

Study on Electromagnetic Levitation System for Ultrathin Flexible Steel Plate Using Magnetic Field from Horizontal Direction

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In the transport system of a thin-steel-plate production line, the quality of the plate surface deteriorates over time because of contact with rollers. As a solution to this problem, we have proposed the use of electromagnets to control the horizontal displacement of the steel plate. Vertical force to support the steel plate and horizontal force to suppress elastic vibration are applied to the steel plate by using the horizontal electromagnet. Focusing on these forces, we proposed a magnetic levitation system for the steel plate using only electromagnets installed in the horizontal direction. In this paper, the suspension force in the proposed system is analyzed by the finite element method, and the possibility of applying the proposed system for thinner steel plates is considered. Suspension force is effectively generated owing to the thinness of the steel plate. The results, indicate the proposed magnetic levitation system to be effective for thin steel plates. To verify the validity of the analytical conclusion, an electromagnetic suspension experiment has been carried out, and suspension force generated by the electromagnet has been measured. The agreement between the experimental and analytical results, confirmed the validity of the analytical results.

Key words: electromagnetic levitation, thin steel plate, noncontact support, finite element method

1. Introduction

Thin steel plates are widely used in various industrial products. However, there are the problems of the deterioration of the surface quality and the occurrence of metal plating during transport owing to contact between the steel plate and rollers. As a solution to these problems, a noncontact transport of steel plates using electromagnetic force has been proposed¹⁻⁴. However, in these considerations, electromagnets are installed in the vertical direction. In this method, if the steel plate is thin and does not have sufficient flexural rigidity, it is difficult to add suspension force for levitation over the entire steel plate. Previously, the electromagnetic levitation system for steel plates had electromagnets installed in the horizontal direction as well as the vertical direction. This system is able to transport a magnetically levitated steel plate⁵. Moreover, a similar experiment for an ultrathin steel plate was performed, and the noncontact transport of ultrathin steel plates was demonstrated⁶⁻⁷. However, since this proposed system requires a number of control channels, there are the problems of complexity and high cost.

Because of the magnetic field of the added electromagnets, attractive force acts in the steel plate as the vertical suspension force as well as the horizontal tension force. The tension force can add the suspension force to the entire steel plate, and it becomes possible to improve the levitation stability. Moreover, the tension can prevent the plastic deformation of the steel plate, such as dimpling and folding. This can be expected to lead to surface quality improvement of the steel plate. Focusing on these forces, the feasibility of a magnetic levitation system for steel plates using only electromagnets installed in the horizontal direction was

considered. Electromagnetic field analysis by the finite element method (FEM) was performed, and we confirmed that the proposed system could levitate a steel plate with a thickness of 0.3 mm⁸. However, these results have not been verified experimentally. Furthermore, the effectiveness of this system for thinner steel plates has not been considered. In this study, the suspension force in the proposed system is analyzed by the FEM and the applicability of the proposed system to thinner steel plates is considered. In addition, electromagnetic suspension experiments are performed with the steel plate thickness of 0.30 mm or 0.24 mm. To show the effectiveness of this system for thinner steel plates, analytical and experimental results are discussed in detail.

2. FEM analyses of suspension force of electromagnet

Figure 1 shows an outline of the proposed system. A zinc-coated steel plate is levitated and positioned in the noncontact mode by the attractive forces of electromagnets that are controlled on the basis of feedback signals from laser sensors.

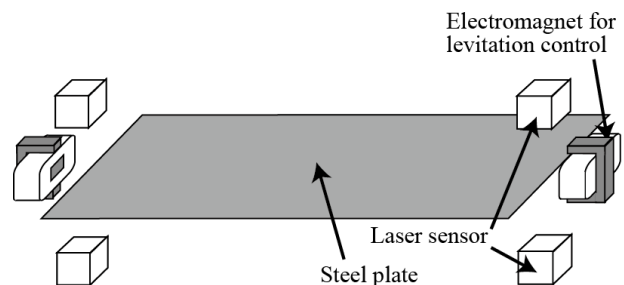


Fig. 1 Electromagnetic levitation system for steel plate using only electromagnets installed in horizontal direction.

