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# Vibration of Thin Steel Plate Under Magnetic Field Using Permanent Magnets

by

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**Abstract**

In this study, the vibration of a thin steel plate under a magnetic field using permanent magnets was examined. In particular, the effects of the polarity and arrangement of the magnets were considered. On the basis of the result of the basic study using a single-degree-of-freedom model, a steel plate was examined. The attractive force of the permanent magnets was analyzed by the finite element method, and the vibration of the steel plate was calculated by the finite difference method. To verify the usefulness of a permanent magnet system, experiments were performed on a steel plate. As a result, it was confirmed that the permanent magnets could increase the damping factor of the vibration of the steel plate.

***Keywords***: Permanent Magnet, Arrangement of Magnets, Steel Plate, Aluminum Plate, Damping, FEM

## 1. Introduction

Thin steel plates are currently widely used in industries such as those of automobiles, electrical appliances and structural materials. Due to the increasing demand from various fields, the required surface quality has been increasing. However flaws on the plate surface and peeling during the surface treatment process are induced due to the use of many rollers in the conveyance process . These lead to deterioration of the quality of the plate surface. Under such circumstances, a new method involving the application of electromagnetic technology is under consideration for improving the surface quality of steel plates, the deterioration of which has been observed in the conventional contact conveyance system[(1)-(3)]. The authors discuss the magnetic levitation control of a rectangular steel plate, in which the two sides facing each other are reinforced using beams, and report the feasibility of levitation and the suppressive effect of elastic vibration[(4)].

The use of a limited number of electromagnets cannot suppress static deflection and high-order-mode elastic vibration, which are the characteristics of a flexible magnetic material. Under such circumstances, we propose the use of the magnetic force of permanent magnets for the stable levitation of steel sheets, by distributing permanent magnets in the areas where the attractive force of electromagnets is negligible, as shown in Fig. 1[(5)]. It has been reported that the vibration characteristics of levitated steel plates change due to the effect of permanent magnets[(6)-(11)]. However, those reports concerned only the cases in which the polarity of the permanent magnets was uniformly arranged. The effect of polarity and the arrangement of polarity was not discussed.

In this initial stage of our research, a small part of a steel plate is the subject of this study, instead of targeting the entirety of a relatively large steel plate (Fig. 1) levitated by magnetic force. Based on this, fundamental discussion on the effect of the permanent magnet on the vibration characteristics of a steel plate is carried out. First, it is assumed that the steel plate is subjected to translational motion. Experimentation and numerical analysis were carried out using a rigid steel plate supported by coil springs, to investigate the effect of permanent magnets on the vibration of the steel plate. In addition, to examine the validity of the analytical method adopted in this study, a comparative experiment using an aluminum plate, on which static attractive force of the permanent magnet does not act, was also carried out.

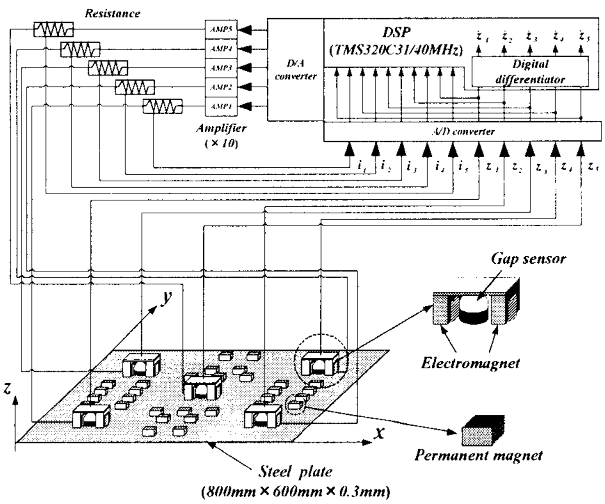


**Fig.1** Electromagnetic levitation control system for a rectangular sheet steel with permanent magnets.

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## 2. Modeling and characteristics of attractive force of permanent magnet

