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Effect of a Magnetic Field from the Horizontal Direction on a Magnetically Levitated Steel Plate
(Fundamental Considerations on Levitation Probability)

by

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Abstract

Thin steel plates are widely used in various industrial products. However, they have problems of flaws in the coating caused by contact support during transport, and deterioration of surface quality. As a solution to these problems, a noncontact transport of steel plates using electromagnetic force has been considered. However, there is a risk that side slipping or dropping of the plate may occur owing to inertial force because the levitation control system does not provide a restraint for the direction of travel. Therefore we have proposed the addition of electromagnetic actuators to control the horizontal motion of levitated steel plate. In this study, we calculated the shape of steel plate with horizontal attractive force using the Finite Difference Method (FDM). We carried out basic experiments to discuss the effect of a horizontal attractive force applied to the stationary levitated steel plate on its elastic vibration. The result shows that the application of a magnetic field in the horizontal direction was confirmed to suppress deflection in the levitated flexible steel plate. In addition, the application of a magnetic field in the horizontal direction improves the levitation stability of steel plates.

Keywords: Electromagnetic Levitation Control, Steel Plate, FDM, Elastic Vibration

1. Introduction

Thin steel plates are widely used in various industrial products; however, they have problems of flaws in the coating caused by contact support during transport and the deterioration of surface quality [1)]. To solve this problem, studies of electromagnetic levitation technology have been carried out [2-7)]. We have considered a noncontact transport of steel plates using electromagnetic force. However, there is a risk that side slipping or the dropping of the plate may occur owing to inertial force because the levitation control system does not provide a restraining for the direction of travel. Therefore we have proposed the addition of electromagnetic actuators to control the horizontal motion of levitated steel plate.

Previously, our research group examined a 0.3-mm-thick rectangular steel plate as a sample, and confirmed that noncontact transport is possible when applying magnetic fields to the magnetically levitated steel plate in the horizontal direction [8,9)].

Moreover, we performed a similar examination for an ultrathin steel plate with a thickness of 0.18 mm, and demonstrated that the noncontact transport of ultrathin steel plates, which have been difficult to levitate using the conventional system, is also possible[10,11)]. However, the effect of the magnetic field in the horizontal direction on the highly flexible and magnetically levitated ultrathin steel plates of 0.18 mm thickness has not been examined in detail.

In this study, we performed an electromagnetic field analysis on a 0.18 mm steel plate, and calculated the distribution of the attractive force induced by electromagnets. Using the finite difference method (FDM), we obtained the shape of the steel plate when the force applied by the electromagnets acted in the horizontal direction. Finally, we carried out basic experiments to discuss the effect of a horizontal attractive force applied to the stationary levitated

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steel plate on its elastic vibration, with the aim of obtaining basic findings on various phenomena during motion.

2. Outline of Electromagnetic Levitation and Transportation System

Figure 1 is a schematic illustration of the electromagnetic levitation control system with a horizontal positioning controller. A zinc-coated steel plate (length 800mm, width 600mm, thickness 0.18mm, material SS400 steel) is levitated and positioned in a noncontact mode by attractive forces of electromagnets which are controlled by feedback signals from gap sensors. Figure 2 is photograph of the electromagnetic conveyance system.

The vertical displacement of the plate and the current through the magnet are acquired using five eddy-current-type displacement sensors and five resistors connected in series to the magnetic circuit, respectively.

These values are converted from analog to digital in the sampling interval of 1.0 ms, to allow them to be processed in a Digital Signal Processor (DSP). The five velocities of the plate are detected by differentiating the signals from the displacement sensors in the computer. The control forces (voltage) are calculated in the DSP and are fed to the five electromagnets through the D/A converter and five power amplifiers.

The horizontal displacement of the plate and the current through the magnet are acquired using four laser beam displacement sensors and four resistors connected in series to the magnetic circuit, respectively. The four velocities of the plate are detected by differentiating the signals from the displacement sensors in the computer. The control forces are calculated on a computer using these twelve values (sampling interval is 1.0 ms). These sensors and electromagnets are installed in the frame.