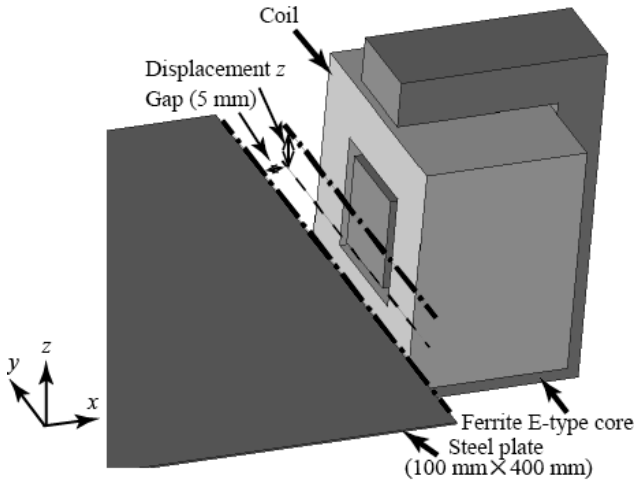


Fig. 2 FE analytical model.

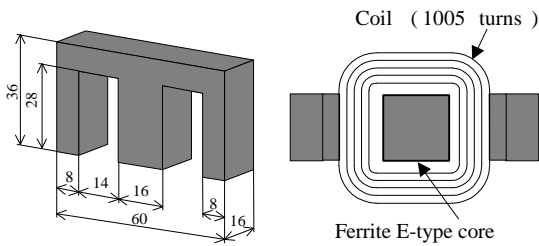


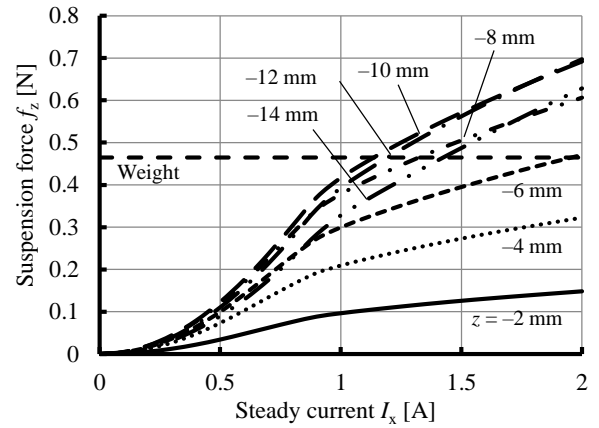
Fig. 3 Schematic illustration of electromagnet.

In the previous study⁷⁾, it has been confirmed that this control system can control horizontal displacement of the steel plate (length 400 mm, width 100 mm, thickness 0.18 mm, material SS400 steel), and suppress the standard deviation of horizontal displacement less than 0.1 mm. From the above, it was confirmed that the proposed system has a practically sufficient control performance for positioning control in the horizontal direction.