2.1 Experimental apparatus and analytical model

To examine the effect of permanent magnets on the magnetically levitated steel plates under translational motion, the experimental apparatus shown in Fig. 2 was manufactured. A thin steel plate (100 mm × 100 mm × 0.3 mm) was reinforced using an acrylic board of the same dimensions, so that the thin steel plate could be considered to be a rigid body. Permanent magnets (30 mm × 30 mm × 15 mm) with a surface flux density of 0.12 T were arranged as shown in Fig. 3. Inexpensive ferrite permanent magnets were used in consideration of practical applicability. In Fig. 3(a), all of the permanent magnets are arranged so that the N pole is upwards (4N arrangement, hereafter), while in Fig. 3(b), N and S poles are arranged alternately (NS arrangement, hereafter). The distance between the steel plate and the permanent magnet (gap, hereafter) was varied within the range of 45 and 60 mm, to examine the corresponding change in the vibration characteristics of the steel plate.

The equations of motion of this model are represented as

$$m\ddot{\xi} + c\dot{\xi} + k\xi = f_m + f_e \qquad (1)$$

using the attractive force of the permanent magnet as the external force applied to the steel plate, $f_m$, and Lorentz force, $f_e$. Here, $m$ is the sum of the masses of the steel plate and acrylic board, $c$ the damping coefficient of the coil spring, $k$ the spring constant of the coil spring. For the aluminum plate, since no attractive force of the permanent magnet acts on the aluminum plate, $f_m = 0$. For the numerical analysis of the plate under translational motion, the finite difference method is used. Table 1 lists parameter values used in the numerical analysis. For the analysis of the magnetic field and postprocessing, Photon EDDY (Photon Co. Ltd.) and FEMAP (Enterprise Software Products, Inc.) were used, respectively.

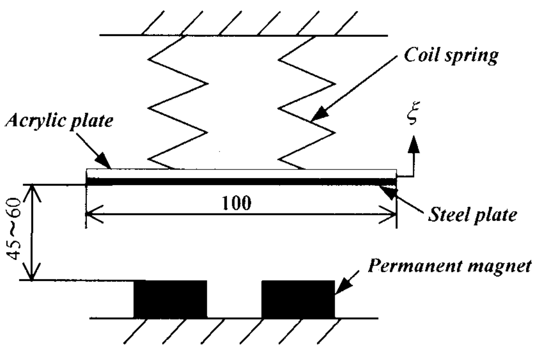
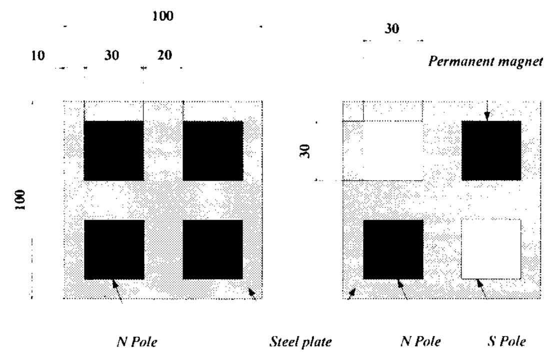



**Fig.2** Experimental apparatus.




(a) 4N arrangement (b) NS arrangement

**Fig.3** Arrangement of the magnets.

**Table 1** Parameters of steel plate and aluminum plate.

| | Steel plate | Alminum plate |
|---|---|---|
| $m$ [kg] | $8.41\times10^{-2}$ | $11.53\times10^{-2}$ |
| $c$ [Ns/m] | $1.08\times10^{-2}$ | $1.03\times10^{-2}$ |
| $k$ [N/m] | 83.10 | 83.10 |

2.2 Characteristics of attractive force of permanent magnet

Attractive force is calculated by measuring the change in the dead weight of a thin steel plate when it is fixed on an electronic mass balance and permanent magnets are brought near it, as shown in Fig. 4. Figure 5 shows the experimental results of attractive force along with the results obtained by the analytical method explained above. The two sets of results are in good agreement.

