A study on levitation performance improvement of bent flexible steel plate


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Abstract
Levitation improvement of the bending levitation performance of thin steel plate was performed. First, the point of the steel plate where the vibration is predominantly generated was estimated using an ultrathin steel plate with a thickness of 0.18 mm. Furthermore, to decrease the vibration, levitation experiments by means of changing the bending shape and using permanent magnets were performed and the standard deviation of the displacement and levitation probability were evaluated. In addition, to determine the effect of the permanent magnets, the shape of the steel plate was analyzed using the finite difference method. As a result, the main vibration generating area was confirmed to be the longitudinal central edge area of the steel plate. In order to suppress the vibration in this area, the vibration of the steel plate was decreased by making an asymmetrical bending shape. Also, the vibration of the steel plate was suppressed by placing the permanent magnets in the positions that matched with the results of the analysis.

Keywords: Bending levitation, Magnetic levitation, Thin steel plate, Vibration control

1. Introduction

Recently, the weight reduction of mechanical products has become an important issue from the perspective of energy conservation. There is a great demand for thin and light steel plate used for various industrial products. Steel plates with good productivity and high surface quality are particularly required. However, productivity and surface quality are often reduced owing to the occurrence of scrapes in the rolling process and defective plating in the surface treatment process.

To find a solution for these problems, studies dealing with noncontact transportation using electromagnetic levitation technology are performed. Above all, studies on thin steel plates are actively being carried out. In one study, the application of robust control for a levitation control system was performed to suppress an elastic vibration generated in a steel plate (Namekawa et al., 2006). In another study, a levitation system in which some electromagnets are installed was proposed. The system can control a tilt angle of a steel plate by controlling the gap between the electromagnet and steel plate for each electromagnet (Suzuki et al., 2015). The tilting steel plate can use gravity for horizontal positioning control. This enables the steel plate to maintain a stable levitation for an extended time. However, in many studies, the size of the levitated steel plate is smaller than what would be a realistic size for use in a product, and a successful instance of stable noncontact transportation for very thin steel plate has not been reported.

Our research group has proposed a levitation system utilizing the flex of an ultrathin steel plate conventionally believed to be not appropriate for levitation. This system bends a levitated steel plate so as not to plastically deform the plate and ensure the appropriate rigidity using a minimum number of electromagnets. It is necessary to find the optimal number of electromagnets, their placement and tilt angle in theory considering the length of the steel plate, width, thickness, materials, etc. for bending levitation. We have proposed a simple method to estimate the tilt angle with the highest levitation performance using the finite difference method (FDM) for thin steel plates with some thickness. This
method can obtain the deflection of the bending levitated steel plate generated by the absence of attractive force from the electromagnet. The deflection generates high frequency vibration that deteriorates the stability of levitation control. By bending the steel plate at the estimated tilt angle of the electromagnets, the rigidity of the steel plate is increased, the deflection of the steel plate is reduced. That can improve the levitation stability. Furthermore, the usefulness of this method is confirmed by levitation experiments. However, it is necessary to propose a levitation method that further suppresses the vibration of a steel plate, since it is difficult to maintain a state of stable levitation without a fall or contact to an electromagnet in a practical condition such as when a disturbance occurs.

In this paper, several studies were conducted with the goal of improving the performance of existing levitation systems at low cost. First, we investigated the source of the vibration of the levitated steel plate experimentally from a levitation experiment using a steel plate reinforced with tape. Secondly, based on the results, we conducted an asymmetric bending experiment aiming at suppressing vibration only with the shape of the steel plate. Finally, as a method of suppressing vibration with symmetrical curvature, we investigated a levitation method that uses the attraction force of the permanent magnet (PM) supplementally. We carried out the analysis of the static deflection of the levitated steel plate by FDM and levitation experiment to investigate the change of the levitation performance by changing the PM placement.

