement system using a distance sensor

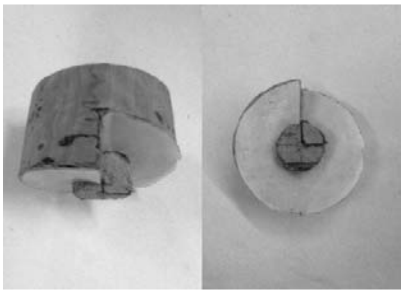

Fig. 8. Photograph of spirally carved hand: the left shows a side view, and the right, bottom view.

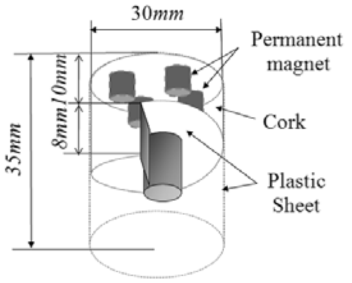

Fig. 9. Oblique projection of the hand with geometrical dimensional information

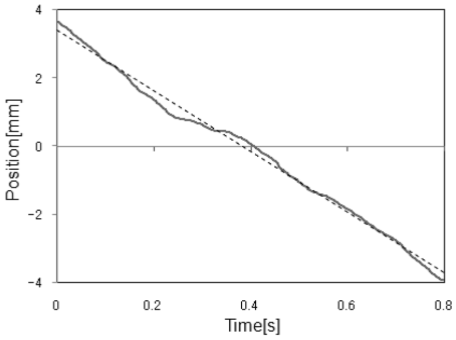

Fig. 10. Experimental result of rotational angle measurement

3 DESIGN OF CONTROLLER

3.1 Positional control of magnetically levitated hand

This section describes the positional control method of the magnetically levitated hand.

The 3-D position of the hand is controlled by manipulating the currents i_1, i_2, i_3,and i_4, each of which is to be input into the corresponding electromagnet: based on the following equations, we can determine i_1, i_2, i_3,and i_4 from $\boldsymbol{u_p} = [u_x, u_y, u_z]$ except that one of the four currents is determined arbitrarily.

$$\begin{aligned} &\Sigma_{j=1,4}\, i_j = u_z \\ &i_1 - i_3 = u_x, \\ &i_2 - i_4 = u_y \end{aligned} \qquad (1)$$

Utilizing the positional sensor information as a feedback signal, we applied a feed-forward PID control to the hand position control. That is, the nonlinear compensators from the levitating position X, Y, Z to the manipulated variables $\boldsymbol{u_p} = [u_x, u_y, u_z]$ were represented by the second order approximate equations, and were utilized for feed-forward signals. The approximate equations had been obtained by a preparatory experiment: while changing the levitating position X, Y, Z, the relationships between the levitating position X, Y, Z and the manipulated variables $\mathbf{u_p} = [u_x, u_y, u_z]$ were measured.

Let $\mathbf{e}_p$ denote the deviation of the present position $\mathbf{p}_p = [p_{px}, p_{py}, p_{pz}]$ from the desired position $\mathbf{r}_p = [r_{px}, r_{py}, r_{pz}]$. If we denote the gains with respect to the position by K_{pp}, K_{ip}, and K_{dp}, and denote the nonlinear compensation with respect to the position by $\mathbf{u}_{fp} = [u_{fpx}, u_{fpy}, u_{fpz}]$, the manipulated variable in the horizontal direction, $\mathbf{u_p} = [u_x, u_y, u_z]$ is given by

$$\mathbf{u}_p = K_{pp}\mathbf{e}_p + K_{ip}\int \mathbf{e}_p dt + K_{dp}\dot{\mathbf{e}}_p + \mathbf{u}_{fp} \qquad (2)$$

3.2 Magnetic flux control (MF control)

As for the hand's positional control in the horizontal plane, a magnetic flux control loop using hall elements was embedded into the inside of the positional control loop. Here, note that, because the electromagnets interfere with each other, it is difficult to control the magnetic fluxes independently. Therefore, as well as the horizontal positional control method described in the section 3.1, we took the differences between the fluxes emitted from the opposing electromagnets to control them.

We constituted a magnetic flux vector $\mathbf{p}_f = [p_{fx}, p_{fy}, 0]$ from the magnetic fluxes b_1, b_2, b_3, b_4: they are measured by the hall elements that are attached at the electromagnets. That is,

$$\begin{aligned} p_{fx} &= b_1 - b_3 \\ p_{fy} &= b_2 - b_4 \qquad (3) \end{aligned}$$

