Evaluation on Edge-supported Magnetic Levitation Apparatus for Thin Steel Plates

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Grasping and conveying an object, by utilizing the frictional force generated by contact is performed in various processes in the manufacturing line for an industrial product. The deterioration of the surface quality due to these contacts is a problem. As a solution to this problem, a noncontact transport of steel plates, using electromagnetic force, has been proposed. However, in these systems, electromagnets are installed vertically. In this method, if the steel plate is thin and does not have sufficient flexural rigidity, it is difficult to add a suspension force for levitation over the entire steel plate. In order to solve this problem, we proposed an edge supported electromagnetic levitation system for flexible steel plates using electromagnets installed horizontally. In order to verify the effectiveness of the proposed system we constructed a prototype of an edge-supported type magnetic levitation system, which applied electromagnetic force only from the horizontal direction of the steel plate. Consequently, we carried out levitation experiment and discussed characteristics of horizontal positioning and levitation suspension.

Key words: electromagnetic levitation, thin steel plate, vibration control, magnetic field

1. Introduction

Thin steel plates are used in many industrial products and their transportation take place by contact with a large number of rollers in the manufacturing process. Recently, the demand of high quality steel is increasing. Therefore, the deterioration of the surface quality is a problem for this type of contact transportation. To solve this problem, the application of a magnetic levitation technology to a non-contact transport system is actively being studied (3-5). The authors’ research group had installed electromagnets not only vertically but also horizontally. Vertical electromagnets’ levitation is applying tension to the steel plate edges. We have confirmed that horizontal electromagnets improve levitation stability in thin steel plates with extremely low flexural rigidity (6-8). Furthermore, they help realize advanced levitation control systems considering the steel plate deflection as well as the vibration characteristics. Levitation control using only electromagnets from the edge direction is important. Hitherto, we have confirmed the characteristics of the suspension force of the edge direction electromagnet acts on the steel plate by experiment and analysis (9). In this study, we made a prototype edge supported electromagnetic levitation system based on these characteristics and we discuss the levitation characteristics.

2. Edge Supported Electromagnetic Levitation System

Figure 1 shows a schematic illustration of the newly made edge supported electromagnetic levitation system. Figure 2 shows the placement of the electromagnet and the sensor view from the top. As Fig. 2 shown, the vertical direction is defined as Z direction, the longitudinal direction of steel plate is defined as Y direction and the transverse direction is defined as X direction. Figure 3 shows a photograph of the electromagnetic levitation system during the levitation of a steel plate. The levitating object is a rectangular galvanized steel plate (material SS400) whose length is 400 mm, width is 100 mm, and thickness is 0.24 mm. In the electromagnetic levitation system, as shown in Fig. 4, two electromagnets facing each other are installed in the longitudinal direction near the edge of the thin steel plate. The attractive force of the electromagnets installed in the X direction, near the edge of the steel plate, perform non-contact positioning control. In a previous study (7), we calculated the deflection shape using magnetic field analysis and the finite difference method. The electromagnets are installed at such position to minimize
deflection and to expect stability on the steel plate. A laser-type sensor, which measure the displacement by the cut-off amount of a belt-like laser beam manufactured by KEYENCE was used to measure the horizontal displacement in X direction of the edge of the steel plate. Thereby, the steel plate is controlled by non-contact positioning by the electromagnets at a distance of 5 mm from the edge of the steel plate. Furthermore, the control law is calculated by detecting the current in each electromagnet from the measured external resistance and, subsequently, inputting eight measurement values into a digital signal processor of an A/D converter. The core, shown in Fig. 5, is an E-type electromagnet, and the material is ferrite. The electromagnet’s core is an enamel wire of 0.5 mm diameter wound around it 1005 times. For evaluating the levitating state of the steel plate, a vertical direction displacement sensor was installed as shown in Fig. 4 and Fig. 6. An eddy current non-contact displacement sensor manufactured by SENTEC was used. To consider the characteristic of suspension force generated by electromagnet, electromagnetic analysis was carried out. The analytical model is consisting of one electromagnet and steel plate (400 mm × 100 mm). The suspension force...
1.8 2 1 1 1.2 0.6 (0.4 (1.2 1.4 0.8 (5 ) (1)