2. Bending levitation system for a thin steel plate

Figure 1 shows an outline of the control system of the bending levitation system. Figure 2 shows a schematic illustration of the experimental apparatus. The object for levitation is a rectangular zinc-coated steel plate (SS400) that is popular in the industrial market with length \(a = 800\) mm, width \(b = 600\) mm, and thickness \(h = 0.18\) mm. The damping performance against the tilt angle \(\theta\) for the steel plate is considered, as shown in the front view of Fig. 2. To accomplish noncontact support of a rectangular thin steel plate using five pairs of electromagnets (No. 1 to 5), the displacement of the steel plate is measured by five eddy-current gap sensors. The detected displacement is converted to velocity using digital differentiation. In addition, the current in the coils of the electromagnets is calculated from the measured external resistance. Thus, the 10 measured values obtained are input into a digital signal processor via an analogue-to-digital (A/D) converter to calculate the control law. A control voltage is then output from a digital-to-analogue (D/A) converter into a current supply amplifier to control the attractive force of the five pairs of electromagnets.

In this paper, we adopted a 1-degree-of-freedom (1DOF) model that produces information on the detected values of displacement, velocity, and coil current of the electromagnets at one position are fed back only to the same electromagnet in the bending levitation system. A control system for this system is designed referring to a previous study based on the optimal control theory of the discrete time system (Marumori et al., 2015a). The weight coefficient used in chapters 3 and 4 to obtain an optimal control law is investigated by trial and error as the standard deviation of the measured displacement is most suppressed. The weight coefficient used in section 5 exhibits deteriorated levitation performance from the weight coefficient used in sections 3 and 4. The arrangement of electromagnetic units is shown in Fig. 3. The electromagnetic units Nos. 1 to 4 around electromagnet No. 5 can be tilted, as shown in the front view of Fig. 2. The distance between the surfaces of the electromagnets and the steel plate was controlled at 5 mm even when \(\theta\) was changed and the horizontal positions of Nos.1 to 4 were adjusted based on the natural flexure shape of the steel plate. In addition,
No. 5 was moved up and down depending on the degree of bending of the thin steel plate. In this paper, the tilt angle of the electromagnet $\theta$ that is best angle for levitation performance is determined to be $15^\circ$ for 0.18 mm thickness of steel plate.

3. Vibration generation mechanism of levitation flexible steel plate

3.1 Preliminary experiment

To determine the vibration generation mechanism for a levitated flexible steel plate, levitation experiments were performed using a reinforced steel plate whose flexural rigidity was increased in some areas using adhesive tape. The results are discussed in terms of the vibration damping performance.

At first, to investigate the influence of the damping effect when the tape is attached to the steel plate, the natural frequency and the damping ratio were calculated using the equipment shown in the Fig. 4. This device was a cantilever beam fixed with a clamp at a position of 300 mm in the longitudinal direction using a steel plate having a length of 400 mm, a width of 100 mm, and a plate thickness of 0.18 mm. The vibration of the beam was measured from the sensor which is installed at a position 5 mm above the end of the beam. The tape made of PVC and having a thickness of 0.20 mm was attached to the entire cantilevered part of the steel plate. In order to ensure the uniform rigidity of the reinforcing steel plate, the tape was attached without generation of wrinkles and air bubbles. From the basic experiment, it was confirmed that the rigidity is not changed by the tape. As a result of conducting this free vibration experiment with a steel plate with no tape and tape attached, the natural frequency without tape was 1.70 Hz, and the damping ratio was 0.0157. The natural frequency with tape was 1.58 Hz, and the damping ratio was 0.0160. The natural frequency decreased due to increase in mass, not increase in rigidity. However, since the damping ratio is approximated before and after tape attaching, it was found that there is almost no influence of the damping effect due to attaching the tape on the steel plate.
3.2 Vibration suppression effect using tape

Since it was found that there was almost no influence of the damping effect when the tape was pasted on the steel plate, levitation experiment is carried out using a steel plate to which a tape is affixed. The reinforced areas of the steel plate in the preliminary experiments are shown in Figs. 5 (a)-(e), where the adhesive tape was attached on the steel plate in the dark areas. The tape was made of PVC and had a thickness of 0.20 mm. To ensure uniform rigidity of the reinforced steel plate, the tape was attached without the generation of wrinkles and bubbles. Furthermore, the area of each reinforced region was the same. Each pattern in Fig. 5 had the purpose of reinforcing the steel plate as follows: (a) the region outside electromagnet unit Nos. 1 to 4 in the longitudinal direction, (b) the region containing electromagnet unit Nos. 1 to 4 in the longitudinal direction, (c) the central region in the longitudinal direction, (d) the region outside electromagnet unit Nos. 1 to 4 in the transverse direction, (e) the central region in the transverse direction. Patterns (a)-(c) aim to reinforce the region in the longitudinal direction, and patterns (d) and (e) aim to reinforce the region in the transverse direction.