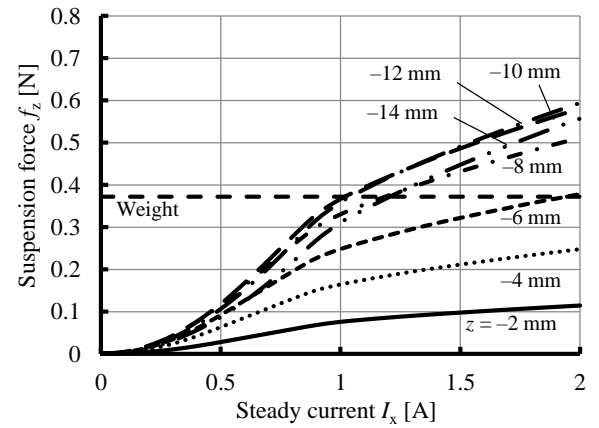
2.1 FE model and analytical conditions

To discuss the effectiveness of this system, suspension force is analyzed by the FEM. The electromagnetic field analysis is carried out using the finite-element method software JMAG (Ver. 11). The analytical model is shown in Fig. 2. The steel plate (length 400 mm, width 100 mm, material SS400 steel) is levitated with electromagnets shown in Fig. 3. In previous studies⁸⁾, analytical results showed that this electromagnet can generate a sufficient horizontal tension for positioning control more than 2 times greater than vertical suspension force. Furthermore, it has been confirmed that the steel plate is hardly displaced in the control direction with horizontal positioning control⁷⁾. Therefore, the analysis is carried out on the assumption that the steel plate does not displaced from the control point.

The analytical conditions are as follows. Vertical displacement z is changed from -2 mm to -14 mm. The gap between the edge of the steel plate and the surface of electromagnets is 5 mm. The steady electromagnet current I_x is in the range from 0.1 A to 2.0 A. The



(a) Thickness $h = 0.30$ mm



(b) Thickness $h = 0.24$ mm

Fig. 4 Relationship between thickness of steel plate h and vertical attractive force f_z for each displacement z .

thickness of the steel plate h is changed from 0.06 mm to 0.30 mm with each increase in thickness of 0.06 mm.

2.2 Numerical results by FEM

Figure 4 shows the relationship between steady current I_x [A] and vertical suspension force f_z [N]. Figure 4(a) shows the analytical result for the steel plate with a thickness of 0.30 mm. Figure 4(b) shows the result for a plate thickness of 0.24 mm. Dotted lines in these figures mean the weight of the steel plate. If the generated suspension force is equal to the weight of the steel plate, the steel plate can be levitated. Analytical results show that increasing the steady current leads to upward displacement of the steel plate. When the steady current is greater than 1.0 A, the suspension force is increased gradually, because magnetic saturation occurs in the core. When the steel plate is displaced downward, suspension force increases. The results in Fig 4(a) indicate that the steel plate can be levitated when displacement is greater than -6 mm. However, even if the steel plate is displaced more than -10 mm, suspension force does not increase further. The cause of this result is the magnetic field generated from the convex portion of the lower part of the electromagnet core. Although suspension force

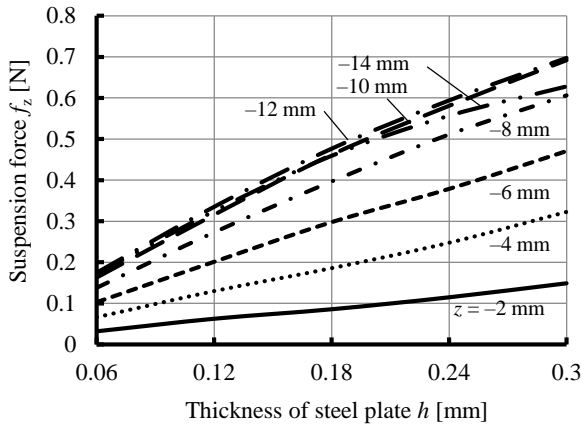


Fig. 5 Relationship between thickness of steel plate h and suspension force f_z for each displacement z (steady current $I_x = 2.0$ A).

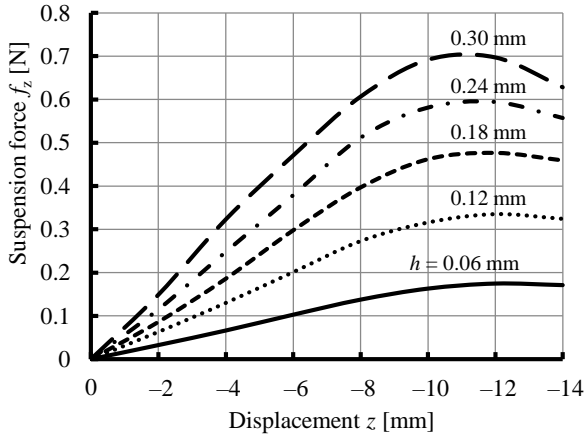


Fig. 6 Relationship between displacement z and suspension force f_z for each thickness of steel plate h (steady current $I_x = 2.0$ A).

generally decreases, the result for the plate with 0.24 mm thickness shows the same tendency as that for the plate with 0.30 mm thickness, as shown in Fig. 4(b).