7 shows the relationship between the vertical direction applied on the steel plate in the z direction from the electromagnet, which is obtained from the magnetic analysis. Each data shows the suspension force that was from electromagnet surface in the x direction \( x_{sp} \) [mm] and from center of electromagnet in the z direction \( z_{sp} \) point in the edge of steel plate. We confirmed that the study, the suction force is regarded generated in one electromagnet core and the steel plate size used in this equilibrium state. Attractive force by magnetic field from steel plate 8). From the previous study, in the installed electromagnet is generated near edge of the steel plate 3mm, when the steel plate is levitate horizontally in equilibrium state. Attractive force \( F \) of equilibrium levitating state \( [N] \), \( F_0 \) is distance from center of electromagnet to edge of steel plate in equilibrium levitating state \([mm]\), \( x \) is steel plate displacement in horizontal direction on equilibrium levitating state \([m]\), \( z \) is steel plate displacement in vertical direction on equilibrium levitating state \([m]\), \( i \) is current fluctuation value of coil \([A]\). In the proposed system installed so that the electromagnets are opposed to each other across the steel plate, attractive force \( f_1, f_2 \) that generated by each electromagnet suppose that occurs from the steel plate edge towards the center of each electromagnet core as shown in Fig. 9. When on the \( f_1 \) side steel plate is displaced by \( \Delta x \), on the \( f_2 \) side steel plate is displaced by \(-\Delta x\). Also, to perform positioning control, when on the \( f_1 \) side the current changes \( \Delta i \), on the \( f_2 \) side the current changes \(-\Delta i\). Also, when steel plate is displaced in \( x \) direction, both electromagnets are \( \Delta x \) displaced. Attractive force \( f_1, f_2 \) near the equilibrium levitating state, are as follow.

\[
f_1 = F(X_0 + \Delta x, Z_0 + \Delta z, I_0 + \Delta i) \quad (4)
\]

\[
f_2 = F(X_0 - \Delta x, Z_0 + \Delta z, I_0 - \Delta i) \quad (5)
\]

When attractive forces from both electromagnets and the angle formed by the \( x \) axis defined as \( \theta_1, \theta_2 \), the \( x \) direction component in attractive force, are as follow.

\[
f_1 \cos \theta_1 + f_2 \cos \theta_2 = \frac{Z_0}{I_0^2} F(X_0 + \Delta x, Z_0 + \Delta z, I_0 + \Delta i) + \frac{Z_0}{I_0^2} F(X_0 - \Delta x, Z_0 + \Delta z, I_0 - \Delta i) \quad (6)
\]

The \( z \) direction component in attractive force, are as follow.

\[
f_1 \sin \theta_1 + f_2 \sin \theta_2 = \frac{X_0}{I_0^2} F(X_0 + \Delta x, Z_0 + \Delta z, I_0 + \Delta i) - \frac{X_0}{I_0^2} F(X_0 - \Delta x, Z_0 + \Delta z, I_0 - \Delta i) \quad (7)
\]

The weight of the steel plate to be supported by a pair of electromagnets is \( m \). As, \( \Delta x = -x \), \( \Delta z = -z \), \( \Delta i = i \) establishing the equation of motion shows it, as follows.

\[
F = \frac{I_0^2}{2} \gamma_{sp}^2 i^2
\]

Where \( i_m \) is coil current \([A]\), \( \gamma_{sp} \) is distance from center of electromagnet to edge of the steel plate \([mm]\), \( L_{eff} / \gamma_{sp} \) is a constant corresponding to the effective magnetic flux of the electromagnet. It is also,

\[
\gamma_{sp} = \sqrt{X_{sp}^2 + Z_{sp}^2}
\]