The results of each pattern are shown in Fig. 6. Figures on the left side are time histories of the steel plate from the control point and the others are spectrums of these displacements. The displacement is measured at electromagnet unit No. 1. It has been confirmed previously that displacements measured at the other electromagnet units showed the same trend as the result of No. 1. These time histories include irregular vibration. Therefore, the control performance is evaluated by standard deviation of displacement measured in 5 s. Each standard deviation is shown in a figure of time history as standard. Focusing on time history, patterns (a) and (e) can suppress the amplitude of vibration. Furthermore, focusing on the spectrum, high frequency vibration including 50~100 Hz can be suppressed. These results show that reinforcing the steel plate near the center of the longitudinal ends effectively suppresses the vibration.

3.3 Effect of steel plate longitudinal end

Based on the results of the previous section, bending levitation experiments using the reinforced steel plate are performed under the tilt angle $\theta = 15^\circ$. The steel plate is reinforced near the center of the longitudinal ends, as shown in Fig. 7, with the adhesive tape. The amount of the weight increase of the steel plate reinforced by only tape is 10% or less relative to the weight of the non-reinforced steel plate and does not cause any change to the vibration characteristic with weight increase.

Figure 8 shows the result of the levitation experiment using non-reinforced steel plate, and Fig. 9 shows the result using reinforced steel plate as Fig. 7. Figs. 8(a) and 9(a) show the time histories of displacement of the steel plate with measuring at electromagnets unit No. 1, and Figs.8(b) and 9(b) show the spectrums of displacement. A comparison of these results shows that reinforcement of the steel plate near the center of the longitudinal ends can suppress vibration near 80 Hz. It is considered that the area of the steel plate where the attractive force generated by electromagnets does
Fig. 6. Bending levitation result with tape patterns.

Fig. 7. Tape placement of the steel plate.

Fig. 8. Symmetric bending levitation result without tape. ($\theta = 15^\circ$)

Fig. 9. Symmetric bending levitation result with tape. ($\theta = 15^\circ$)
not act, generates vibration near 80 Hz with the result of deflection of the steel plate. Hereafter (chapter 4 and 5), based on these results, a more practical levitation method for thin steel plate without partial reinforcement is considered with the aim to suppress the vibration of steel plate.

4. Asymmetrical bent magnetic levitation control

4.1 Experiment method

For past bending levitation experiments, electromagnetic units (No. 1 to 4) installed on the periphery were all set at a uniform tilt angle according to the degree of bending. The bending levitation method attempted in this section was a levitation experiment carried out by setting different tilt angles for cross section A and cross section B as shown in Fig. 10 in order to perform control only by the steel plate shape with the part that vibrates conspicuously bent based on the results in the previous chapter. This was predicted to control vibration on the central part in the longitudinal direction, where vibration control effects appeared in the previous chapter based on tension in the x-axis direction or on restoring the force in the y-axis direction. The tilt angle of the electromagnets used were \( \theta = 0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ \) at which the possibility of achieving this was confirmed in a past report (Marumori et al., 2015b) of symmetrical levitation, combined in order to form asymmetrical bending on cross-section A and on cross-section B.

The central electromagnet No. 5 in each combination of outside electromagnets was at a tilt angle of 0° as in symmetrical bending, and its vertical position was set according to the combination of outside electromagnets so that the distance between the steel plate and electromagnet would be 5 mm.