Figure 5 shows the relationship between plate thickness and suspension force for each displacement when the steady current is 2.0 A at maximum. The suspension force is reduced in proportion to the decrease in the thickness. The reason for this is considered that the part for generating suspension force becomes smaller when the thickness of steel plate is thinner. Figure 6 shows the relationship between suspension force and displacement for each thickness when the steady current is 2.0 A. The suspension force is linearly proportional to the displacement when the displacement is less than -8 mm. In this linear range, even if the steel plate is vertically displaced by a disturbance, the suspension force acts as a restoring force. With this restoring force, the steel plate stabilizes passively.

Figure 7 shows the relationship between steady current and suspension force for each thickness of steel

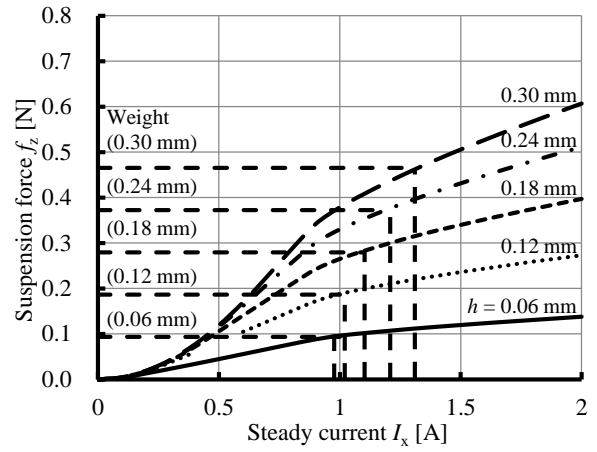


Fig. 7 Relationship between steady current I_x and suspension force f_z for each thickness of steel plate h (displacement $z = -8$ mm).

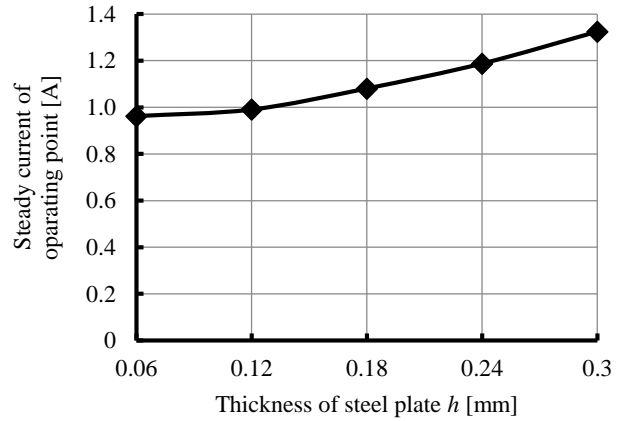


Fig. 8 Relationship between thickness of steel plate h and steady current of operating point (displacement $z = -8$ mm).

plate with $z = -8$ mm. The dotted lines indicate the weight of the steel plate for each thickness. At the operating point where suspension force is equal to its own weight, the steel plate can be levitated. As the steel plate becomes lighter when it becomes thinner, it seems to be more easily levitated. On the other hand, the suspension force is also decreased. From these analytical result, it is found that the decrease in the suspension force is smaller than the decrease in the weight of the steel plate. These results show that decreasing the thickness of the steel plate can reduce the steady current of the operating point. The relationship between the thickness of the steel plate and the steady current of the operating point is shown in Fig. 8. Compared with the result for the thickness of 0.30 mm, the steady current of the operating point is reduced 18.4% in the case of the 0.18 mm thickness, and 27.3% in the case of the 0.06 mm thickness. Suspension force is more effectively generated with increasing thinness of the steel plate. The proposed magnetic levitation system is superior for thin steel plates that are difficult to levitate by the conventional method.