As well as 3.1, let $\mathbf{e}_f$ denote the deviation of the present magnetic flux $\mathbf{p}_f$ from the desired magnetic flux $\mathbf{r}_f$. If we denote the gains with respect to the magnetic flux by K_{pf}, K_{if}, and K_{df}, and denote the nonlinear compensation with respect to the magnetic flux by $\mathbf{u}_{ff} = [u_{ffx}, u_{ffy}]$, the manipulated variable in the horizontal direction, $\mathbf{u}_f = [u_x, u_y, u_z]$ is given by

$$\mathbf{u}_f = K_{pf}\mathbf{e}_f + K_{if}\int \mathbf{e}_f dt + K_{df}\dot{\mathbf{e}}_f + \mathbf{u}_{ff} \qquad (4)$$

where

$$\begin{aligned} \mathbf{e}_f &= \mathbf{r}_f - \mathbf{p}_f \\ \mathbf{r}_f &= K_{pp}\mathbf{e}_p + K_{ip}\int \mathbf{e}_p dt + K_{dp}\dot{\mathbf{e}}_p + \mathbf{u}_{fp} \\ \mathbf{e}_p &= \mathbf{r}_p - \mathbf{p}_p \end{aligned}$$

The nonlinear compensators are represented by approximate equations that were obtained by a preparatory experiment: while changing the manipulated variable values, that is, the levitating position X, Y, Z and the control currents i_1, i_2, i_3, i_4, we measured the magnetic fluxes $\mathbf{b} = [b_1, b_2, b_3, b_4]$.

The block diagram of the magnetic flux controller before-improvement is shown in Fig. 11. The block of [CONV2] in the block diagram represents the transformation from $\mathbf{b}$ into $\mathbf{p}_f$ by Eq.(3). And, the block of [CONV1] represents the transformation from $\mathbf{u}_f$ into i_1, i_2, i_3, i_4 as in the followings.

$$\begin{aligned} &\Sigma_{j=1,4}\, i_j = u_z \\ &i_1 - i_3 = u_x, \\ &i_2 - i_4 = u_y \qquad (5) \end{aligned}$$

where $\mathbf{u}_f = [u_x, u_y, u_z]$

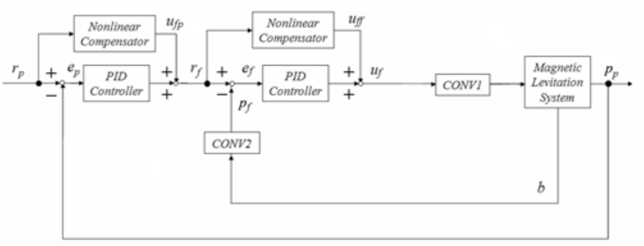

Fig. 11. Block diagram of MF control

3.3 Rotation suppressing control

The authors introduced a control method to suppress the unwilled rotational oscillation around the vertical axis in the magnetic levitating system.

We found an important behavior from experimental data: when hand suffering rotation oscillation, the rotational oscillation was in phase with the perturbation of the sum value of four pieces of the magnetic flux emitted from the four electromagnets. It means that the magnetic flux sum value has a dominant effect on the rotational oscillation, and it suggested us the necessity of suppressing the perturbation of the sum value. Taking sum of the magnetic fluxes in the X-direction, and that in the Y-direction, we apply a PID control for the rotation suppression: the desired value of the sum in the X-direction is denoted by r_{sx}, and that in the Y direction is by r_{sy}, and the measured value of the sum in the X-direction is denoted by p_{sx}, and that in the Y direction is p_{sy}. If the deviation of r_{sx} from r_{sy} is denoted by r_s and that of p_{sx} from p_{sy} is by p_s, they are shown by

$$\begin{aligned} &r_s = r_{sx} - r_{sy} \\ &p_s = p_{sx} - p_{sy}, \quad p_{sx} = b_1 + b_3, \quad p_{sx} = b_2 + b_4 \qquad (6) \end{aligned}$$

If the deviation of r_s from p_s is denoted by e_s, and if the gains with respect to the magnetic flux are K_{ps}, K_{is}, and K_{ds}, the manipulated variable in the horizontal direction, $\boldsymbol{u}_s = [u_x, u_y, u_z]$, is given by the following PID control.

$$\boldsymbol{u}_s = K_{ps}\, e_s + K_{is} \int e_s dt + K_{ds}\, \dot{e}_s \qquad (7)$$

By adding $\boldsymbol{u}_s$ of Eq. (7) to $\boldsymbol{u}_f$ of Eq. (4), the input for the [CONV1] in the block diagram, $\boldsymbol{u}_f'$ shown in Fig. 12 is given by

$$\boldsymbol{u}_f' = K_{pf}\boldsymbol{e}_f + K_{if} \int \boldsymbol{e}_f dt + K_{df}\dot{\boldsymbol{e}}_f + \boldsymbol{u}_{ff} + \boldsymbol{u}_s \qquad (8)$$

The block diagram of the proposed magnetic flux control is shown in Fig. 12 where the sampling time of the positional control loop was set at 4 ms, and that of the magnetic flux control loop 1 ms.