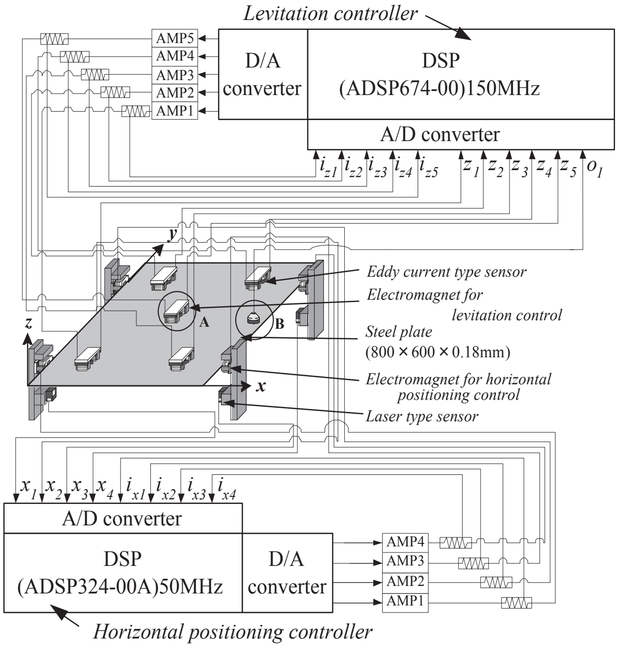


Fig.1 Electromagnetic levitation system

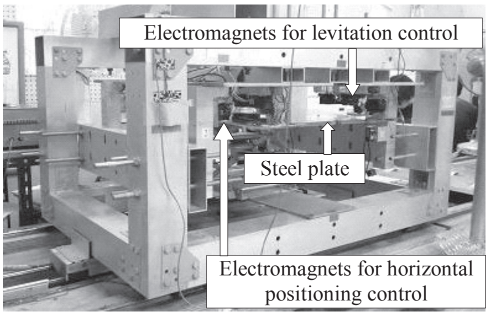


Fig.2 Photograph of experimental apparatus with horizontal positioning controller

3. Control Theory

3.1 *Electromagnetic levitation control system*

A single degree of freedom model in which the design of the control system is simplified through consideration of centralized control at the location of the electromagnet is considered. The steel plate is imaginarily divided into five parts, and each part is modeled as a single-degree-of-freedom electromagnetic levitation model, as shown in Fig.3. Consequently, the displacement, the velocity and the coil current detected at one electromagnet position are used for the control of that electromagnet. In this study, eddy current sensors are used to detect vertical displacements of the steel plate.

In an equilibrium levitation state, magnetic forces are determined so as to balance with gravity. The equation of small vertical motion around the equilibrium state of the steel plate subjected to magnetic forces is expressed as

$$m_z \ddot{z} = 2 f_z \tag{1}$$

where m_z is mass of the steel plate [kg], z is vertical displacement [m], and $f_z(t)$ is dynamic magnetic force [N].

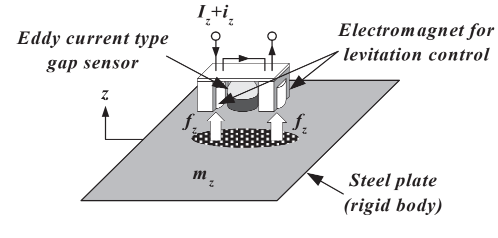


Fig.3 Theoretical model of levitation control of the steel plate

Figure 4 shows a schematic illustration of the electromagnet. The number of turns of electromagnet coil is 1005 (diameter of wire is 0.5mm), and the sectional area passing the magnetic flux of the E - type core, which was made from ferrite, is 225mm^2. Characteristics of the electromagnet are estimated on the basis of the following assumptions:

The permeability of the core is infinity, the eddy current inside the core is neglected, and the inductance of the electromagnetic coil is expressed as a sum of the component inversely proportional to the gap between the steel plate and magnet and the component of leakage inductance. The electromagnetic attractive forces used for levitation control are shown in Fig.5

If deviation around the static equilibrium state is very small, the characteristic equations of the electromagnet are linearized as

$$f_z = \frac{2F_z}{Z_0} z + \frac{2F_z}{I_z} i_z \tag{2}$$

$$\frac{d}{dt} i_z = -\frac{L_{eff}}{L_z} \cdot \frac{I_z}{{Z_0}^2} \dot{z} - \frac{R_z}{2L_z} i_z + \frac{1}{2L_z} v_z \tag{3}$$

$$L_z = \frac{L_{eff}}{Z_0} + L_{lea} \tag{4}$$

Using the state vector, the equations (1) ~ (4) are written as the following state equations:

$$\dot{\boldsymbol{z}} = \boldsymbol{A}_z \boldsymbol{z} + \boldsymbol{B}_z v_z \tag{5}$$

$$\mathrm{z} = \begin{bmatrix} z & \dot{z} & i_z \end{bmatrix}^{\mathrm{T}}$$

where F_z is magnetic force of the coupled magnets in the equilibrium state [N], Z_0 is gap between the steel plate and electromagnet in the equilibrium state [m], I_z is current of the coupled magnets in the equilibrium state [A], i_z is dynamic current of the coupled magnets [A], L_z is inductance of one magnet coil in the equilibrium state [H], R_z is resistance of the coupled magnet coils [Ω], v_z is dynamic voltage of the coupled magnets [V], and L_{lea} is leakage inductance of the one magnet coil [H].

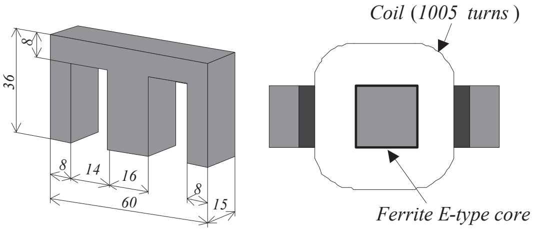


Fig.4 Specification of the electromagnet core

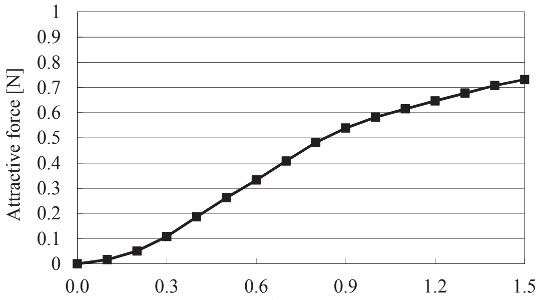


Fig.5 Experimental result of the relationship between steady current and attractive force of electromagnet

3.2 *Horizontal positioning control system*

Horizontal positioning control was carried out using the electromagnets installed at two edges of the steel plate. The banded laser beam sensor, keeping a 5mm clearance between the edge of the steel plate and each electromagnet surface, measured the horizontal displacement. For the basic examination, the horizontal motion of the steel plate was modeled to have single degree of freedom in the transport direction, as shown in Fig.6.

Therefore, the same attractive forces were generated from two electromagnets placed at one side of the steel plate. The equation of small horizontal motion around the equilibrium state of the steel plate subjected to the same static magnetic forces from the electromagnets at two edges is expressed as

$$m\ddot{x} = f_1 - f_2 = f_x \tag{6}$$

$$f_x = \frac{4F_x}{X_0} x + \frac{4F_x}{I_x} i_x \tag{7}$$

$$\frac{d}{dt} i_x = -\frac{L_{xeff}}{L_x} \cdot \frac{I_x}{{X_0}^2} \dot{x} - \frac{R_x}{2L_x} i_x + \frac{1}{2L_x} v_x \tag{8}$$

