Optimal Placement of Permanent Magnets in a Hybrid Magnetic Levitation System for Thin Steel Plate
(Experimental Consideration on Levitation Probability)

by

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Abstract
Thin steel plates are used in many industrial products including those of the automobile industry. We proposed a system of controlling the magnetic levitation and confirmed its realization by means of a digital control experiment. However, the use of a limited number of electromagnets cannot suppress static deflection or high-order-mode elastic vibration, which are characteristics of flexible magnetic materials. We therefore propose a hybrid system to control levitation of thin steel plates to solve this problem, using the magnetic force generated by permanent magnets, which incur no operational costs. In this study, we attempted to determine the optimal gap, placement, and number of permanent magnets to reduce the deflection of thin steel plates under a generated magnetic field. The experiments on deflection were carried out on magnetically levitated thin steel plates to verify how useful the optimal placement of the permanent magnets was.

Keywords: Steel Plate, Electromagnetic Levitation Control, Permanent Magnet, FDM, Genetic Algorithm

1. Introduction
Thin steel plates widely used in various industrial products are generally conveyed while in contact with rollers in the conveyance process. This leads to deterioration in the quality of the plate surface, such as flaws and peeling of the plated layer. As countermeasures to these problems, research on noncontact conveyance using magnetic levitation technology has been actively carried out recently1-3). The researchers in our laboratory have been involved in examining noncontact magnetic levitation control of the conveyance of a rectangular thin steel plate. For stable levitation, we proposed a hybrid magnetic levitation control system for a thin steel plate using the magnetic force of permanent magnets in an almost uniform distribution above the steel plate at the areas where no electromagnets are placed, as shown in Fig. 1.

In the previous studies, fundamental research on the optimal conditions in terms of the number and position of permanent magnets, was carried out, in which the attractive force of the permanent magnet applied to the rectangular thin steel plate was simplified and modeled4-6). Furthermore, the optimal position and uniform distribution of the permanent magnets were experimentally examined to verify the

![Fig.1 Electromagnetic levitation control system for steel plate with permanent magnets](image-url)
effectiveness of the permanent magnets. In this study, the gap, number and optimal position of permanent magnets for suppressing the displacement of a magnetically levitated thin steel plate were investigated using thin steel plates. In addition, levitation experiments were carried out on the basis of the results obtained by comparing the levitation stabilities of the thin steel plate vibrated in the 1st, 2nd, and 3rd elastic modes.

2. Electromagnetic Levitation System

2.1 Outline of system

Figure 1 shows an outline of the control system. The object of electromagnetic levitation is a rectangular zinc-coated steel plate (SS400) with length \( a = 800 \) mm, width \( b = 600 \) mm. To accomplish noncontact support of a rectangular thin steel plate using 5 pairs of electromagnets (Nos. 1-5) as if the plate was hoisted by strings, the displacement of the steel plate is measured using five eddy-current gap sensors. Here, the electric circuits of paired electromagnets are connected in series, while an eddy-current gap sensor is positioned between the two magnets of each pair. The detected displacement is converted to velocity using digital differentiation. In addition, the current in the coil of the electromagnets is calculated from the measured external resistance, and a total of 15 measured values are input into the digital signal processor (DSP) via an A/D converter to calculate the control law. A control voltage is output from the D/A converter into a current-supply amplifier to control the attractive force of the 5 pairs of electromagnets in order that the steel plate is levitated below the surface of the electromagnets by 5 mm.

2.2 Modeling of electromagnetic levitation system

In this model, independent control is carried out, in which information on detected values of displacement, velocity and coil current of the electromagnet under study at one position are fed back only to the same electromagnet. Therefore, as shown in Fig. 2, the steel plate is divided into 5 hypothetical masses and each part is modeled as a lumped constant system (local model).

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

\[
m_z \ddot{z} = 2f_z
\]

where \( m_z = m/5 \) [kg] (in which the effect of the attractive force of the permanent magnets has been considered), \( z \): vertical displacement [m], and \( f_z \): dynamic magnetic force [N].