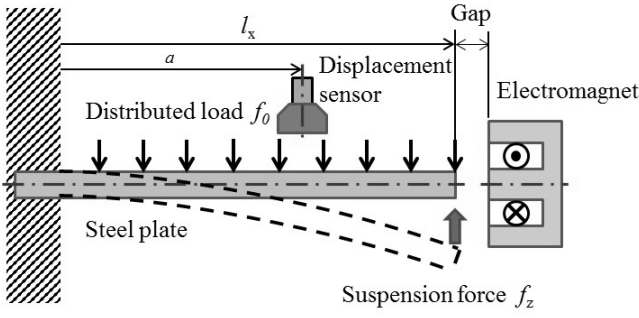


Fig. 9 Experimental model of electromagnetic suspension force.

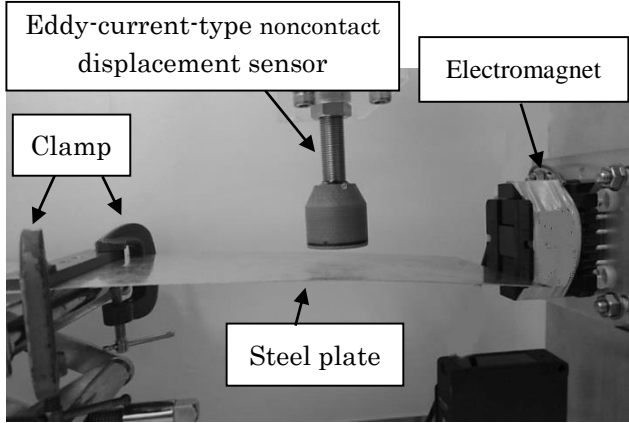


Fig. 10 Photograph of experimental apparatus for electromagnetic suspension.

3. Electromagnetic suspension experiment

3.1 Experimental model

To verify the validity of the above analytical results, the electromagnetic suspension experiment is carried out. Experimental model is shown in Fig. 9. An electromagnet is installed near the end of the fixed steel plate. An eddy-current-type noncontact displacement sensor is installed above the steel plate to measure the displacement of the steel plate. Distributed and concentrated loads act on the steel plate. Distributed load is due to its own weight, and concentrated load is due to suspension force by from the electromagnet.

Vertical displacement z' [m] of the steel plate without suspension force f_z [N] from the electromagnet and vertical displacement z [m] with f_z are expressed as ⁹⁾

$$z'(x) = \frac{f_0}{EI} \left(\frac{1}{24} x^4 - \frac{l_x}{6} x^3 + \frac{l_x^2}{4} x^2 \right) \quad (1)$$

$$z(x) = z'(x) + \frac{f_z}{EI} \left(-\frac{1}{6} x^3 + \frac{l_x}{2} x^2 \right). \quad (2)$$

Distributed load f_0 [N/m] due to self-weight is expressed as

$$f_0 = \rho g h l_y, \quad (3)$$

where x is the horizontal displacement [m], l_x the length of the steel plate [m], l_y the width of the steel plate [m], h

Table 1 Parameters and values.

Parameter	Value
ρ	7500 kg/m ³
l_x	0.20 m
l_y	0.10 m
h	0.30×10 ⁻³ m, 0.24×10 ⁻³ m
a	0.115 m
E	206 GPa
g	9.81 m/s ²

the thickness of steel plate [m], ρ the plate density [kg/m³], g the acceleration due to gravity [m/s²], E Young's modulus of the thin steel plate [N/m²], I the second moment of area [m⁴], and a the sensor position from the fixed end [m].