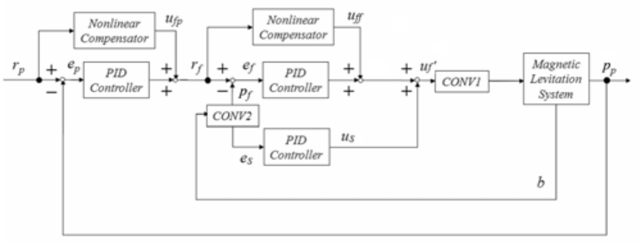

Fig. 12. Block diagram of proposed MF control with rotation suppressing control

4 EXPERIMENT

To confirm the effectiveness of the proposed method, the authors implemented the above-described controller, and carried out some magnetic levitation experiments.

First of all, to make clear the problem of the existing method that is represented by Eq. (4), a result of before-improvement p_s is shown in Fig. 13 where the hand was levitated at the height of Z=5 mm. Next, to make clear the effectiveness of the proposed rotational measurement system, the measured values after the hand's Z positional correction, the converted hand's rotational angles are shown in Fig. 14. Contrary to Fig.13 and Fig. 14, after-improvement result of p_s is shown in Fig. 15 where the proposed controller by Eq. (8) is implemented, and the corrected hand's rotational angle is also shown in Fig. 16.

As you can see from Fig. 13 and Fig. 14, they were found that the magnetic flux p_s has a strong correlation with the hand's rotational angle, and that the hand oscillates periodically within the range of -110 degree ~ +110 degree. The findings support the validity of the principle of the rotation-suppressing-control described in the section 3.3. Next, from Fig. 15 and Fig. 16, by virtue of the proposed controller, the periodic oscillation in the magnetic flux p_s has been markedly suppressed, and the consequently occurring periodic oscillation in the hand's rotational angle has also been effectively suppressed within the range of -15 degree ~ +15 degree.

As a result, it can be concluded that the proposed method effectively decreased the unwilled rotation around Z-axis much more than the existing method.

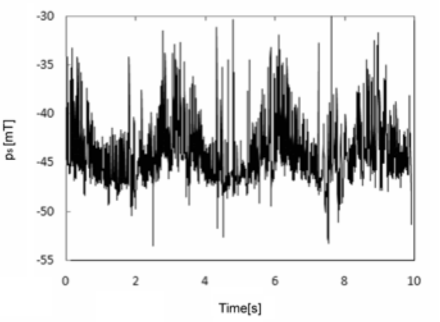

Fig. 13. Experimental result of p_s by MF controller

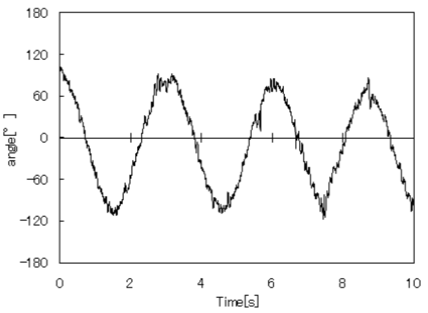

Fig. 14. Rotation angle by MF controller

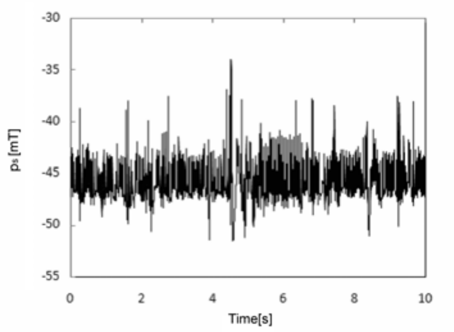

Fig. 15. Experimental result of p_s by proposed controller

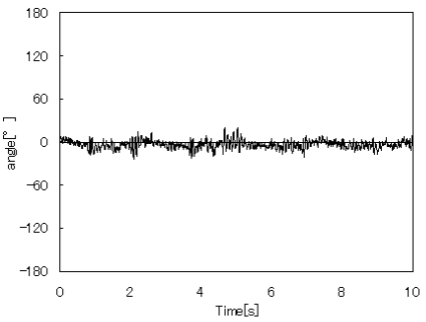

Fig. 16. Rotation angle by proposed controller

5 CONCLUSION

A controller to suppress the oscillation around the vertical axis was presented in this paper. The main points are as follows:

(1) Carrying out some magnetic levitating experiments, we have found an interesting behavior: the rotational oscillation was in phase with the perturbation of the sum value of four pieces of the magnetic flux respectively emitted from the four electromagnets. It means that the magnetic flux sum value has a dominant effect on the rotational oscillation, and it suggested us the necessity of suppressing the perturbation of the sum value.

(2) Considering this necessity, we designed a controller for stabilizing the magnetic-flux sum, and developed a trial system of the controller.

(3) We carried out some magnetic levitating experiments:the perturbation of the sum of four pieces of the magnetic flux was markedly decreased, and the ill rotational oscillation around the vertical axis was successfully suppressed. As a result, the effectiveness of the proposed method was confirmed.

In the future, based on the rotational oscillation suppression technique, we are directed to enhance the control characteristics of the magnetic levitating system: if we can arbitrarily control the rotation around the vertical axis, the system would be applied to more wide range of areas.

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