$$L_x = \frac{L_{xeff}}{X_0} + L_{xlea} \tag{9}$$

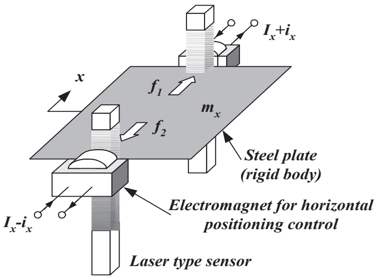


Fig.6 Theoretical model of horizontal positioning control of the steel plate

Using the state vector, equations (6) ~ (9) are written as the following state equations:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}_x \ \boldsymbol{x} + \boldsymbol{B}_x \ v_x \tag{10}$$

$$\mathrm{x} \ = \begin{bmatrix} x & \dot{x} & i_x \end{bmatrix}^{\mathrm{T}}$$

where F_x is magnetic force of the coupled magnets in the equilibrium state [N], X_0 is gap between steel plate and electromagnet in the equilibrium state [m], I_x is current of the coupled magnets in the equilibrium state [A], i_x is dynamic current of the coupled magnets [A], L_x is inductance of the one magnet coil in the equilibrium state [H], R_x is resistance of the coupled magnet coils [Ω], v_x is dynamic voltage of the coupled magnets [V], and L_{xlea} is leakage inductance of the one magnet coil [H].

4. Shape Analaysis of Steel Plate

The distributions of the vertical attractive force of the electromagnets and the horizontal tension were calculated using JMAG software, which is used to analyze electromagnetic fields, to examine the effect of horizontal magnetic fields on a levitated steel plate. The analytical conditions were as follows: the steady current used for horizontal positioning control of the steel plate was I_z = 0A~1.0A and the vertical downward displacement of the entire steel plate was set to 2 mm. Figure 7 shows the analytical result for a steel plate with a thickness of 0.18 mm. This figure shows the distribution of the vertical attractive force of the electromagnets applied to each of the analytical points (800 × 600). The vertical attractive force acting on the entire steel plate was 0.10 N.

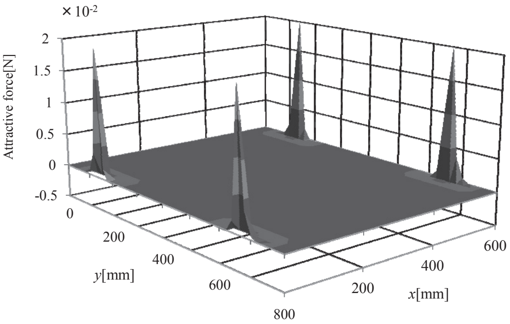


Fig.7 Distribution of vertical attractive force of electromagnet

The shape of the thin steel plate while being levitated by the above-mentioned attractive force is determined below. The equations for the static displacement of the rectangular thin steel plate are expressed as

$$D\nabla^4 z = f_z + f_x \frac{\partial^2}{\partial x^2} z + f - \rho h g \tag{11}$$

$$D = \frac{Eh^3}{12(1-\nu^2)}, \ \nabla^4 = \frac{\partial^4}{\partial x^4} + 2\frac{\partial^4}{\partial x^2 \partial y^2} + \frac{\partial^4}{\partial y^4}$$

where E is the Young's modulus of the thin steel plate [N/m^2], h is the plate thickness [m], ν is the Poisson ratio, x and y are the coordinates in the width and longitudinal directions [m], respectively, z is the vertical displacement of the plate [m], f is the dynamic magnetic force applied to the plate from the vertical direction by the permanent magnets [N/m^2], ρ is the plate density [kg/m^3], and g is the acceleration due to gravity [m/s^2]. Using eq.(11), the displacement of the thin steel plate is calculated by the finite difference method. We calculated as the steel plate is simply supported at the position of the electromagnets.