In equilibrium levitating state, \( X_0 \) is static displacement in \( x \) axis direction \([mm]\), \( Z_0 \) is static displacement in \( x \) axis direction \([mm]\) and \( I_0 \) is steady current of electromagnet \([A]\). The eq. (1) is linearized by performing Taylor expansion.

\[
F(X_0 + \Delta x, Z_0 + \Delta z, I_0 + \Delta i) = F_0 - 2 \frac{F_0}{I_0^2} \Delta x \Delta i - 2 \frac{F_0}{I_0^2} \Delta z \Delta i + 2 \frac{F_0}{I_0^2} \Delta \Delta i
\]

3. Control Model of Edge Supported Electromagnetic Levitation System

3.1 Equation of motion for levitated thin steel plate

As shown in Fig. 8, edge of the steel plate is displaced from electromagnet surface in the \( x \) direction \( x_{sp} \) [mm] and from center of electromagnet in the \( z \) direction \( z_{sp} \) [mm], when the steel plate is levitate horizontally in equilibrium state. Attractive force by magnetic field from installed electromagnet is generated near edge of the steel plate 9). From the previous study, in the electromagnet core and the steel plate size used in this study, the suction force is regarded generated in one point in the edge of steel plate. We confirmed that the attractive force generated on the steel plate by the electromagnet is generated toward the tip of center convex part of the electromagnet core. Attractive force \( F \) generated on the steel plate is shown by the following equation.

\[
F = \frac{I_0^2}{2} \gamma_{sp}^2 i^2
\]

where \( i_m \) is coil current \([A]\), \( \gamma_{sp} \) is distance from center of electromagnet to edge of the steel plate \([mm]\), \( L_{eff} / \gamma_{sp} \) is a constant corresponding to the effective magnetic flux of the electromagnet. It is also,

\[
\gamma_{sp} = \sqrt{X_{sp}^2 + Z_{sp}^2}
\]
\[
m \frac{d^2 x}{dt^2} + 4 F_x x^2 + 4 F_z z^2 = 0
\]
(8)

\[
m \frac{d^2 z}{dt^2} + 4 F_z z^2 = 2 F_0 \frac{Z_0}{T_0} - mg
\]
(9)

At this time, taking the values of \( F_0, Z_0, F_z \) which satisfy the following equation, steel plate can be magnetically levitated.
\[
2 F_0 \frac{Z_0}{T_0} - mg = 0
\]
(10)

As described above, we obtained the motion of \( x \) direction by attractive force from facing electromagnet is depend on amount of change from stationary value of pair electromagnets, the motion of \( z \) direction is depending on stationary value of electromagnet. Therefore, in this paper, focusing only on the horizontal direction, a position control model is constructed with \( Z_0 = x_0 = 0, \ T_0 = x_0 \).

### 3.2 Horizontal positioning control model

Although the flexible thin steel plate exhibits elastic vibration in the vertical direction, it can be regarded as a rigid body in the \( X \) direction. The proposed system virtually divides the steel plate into two parts as shown in Fig. 10. We modeled the motion of the steel plate in the \( X \) direction using a 1-DOF model that actively controls each part. The same static attractive force is applied by the two installed electromagnets in order to sandwich the steel plate and, the equilibrium position of the steel plate is at the same distance from each electromagnet. The displacement of the steel plate from the equilibrium position is defined as \( x \) and the motion and circuit equations are as follows. Furthermore, the attractive force of the electromagnets at the equilibrium point was linearized.

\[
m \ddot{x} = f_x - f_z = f_x
\]
(1)

\[
f_x = 4 F_x x^2 + 4 F_z x^2
\]
(2)

\[
\frac{d}{dt} i_x = -L_{\text{eff}} \left( \frac{L_x}{X_0^2} \dot{x} + \frac{R_x}{2L_x} i_x + \frac{1}{2L_x} v_x \right) + L_{\text{lea}} \left( \frac{L_x}{X_0^2} \right)
\]
(3)

\[
\frac{d}{dt} i_x = 4 F_x x^2 / m_x X_0^2
\]
(4)