4.2 Experiment results

Table 1 shows the standard deviation of displacement amplitude in the case where the electromagnet tilt angles were combined (average value of 10 experiments). For reference, the results of the symmetrical bending levitation are also shown (shaded boxes). Cases where levitation did not occur according to the combination are represented by “—”. This table shows that the combination that shows the largest vibration control effects is \( \theta = 10^\circ, 15^\circ \) at 0.025 mm, which is a reduction of about 35% from \( \theta = 15^\circ \), where the standard deviation of displacement is smallest in symmetrical levitation. Figure 11 shows the time history waveform at \( \theta = 10^\circ, 15^\circ \). A comparison of this result to the time history waveform of the symmetrical bending of \( \theta = 15^\circ \) in Fig. 8 confirms that vibration near 80Hz was controlled.

However, a look at Table 1 confirms that if the difference between the tilt angles of cross-sections A and B is equal to or larger than approximately 10°, the standard deviation of the displacement increases, and the performance is poorer than in the case of symmetrical levitation.

It is also confirmed that at such a combination of tilt angles, the effect of the restoring force acting on the steel plate increases, and the surface on which the attractive force of the tilted electromagnet units (No. 1 to 4) acts and the surface on which magnetism acts on the steel plate are not parallel.

It is, therefore, assumed that the attractive force of the electromagnets does not act effectively on the steel plate, causing vibration control performance to deteriorate.

5. Study of bending levitation by installing permanent magnets

5.1 Experiment method

In Chapter 3, levitation stability was improved by partially increasing the rigidity of the steel plate. In Chapter 4, we proposed a method to improve the levitation performance by increasing the rigidity by devising the shape of the steel plate asymmetrically and confirming the damping effect. However, the method of deciding the optimum combination of angles was a trial and error method, easily improving levitation performance remains problem. In our past research, permanent magnet, and the levitation stability is improved (Narita et al., 2013). Therefore, in this chapter, improving levitation performance by installing permanent magnets on a symmetrically bent steel plate was attempted. Our research the rigidity of the steel plate which does not bend is partially increased by using the attractive force generated by the group has repeatedly studied a hybrid magnetic levitation system applying the most appropriate method of placing the permanent magnets in order to control the deflection of a steel plate that has not been bent (Narita et al., 2013). This study was our first attempt using bent steel plate; considering the vibration control effects up to the previous chapter, we
studied the placement of the permanent magnets by varying the center line in the long side direction from the center of the steel plate to its ends, as shown in Fig. 12. The ferrite magnets used were 30 mm × 30 mm in size with thickness of 15 mm, and their surface magnetic flux density was 0.12 T. The distance \( z_{PM} \) from the permanent magnet surfaces to the surface of the thin steel plate was sought by trial and error and set as a constant 25 mm. In this system, the polarities of the electromagnets and permanent magnets were set so that the steel plates that are to be levitated were always the N-pole.

In order to evaluate the levitation performance for the locations of the permanent magnets, the standard deviation of displacement and levitation probability of the steel plate were obtained. The levitation probability was expressed as a percentage by performing 50 experiments under each condition and considering a case of levitation for 30 seconds or longer to be levitation performance. A preliminary experiment had confirmed that a case where levitation occurred for 30 seconds or longer indicated that it is possible for levitation to continue for more than 10 minutes, which is sufficient for practical application.

5.2 Attractive force properties of permanent magnets

The attractive force of the permanent magnets is distributed on the steel plate, but performing an analysis considering the distribution of the attractive force in detail would require lengthy computation, so it was assumed that the attractive force was applied at one point on the steel plate. To obtain the attractive force of the permanent magnet, a steel plate of 0.18 mm thickness reinforced with a non-magnetic acrylic plate so as not to deform was set on the electronic balance. Permanent magnet was installed under the steel plate, and the attractive force was calculated from the increase in the weight of the electronic balance. It has been confirmed that the experimental value and theoretical value of the attractive force for a gap generally conform, as shown in Fig. 13. Furthermore, the theoretical value of the attractive force \( F_{PM} \) on the same figure was obtained by the following formulae (Yamakawa et al., 1992).
Fig. 12. Permanent magnets placement of the steel plate.