Figure 8 shows the analytical result for the deflection of the entire steel plate as a bird's eye view, revealing the regions of the steel plate that were severely bent. Figure 9 shows the deflection in the x-direction when y = 140 mm in Fig.8. The solid, dashed, and dotted lines show the cross-sectional shapes of the steel plate when it is levitated without horizontal positioning control and with horizontal positioning control at steady-state currents of 0.5 A and 1.0 A, respectively. The maximum deflection is reduced by 18% (0.5 A) and 27% (1.0 A) by applying a magnetic field in the horizontal direction, compared with the case without

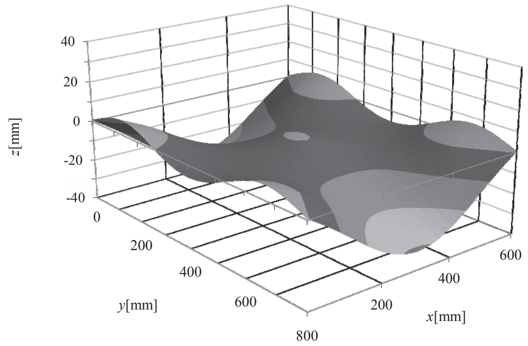


Fig.8 Shape of steel plate (bird's-eye view)

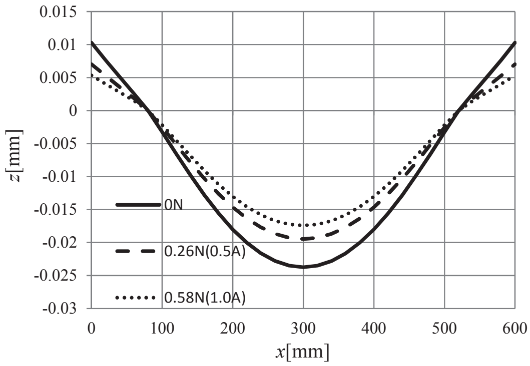


Fig.9 Shape of steel plate (x-direction section at y=140mm)

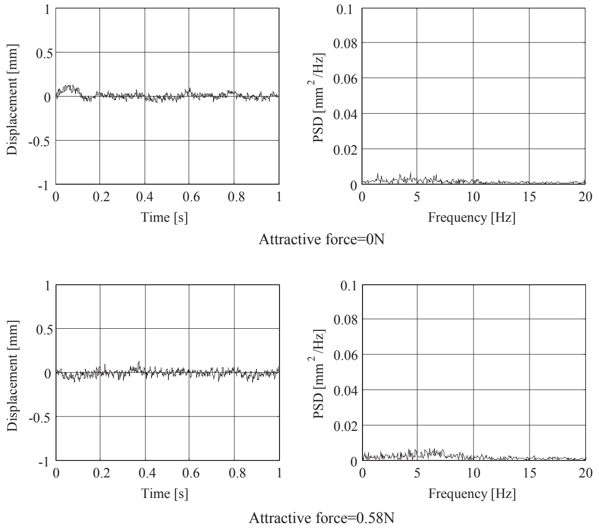
horizontal positioning control. Thus, it was confirmed that the horizontally applied magnetic fields contribute to raising the edges of the thin steel plate weighed down by gravity, making it almost flat.