Using the state vector, Eqs. (1)-(4) can be rewritten as follow.

\[
\dot{x} = \begin{bmatrix} \dot{x} \\ \dot{z} \\ \dot{i_x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 4 F_x x^2 / m_x X_0^2 & 0 & 4 F_z z^2 / m_x i_x \\ 0 & -L_{\text{eff}} / L_x \left( i_x / X_0^2 - R_x / 2L_x \right) \end{bmatrix} x + \begin{bmatrix} F_x \\ 0 \\ 0 \end{bmatrix} v_x
\]
(5)

\[
A_x = \begin{bmatrix} 0 & 1 & 0 \\ 4 F_x x^2 / m_x X_0^2 & 0 & 4 F_z z^2 / m_x i_x \\ 0 & -L_{\text{eff}} / L_x \left( i_x / X_0^2 - R_x / 2L_x \right) \end{bmatrix}
\]

### Table 1 Coefficient of the control model.

| Symbol | Value |
|--------|-------|
| \( X_0 \) | \( 5 \times 10^{-3} \) m |
| \( L_{\text{eff}} \) | \( 1.25 \times 10^{-5} \) H |
| \( L_{\text{lea}} \) | \( 1.89 \times 10^{-4} \) H |
| \( L_x \) | \( 1.92 \times 10^{-4} \) H |
| \( R_x \) | \( 10 \) Ω |
| \( m_x \) | \( 3.74 \times 10^{-2} \) kg |

### Table 2 Feedback gain of \( F_x \).

| \( k_1 \) | \( k_2 \) | \( k_3 \) |
|---------|---------|---------|
| \( 1.04 \times 10^2 \) | \( 3.66 \times 10^2 \) | \( 4.2 \times 10^2 \) |

### Fig. 10 Experimental model of electromagnetic

\[
B_x = \begin{bmatrix} 0 & 0 & 1 / 2L_x \end{bmatrix}^T
\]

where \( F_x \) is the magnetic force of the coupled magnets in the equilibrium state [N], \( L_x \) is the gap between the steel plate and the electromagnet in the equilibrium state [m], \( L_x \) is the current of the coupled magnets in the equilibrium state [A], \( \dot{x} \) is the dynamic current of the coupled magnets [A], \( L_x \) is the inductance of the magnet coil in the equilibrium state [H], \( R_x \) is the resistance of the coupled magnet coils [Ω], \( v_x \) is the dynamic voltage of the coupled magnets [V], \( L_{\text{eff}} / X_0 \) is the effective inductance of the one magnet coil [H], and \( L_{\text{lea}} \) is the inductance leakage of the magnet.

Using the state vector, Eqs. (1)-(4) can be rewritten as follow.

\[
\dot{x} = A_x x + B_x v_x
\]
(5)

\[
A_x = \begin{bmatrix} 0 & 1 & 0 \\ 4 F_x x^2 / m_x X_0^2 & 0 & 4 F_z z^2 / m_x i_x \\ 0 & -L_{\text{eff}} / L_x \left( i_x / X_0^2 - R_x / 2L_x \right) \end{bmatrix}
\]

### 4. Levitation Experiment of Steel Plate by Edge Supported Electromagnetic Levitation System

#### 4.1 Experimental conditions

The steady current \( I_x \) of the electromagnet was varied. In order to evaluate the levitating characteristics of the steel plate at that time, we carried out a magnetic steel plate experiment. The steel plate is supported by jack, and levitated by lowering the jack. The parameter that was used to design the control system is shown Table 1.
Furthermore, we searched for the feedback gain $F_i$ of equation (6), which was determined by trial and error and is shown in Table 2. For the experimental conditions, the range of steady current was changed to $I_x = 0.9 ~ 1.2$ A.