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

\[
\begin{align*}
\dot{z} & = A_z z + B_z v_z \\
z & = [z \quad \dot{z} \quad i_z]
\end{align*}
\]
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\[ A_z = \begin{bmatrix} 0 & 1 & 0 \\ \frac{2F_z}{m_z Z_0} & 0 & \frac{2F_z}{m_z I_z} \\ 0 & -\frac{L_{\text{eff}}}{L_z} \frac{I_z}{Z_0^2} & -\frac{R_z}{2L_z} \end{bmatrix} \]

\[ B_z = \begin{bmatrix} 0 & 0 & \frac{1}{2L_z} \end{bmatrix} \]

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

3. Optimization of Hybrid Magnetic Levitation System

3.1 Analysis model

In this study, the displacement of the rectangular thin steel plate subjected to gravity and the attractive force of the permanent magnets is calculated. The equations for the static displacement of the rectangular thin steel plate are expressed as

\[ D V^4 z = f - \rho h g \]  \hspace{1cm} (6)

\[ D = \frac{E h^3}{12(1 - \nu^2)} \]

where \( E \) is the Young’s modulus of the thin steel plate [N/m²], \( h \) is the plate thickness [m], \( \nu \) 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/m²], \( \rho \) is the plate density [kg/m³], and \( g \) is the acceleration due to gravity [m/s²].

Using eq. (6), 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. When the distribution of the attractive force is rigorously taken into consideration, as shown in Fig.4, considerable calculation time is expected for the analysis of the attractive force applied to the rectangular thin steel plate by the permanent magnets. Therefore, analysis is carried out using a model in which the attractive force is assumed to be concentrated at one point. The size of FDM mesh is 10mm \times 10mm. The characteristics of the attractive forces of permanent magnet used for levitation control are shown in Fig.5.

3.2 Search method of optimization

In this study, the distance between the surface of each permanent magnet and the thin steel plate (hereafter, gap) is set in the range of 35-100 mm, considering that the permanent magnets are installed in the electromagnetic levitation control system shown in Fig.1. The gap is changed by increments of 5 mm. Here, the distance of the permanent magnets above the thin steel plate was the same for all magnets.

The optimal number and position of the permanent magnets were sought for this range of the gap at the same time. It is practically impossible to search for the optimal position of the permanent magnets by experiment because the number of combinations of search patterns is huge. Therefore, the optimal position is sought using a genetic algorithm, the effectiveness of which was previously confirmed when searching for the optimal position of permanent magnets using a free-free beam as an optimization algorithm.
Figure 6 shows a flowchart of the genetic algorithm. First, the number and initial position of permanent magnets are randomly determined (referred to as initialization in Fig. 6; number of initial groups: 30). Then the shape of the thin steel plate subjected to gravity and the attractive force of the permanent magnets is determined (referred to as “deflection analysis of steel plate”) and the evaluation function is calculated (“calculation of the evaluation value”). Using the evaluation function, candidates for the optimal position are selected (“selection”; the elite preservation rule by which the top 40% are selected unconditionally is applied). Furthermore, from among the candidates, new positions are generated with a certain probability to obtain an optimal solution (“crossover”; the crossover rate is 90% in uniform crossover, as shown Fig. 7).

However, because there is a possibility that a group including similar position patterns gives a local solution, the position patterns are dispersed with a probability of 5% to maintain the diversity of position patterns (“mutation”, as shown Fig. 8).

The computation ends when the final value of the evaluation function does not change for over 200 generations. The number of permanent magnets is determined such that the total attractive force of the permanent magnet is no more than 50% of the total weight of the thin steel plate, considering the controllability the magnetically levitated thin steel plate.

In addition, an evaluation value is calculated to compare the shape of the thin steel plate for different positions of permanent magnets. The purpose of this study is to suppress the displacement of the thin steel plate. The evaluation function $J$ is defined as eq. (7),

$$J = \frac{J_Z}{J_{Z0}} \times w_Z + \frac{J_D}{J_{D0}} \times w_D \quad (7)$$

where $J_Z$ is the evaluation function of the mean deflection, $J_D$ is the evaluation function of the maximum deflection, $z_{max}$ is the maximum deflection of the thin steel plate and $z_i$ is the displacement at each analysis point on the thin steel plate. $N$ is the total number of analysis points.