5. Levitation Experiment for Steel Plate

5.1 *Levitation experiment*

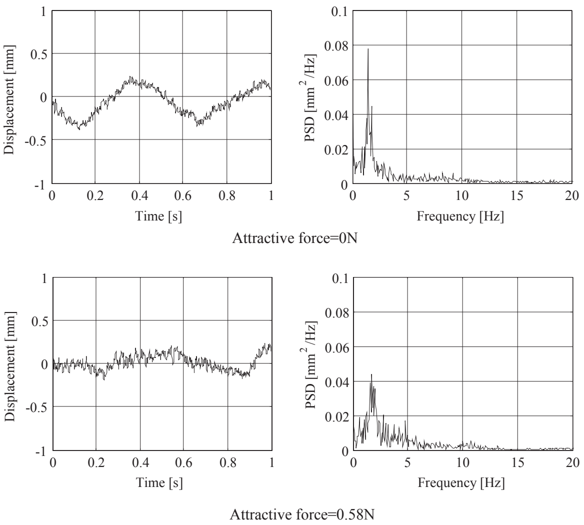
A levitation experiment was carried out using the feedback gain obtained by applying the optimal control theory to determine the effect of the change in magnetic field applied in the horizontal direction on a magnetically levitated steel plate. The displacement of the steel plate was measured by placing two noncontact eddy-current-type displacement sensors at measurement points A (point A) and B (point B) as shown in Fig. 1. Figures 10(a) and 10(b) show the time history waveforms and frequency spectra obtained at point A, respectively, without horizontal positioning control (upper) and with horizontal positioning control at a current of 1.0 A (lower). Figure 11 shows the results for point B under similar conditions. As shown in Fig. 11(a), point B, located near the edge of the steel plate, significantly vibrates. The frequency spectra in Fig. 11(b) indicate that the component with a frequency of 2 Hz, which is near the resonant frequency of the 1st elastic mode in the *x*-direction, is markedly suppressed. With horizontal positioning control, the amplitude at point A negligibly changes; however, that at point B is significantly suppressed. This is because point A is the control point of levitation and its vibration is controlled by the electromagnet used for levitation.

The above results confirm that the application of a magnetic field in the horizontal direction suppresses the vibration of levitated ultrathin steel plates.



(a) Time histories (b) Spectrums

Fig.10 Experimental results (measurement point A)



(a) Time histories (b) Spectrums

Fig.11 Experimental results (measurement point B)

5.2 *Experiment to determine levitation probability*

The effect of the magnetic field applied in the horizontal direction on the levitation performance of steel plates levitated using our levitation control system was determined. In the levitation experiment, the steady-state current was increased from 0.1 to 1.0 A with increments of 0.1 A to determine the levitation performance at each steady-state current. The levitation was repeated 100 times at each steady-state current and was considered successful when the levitation continued for at least 30 s. In Fig. 12, the ordinate shows the probability (%) of successful levitation and the abscissa shows the attractive force induced by the electromagnets when each steady-state current calculated in section 4 is applied. The levitation probability significantly increases when the attractive force increases from 0 to 0.02 N. This finding indicates that horizontal positioning control significantly improves the levitation stability. In addition, the levitation probability tends to increase with increasing attractive force. The above findings confirmed that the application of a magnetic field in the horizontal direction improves the levitation stability of ultrathin steel plates.

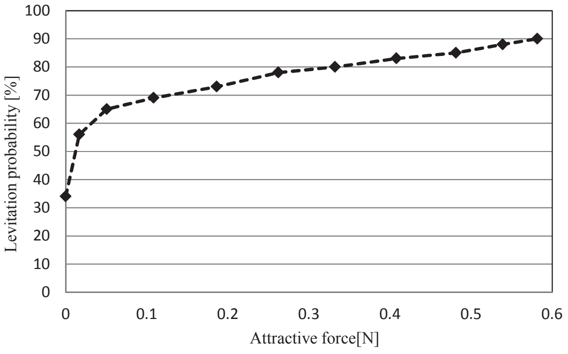


Fig.12 Experimental result of levitation probability

6. Conclusions

In this study, the effect of the magnetic field in the horizontal direction on a highly flexible and magnetically levitated ultrathin steel plate was examined. To this end, electromagnetic field analysis on the steel plate was carried out, and the shape of the plate to which a magnetic field was applied in the horizontal direction was determined by the FDM. The application of a magnetic field in the horizontal direction was confirmed to suppress deflection in the levitated flexible steel plate. In addition, by the levitation experiment, the application of a magnetic field in the horizontal direction was confirmed to suppress the vibration in levitated ultrathin steel plates. Furthermore, an experiment to determine the levitation performance was carried out to confirm that the application of a magnetic field in the horizontal direction improves the levitation stability of ultrathin steel plates.

In future studies, we will determine the vibration of levitated steel plates by simulation, confirm the validity of the simulation results by experiment, and clarify the behavior of steel plates during conveyance, using the results presented herein.

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