Suspension force f_z is obtained by measuring displacements z and z' at sensor position a , as

$$f_z = \frac{EI}{-\frac{1}{6}a^3 + \frac{l_x}{2}a^2} (z(a) - z'(a)) \quad (4)$$

3.2 Experimental conditions

Table 1 shows the specifications of the experiment. Figure 10 is the photograph of the experimental apparatus for electromagnetic suspension. The steel plate is fixed with clamps. In the vertical direction, the electromagnet is installed at the same position as the supporting position. The gap between the surface of the electromagnet and the edge of the steel plate end is 5 mm. Vertical displacement of the steel plate is measured with a sensor when the steady current of the electromagnet is changed from 0 A to 2.0 A. In this experiment, the edge of the steel plate tilts about 5° due to deflection. This experimental condition is different from analytical condition in chapter 2. However, the attractive force generates locally at the only edge of steel plate⁹⁾. Furthermore, we analyzed previously the attractive force generated at steel plate when the steel plate tilts 5°. Comparing analytical result of tilt angle 0° and 5°, amount of change of the suspension force f_z was less than 5%. Therefore, it is confirmed that the deflection of the steel plate does not affect suspension force.

3.3 Experimental results

Figure 11 shows the relationship between steady current and displacement. Figure 11 (a) shows the result for the plate with 0.30 mm thickness. Figure 11 (b) shows the result for the plate with 0.24 mm thickness. Previously, the experimental value measured with a sensor was compared with the calculated value with the steady current of 0 A. The result has confirmed that the differences between experimental and calculated values

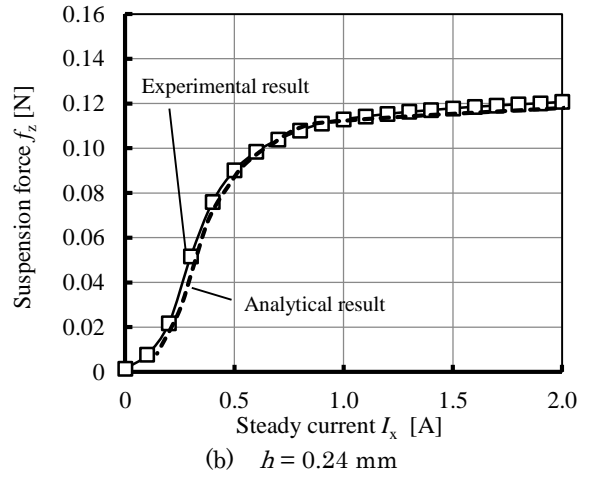
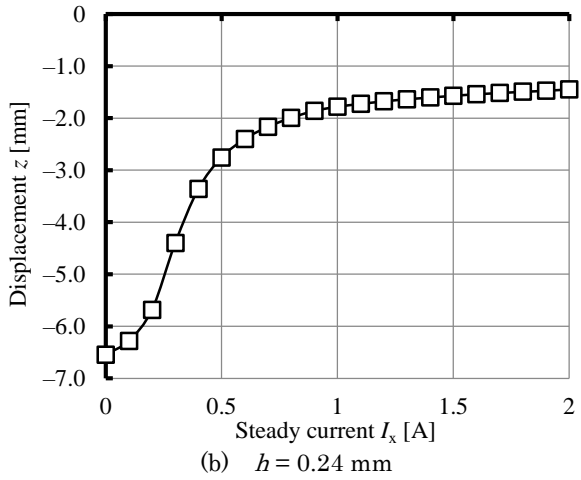
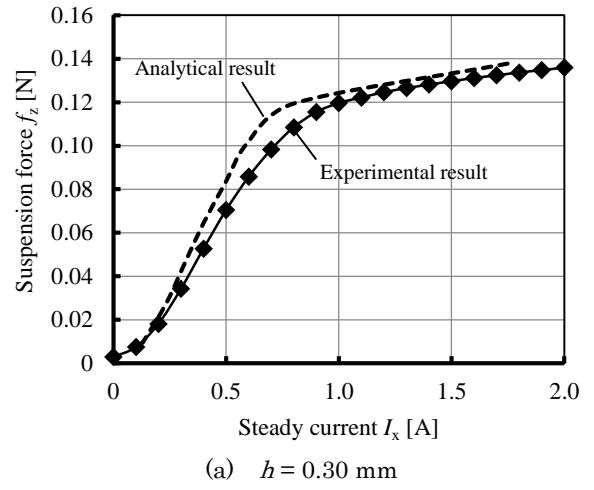
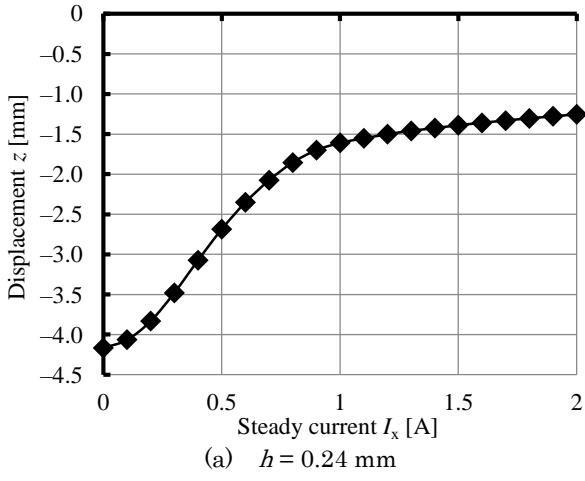