Fig. 13. Attractive force by a permanent magnet for theoretical value and experimental value.

\[ B_z = \frac{B_r}{\pi} \left( \tan^{-1} \frac{ab}{2z_{PM} \sqrt{a^2 + b^2 + 4z_{PM}^2}} \right) \]

\[ -\tan^{-1} \frac{ab}{2(z_{PM} + l_a) \sqrt{a^2 + b^2 + 4(z_{PM} + l_a)^2}} \]  \hspace{1cm} (1)

\[ F_{PM} = \frac{B_r^2 S}{2\mu_0} \] \hspace{1cm} (2)

Where, \( B_r \): residual magnetic flux density, \((3.81 \times 10^3 \text{ Gauss})\), \( B_z \): magnetic flux density [Gauss] of permanent magnets at distance \( z_{PM} \) from the permanent magnet surfaces, \( l_a \): height of permanent magnets \((0.015 \text{ m})\), \( S \): surface area of permanent magnets \((= 2a \times 2b = 0.03 \text{ m} \times 0.03 \text{ m})\), \( z_{PM} \): distance from the permanent magnet surfaces [m], and \( \mu_0 \): magnetic permeability in vacuum \((4\pi \times 10^{-7} \text{ H/m})\).

5.3 Thin steel plate shape analysis during levitation

The attractive force properties of the permanent magnets in the previous section are used to perform a shape analysis of the levitated thin steel plates. On a levitated steel plate, deflection occurs at places where the attractive force of the electromagnets does not act, so it is difficult to achieve stable levitation.

So in order to evaluate the suppression of the deflection, the state in which the thin steel plate is bent and the entire plate is supported on its surface, or in other words, the shape in which deflection is not caused only by bending is defined as the ideal shape. The ideal
Fig. 14. Relationship between placement of permanent magnets and standard deviation of displacement at sensor No. 1.

The shape is, considering the steel plate to be a one-dimensional beam seen on the x-axis, that in which the deflection shape of this beam protrudes into the steel plate. In order to evaluate the total deflection of this ideal shape, the shape when gravity has acted on a bent thin steel plate is calculated (Marumori et al., 2014). The following formula is the equation for deflection of a thin steel plate.

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

However, \[ \nu^4 = \frac{\partial^4 z}{\partial y^4} + 2 \frac{\partial^4 z}{\partial x \partial y^2} + \frac{\partial^4 z}{\partial x^4} \]

Where, \( \nu \): Poisson’s ratio, \( z \): vertical displacement of thin steel plate [m], \( f_{EM} \): attractive force per unit area applied to the thin steel plate from the vertical direction by electromagnetic unit No. 5 [N/m²], \( f_{PM} \): attractive force per unit area applied to the thin steel plate from the vertical direction by the permanent magnets [N/m²].

The deflection of the steel plate is calculated by the finite difference method in formula (3). Assuming that the thin steel plate is simply supported by electromagnetic units No. 1 to 4, the bearing capacity \( F_5 \) generated by electromagnetic unit No. 5 at that time was decided based on measured values. For the part of the steel plate that \( F_5 \) acts upon, \( f_{EM} \) was obtained assuming that it is applied as a distributed load on the nodes in the analysis model. \( f_{PM} \) was obtained based on the attractive force of the permanent magnets \( F_{PM} \) obtained by formula (2) and it was assumed that it similarly acts as a distributed load. The size of the differential analysis lattice was set as 10 mm \( \times \) 10 mm by fully clarifying the shape of deflection and considering the computation time. The suitability of this analysis method has been confirmed by an earlier report (Narita et al., 2013).

The degree that the total quantity of deflection under the ideal shape corresponds to the plate thickness was defined as follows as the evaluation value \( j \).

\[ j = \frac{\sum_{i=1}^{N} |z_i - z_0|}{h \cdot N} \]

Where, \( z_i \): displacement of the \( z \)-constituent at each analysis point of the thin steel plate [m], \( z_0 \): displacement of the \( z \)-constituent of the ideal shape [m], \( N \): total number of analysis points.