At each steady current, there is a position where the steel plate could levitate. We searched the position where the steel plate could levitate at each steady current value by trial and error. The standard deviation of displacement was calculated in order to evaluate the displacement amplitude in the $x$ and $z$ directions of the steel plate. The experiment was conducted five times for each condition and for the evaluation the average of the results was used.

### 4.2 Experimental results

Figure 11 shows the time history of the displacement of the steel plate in the $x$ direction. Figure 12 shows the time history of the displacement of the steel plate in the $z$ direction. Figure 11 and Fig. 12 both show the results of each steady current of (a) 0.9 A, (b) 1.0 A, (c) 1.1 A, and (d) 1.2 A. Figure 13 summarizes the relationship between the steady current and the standard deviation of the $x$ direction in each steady current. The standard deviation of displacement in the $x$ direction was suppressed to 0.1 mm or less in all steady currents. Even in the proposed magnetic levitation system, the sufficiently positioned control in the $x$ direction. Figure 14 summarizes the relationship between the steady current and the standard deviation of the $z$ direction in each steady current. Comparing the results in Fig. 14 for each steady current value, by increasing the steady current value a suppression in vibration of the $z$ direction was confirmed. In the case of the minimum steady current, $I_x = 0.9$ A, the standard deviation of the $z$ direction is 0.474 mm. In the case of the maximum steady current, $I_x = 1.2$ A, the standard deviation of the $z$ direction is 0.179 mm. When the steady currents 0.9A and 1.2A were compared, the vibration in the $z$ direction could be suppressed by 62%.

![Image of graphs showing time histories of horizontal and vertical displacements](image-url)
As the steady current $I_x$ of the electromagnet increased, the tension applied to the steel plate in the $x$ direction increased. As a result, it is considered that the restoring force in the $z$ direction increased and the vibration of the steel plate in the $z$ direction could be suppressed.

5. Levitation Position Measurement Experiment of Steel Plate of Vertical Displacement

For the experimental conditions similar to chapter 4, the range of steady current was changed to $I_x = 0.9 \sim 1.2$ A. The levitation position in the $z$ direction was measured five times for each condition. The average of those results is the experimental value. Figure 15 shows the levitated position of the steel plate in each measured steady current. The dashed line in Fig. 15 which is extracted from the analysis results in Fig. 7 shows the relationship between the levitation position $Z_0$ and the steady current $I_x$ at which the steel plate levitates. Plots in Figure 15 are averaged experimental results. As a result, when the steady current is the minimum, $I_x = 0.9$ A, the levitation position of the vertical direction was 0.474 mm. In contrast when the steady current is the maximum, $I_x = 1.2$ A, the levitation position of the vertical direction was 0.402 mm. The levitated position of the steel plate increase by 0.7 mm. Furthermore, the trend of the experimental values agreed with the analysis result. We confirmed the effectiveness of the electromagnetic field analysis. As a result, using electromagnetic field analysis, even for steel plates of different thickness and material, we confirmed that we could establish such a system's design guidelines.

6. Conclusion

In this study, we constructed a prototype of an edge supported type magnetic levitation system applying electromagnetic force only from the $Y$ direction of a steel plate. We verified the levitating characteristics of the proposed control system. We carried out levitation experiments using an ultra-thin steel plate of 0.24 mm. We confirmed the achieved stable levitation. Furthermore, we carried out levitation experiments by changing the steady current value of the electromagnet. The experimental and analytic results of the calculated vertical levitating position agree with each other. The results showed that it is, possible to experimentally construct a control system for the steel plate stationary vertical direction displacement. In this study, we confirmed the effectiveness of the proposed magnetic levitation system. However, under transient conditions there were instance when it became practically an unstable system. In order to solve the problem, it is necessary to construct a control system that changes steady-state current by feedback of vertical displacement in addition to the proposed control system in this paper. For the future, we will consider in detail a more effective sensing method and modeling for the stability of this method. Furthermore, the shape of the electromagnet to generate more effective attractive force to flexible steel plate would be considered.

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