Fig. 11 Relationship between steady current I_x and measured displacement z by sensor.

Fig. 12 Relationship between steady current I_x and calculated suspension force f_z for measured displacement and analytical results

are less than 1%. Experimental results show that increasing the steady current leads to upward displacement of the steel plate. This trend is significant when the steady current is less than 0.5 A.

Figure 12 shows the relationship between steady current and suspension force calculated using the experimental result. Figure 12 (a) shows the result for the plate with 0.30 mm thickness. Figure 12 (b) shows the result for the plate with 0.24 mm thickness. The plotted point in this figures indicate experimental results. Suspension force increases with increasing steady current. When the steady current is less than 0.5 A, the increment of suspension force is larger. The attractive force of the electromagnet is generated at the steel plate toward the center of the electromagnet core. If the steel plate is displaced further downward, the ratio of suspension force to attractive force is larger. On the other hand, when the steel plate is displaced upward, the ratio of tension to attractive force is larger. It is considered that the cause of saturation is upward displacement of the steel plate.

Dashed line in Fig. 12 indicates analytical results of suspension force. This analytical suspension force is calculated using eq. (2) when the displacement of the

edge of steel plate coincides analysis condition in chapter 2. The analytical steady current is obtained using Fig. 4 when the displacement and analytical suspension force coincides analysis condition.

The experimental results agree the analytical results. In the range of size in this paper, deflection of the steel plate was experimentally confirmed that seldom effect on the suspension force. Furthermore, the agreement of the analytical and experimental results shows the validity of the realization of the magnetic levitation system only using electromagnets in the horizontal direction described in the previous section.

4. Conclusion

In our proposed system using only electromagnets installed in the horizontal direction, vertical suspension force, which was applied to the steel plate by an electromagnet, was analyzed for a steel plate thickness of less than 0.30 mm. In the range of interest in this study, suspension force is more effectively generated as the steel plate becomes thinner. The results indicate the proposed magnetic levitation system to be superior for thin steel plates. To verify the validity of the analytical conclusion,

an electromagnetic suspension experiment was carried out using an experimental apparatus for electromagnetic suspension, and suspension force of the electromagnet was measured. The agreement between the experimental and analytical results showed the validity of the analysis.

In the next stage, in order to realize a magnetic levitation system for noncontact transport and suspension of steel plates, a system with improved stability will be designed by installing more electromagnets.

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