The lower the evaluation value \( j \), the smaller the total quantity of deflection from the ideal shape, signifying that it is a shape that suppresses deflection of the part where the attractive force is not applied. In the next section, the experiment and \( j \) are compared and the optimal location of the permanent magnets based on \( j \) are considered.

### 5.4 Bending levitation experiment using permanent magnets

Figure 14 shows the standard deviation of displacement under permanent magnet location \( y_{PM} \) from the center of the steel plate (measured at electromagnet No. 1 location). Up to the previous chapter of this study, the weight coefficient used was that which obtained the highest levitation performance at \( \theta = 0^\circ \); however, in this study, in order to more
clearly confirm the levitation performance improvement and vibration control effects of installing the permanent magnets, this caused deterioration to the extent that the standard deviation of the displacement amplitude was approximately 3 times that of the maximum performance used above.

The same figure shows that the closer the location $y_{PM}$ of the permanent magnet to the end of the steel plate, the greater the standard deviation of displacement, and that from $y_{PM} = 120$ mm until 200 mm, the standard deviation of displacement is lower than in the case where the permanent magnets are not installed. To take the case where there are no permanent magnets in Fig. 15(a) as an example, the time history of acceleration at (b) $y_{PM} = 120$ mm, (c) $y_{PM} = 240$ mm is shown.

Beginning at $y_{PM} = 220$ mm, the standard deviation of the displacement increases above that in a case where permanent magnets are not installed, then beginning at $y_{PM} = 240$ mm, the vibration of the steel plate increases, and it cannot be levitated. This showed that, unlike the study up to the previous chapter, installing permanent magnets in the center of the longitudinal direction is ineffective and the vibration suppression effects decline.

Fig. 16 shows the levitation probability at $y_{PM}$. Looking at the same figure shows that the closer the locations of the permanent magnets are to the ends of the steel plate, the lower the levitation probability, and that at $y_{PM} = 240$ mm, the probability is lower than in the case where permanent magnets are not installed.
The results of static deflection analysis performed to determine the factors accounting for results such as the above are shown in Fig. 17. The same figure shows the evaluation value $j$ for the permanent magnet locations. As the permanent magnet is installed inside, the evaluation value tends to decrease. Then $j$ increases at the permanent magnet locations near the ends of the steel plate, and beginning at $y_{PM} = 220$ mm, $j$ is higher than it is in the case where there are no permanent magnets installed. As stated above, the lower the value of $j$, the smaller the total quantity of deflection from the ideal shape, but installing permanent magnets so that it is closer to the ideal shape suppresses vibration, increasing the levitation probability.

The results of the experiments and analyses have shown that installing permanent magnets cannot obtain vibration suppression effects in the center in the longitudinal direction. However, it has confirmed that in a case where, at the time of bending, permanent magnets are installed in parts of the plate with relatively high stiffness, vibration suppression effects are obtained, improving levitation performance.

Figure 19 shows the results in a case where permanent magnet locations were varied in the longitudinal direction of the steel plates at the center of the short side as shown in Fig. 18. The same figure confirmed the improvement of levitation performance at all points. From this, it can be stated that it is effective to install permanent magnets on bending magnetic levitation steel plates at parts of the plates where stiffness is relatively high.

6. Conclusions

This paper reports an attempt to specify and solve principal vibration of a levitation steel plate based on static deflection analysis and levitation control experiments in order to improve the levitation performance of steel plates during bending levitation. The study obtained the following results.
1) It is possible to reduce the high frequency vibration that has occurred dominantly during bending levitation by increasing the stiffness of the ends of the center of the longitudinal direction.

2) Considering the result of 1), making the angle of tilt of electromagnets asymmetrical can partially increase the stiffness at a specified tilt angle, reducing vibration.

3) In consideration of ease of modeling, in a symmetrical bending levitation experiment in which a permanent magnet is installed, it has been confirmed that installing permanent magnets to perform levitation experiments improves levitation performance, and based on the results of static deflection analysis using FDM, it was possible to propose a placement location method.

From the above results, it was found that the method of suppressing the vibration in the range where the attraction force of the electromagnet does not reach by using the permanent magnet is useful in the bending magnetic levitation system for thin steel plate.

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References