As reference evaluation values, $J_{Z0}$ is the mean deflection and $J_{D0}$ is the maximum deflection of the thin steel plate when no permanent magnets are used, and each term in eq. (7) is nondimensionalized. $w_Z$ and $w_D$ are the weight coefficients for the mean deflection and maximum deflection of the thin steel plate, respectively. $w_Z = 0.5$ and $w_D = 0.5$, for which deflection is expected to be most greatly suppressed from the results of simulations, were adopted. The values of $J$ are obtained at each gap, and we assume the gap of minimum value of $J$ the optimal gap.
### 3.3 Results of optimization

As a result of optimization, the optimal gap (55mm), the optimal number of permanent magnet (four) and optimal placement are obtained when the thickness of steel plate is 0.30mm. Figure 9 shows placement of permanent magnets. Figure 10 shows the shape of steel plate. Figure 9(a) and Figure 10(a) show without permanent magnet. Figure 9(b) and Figure 10(b) show uniform placement of permanent magnet. Figure 9(c) and Figure 10(c) show optimal placement. The results in Fig.9 and Fig.10 confirmed that the optimal placement can suppress the displacement.

The deflection of the thin steel plate when the permanent magnets were uniformly placed was larger than that when no permanent magnets were used and only electromagnets were employed, as shown in Fig.10. This is because the attractive force of the permanent magnets was applied to inappropriate positions on the thin steel plate and a large deflection of the thin steel plate was induced in the upward vertical direction.

### 4. Levitation Experiment

To verify the effectiveness of the search for the optimal position of permanent magnets, magnetic levitation experiments using rectangular thin steel plate(thicknesses = 0.3mm) were carried out by placing the permanent magnets in the experimental setup shown in Fig. 1. We compared the following three cases: (1) when no permanent magnets are employed, (2) when permanent magnets are almost uniformly distributed above the steel plate at the positions where no electromagnets are placed, and (3) when permanent magnets are optimally placed as shown in Fig. 9. In the levitation experiments, a thin steel plate was levitated under the above three conditions, and a sinusoidal wave with a natural frequency of 4.58, 12.62, or 24.75 Hz, corresponding to the 1st, 2nd, and 3rd elastic modes, respectively, was applied.
to the y-axis direction of the thin steel plate as a disturbance to induce elastic vibration in the plate. The amplitude of the disturbance signal was set at 1 V, approximately 10% of the working voltage applied to the electromagnets. Noncontact eddy-current gap sensors were placed at the measurement positions shown in Fig. 9 to obtain the time histories of the displacement of the thin steel plate in the vertical direction induced by the 1st-, 2nd-, and 3rd-mode elastic vibrations, and the peak-to-peak value of waveforms obtained under different elastic vibrations were compared. During the experiments, the speed gain at the five electromagnet positions was decreased to ease the generation of elastic vibration using the feedback gain calculated by applying the optimal control theory. Figures 11, 12, and 13 show the waveforms in the 1st, 2nd, and 3rd elastic modes, respectively, (a) without permanent magnets, (b) with almost uniformly distributed permanent magnets, and (c) with optimally placed permanent magnets. Under all conditions, the frequency of the waveform is equal to that of the disturbance signal. The phase difference between the disturbance signal and the waveform at each measurement position was determined, and it was confirmed that the thin steel plate vibrates in each elastic mode.
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In the 1st elastic mode, the peak of the waveform caused by the disturbance is suppressed by approximately 15% when permanent magnets are almost uniformly distributed and by approximately 30% when permanent magnets are optimally placed compared with the case when no permanent magnets are employed. In the 2nd elastic mode, the peak of the waveform is suppressed by approximately 20% when permanent magnets are almost uniformly distributed and by approximately 50% when permanent magnets are optimally placed compared with the case when no permanent magnets are employed. In the 3rd elastic mode, the peak of the waveform when permanent magnets are almost uniformly distributed is similar to when no permanent magnets are employed. On the other hand, the peak of the waveform is suppressed by approximately 50% when permanent magnets are optimally placed compared with the case when no permanent magnets are employed. From the above findings, the effectiveness of permanent magnets for the suppression of the vibration of thin steel plates was confirmed.

5. Conclusions

For the hybrid magnetic levitation control system using permanent magnets, the optimal number and position of permanent magnets as well as the optimal gap for maximally suppressing the deflection of a magnetically levitated thin steel plate were sought by finite differential analysis and using a genetic algorithm. We found that the values of permanent magnet parameters effectively suppress the deflection of the thin steel plate levitated by the system. In addition, the levitation stability of the thin steel plate upon the application of a disturbance was confirmed to be improved in the levitation experiments using optimally placed permanent magnets to suppress the deflection of the levitated plate. By the optimization method adopted in this study, the elastic vibration was suppressed without the need to introduce many permanent magnets at the edges of the thin steel plate in the conveying direction. The above findings indicate the possibility of effectively suppressing the vibration of thin steel plates at the start and end of conveyance, and confirm the validity of our method.

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References