With a decreasing gap, the attractive force increases nonlinearly. The attractive force of the NS arrangement sharply increases at a gap of approximately 50 mm or less. The attractive force of the NS arrangement is increased by a maximum of 55% compared with that of the 4N arrangement. The reason for this is discussed below.

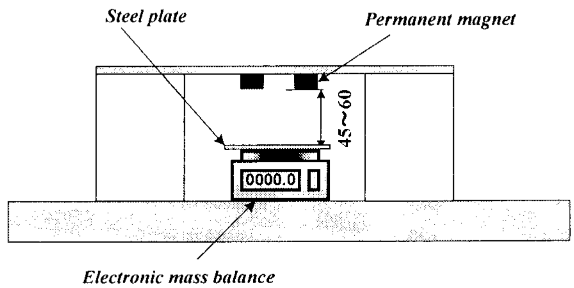



**Fig.4** Measuring device of attractive force of the permanent magnets.

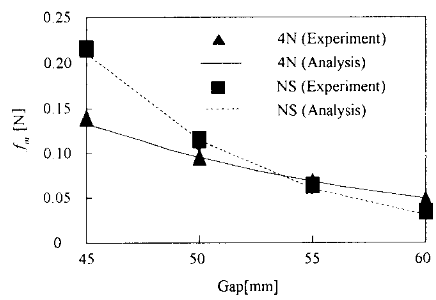



**Fig.5** Attractive force of permanent magnet.

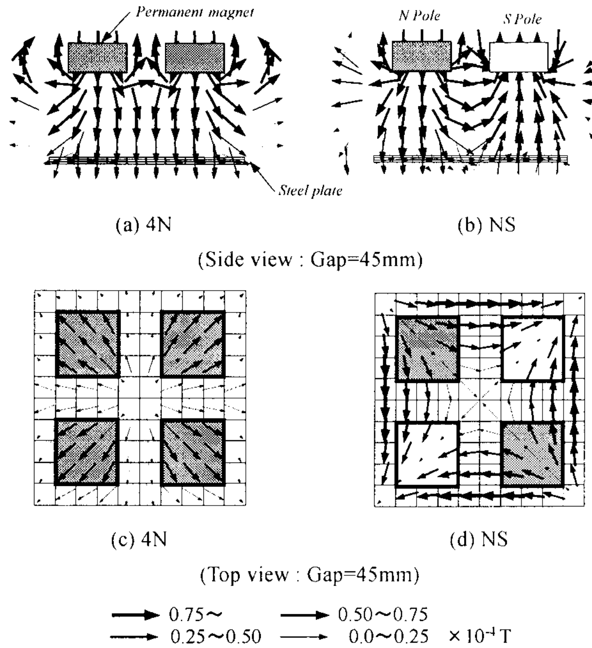



**Fig.6** Distribution of magnetic flux flow.

Figure 6 shows the distribution of magnetic flux flow when the gap is 45 mm. Figures 6(a) and 6(b) show views from the side of the steel plate (side view) and Figs. 6(c) and 6(d) show views from the top (top view). The thickness and length of the arrow indicate the magnitude of the magnetic flux.

When the gap is small, in the 4N arrangement (Fig. 6(a)), no magnetic circuit is constructed and much leakage flux is generated due to the same polarity, leading to a decrease in the amount of magnetic flux applied to the steel plate. In the NS arrangement (Fig. 6(b)), a magnetic circuit is efficiently constructed, as a result, the amount of leakage flux decreased and that of magnetic flux applied to the steel plate increases, leading to an increase in attractive force.

When the gap is large, in the NS arrangement, a magnetic circuit is effectively constructed; as a result, magnetic flux is absorbed by the S pole before it reaches the steel plate. When the gap is larger than the threshold value (Gap = 52 mm or larger in Fig. 5), the attractive force of the 4N arrangement is stronger than that of the NS arrangement.

## 3. Experiment and numerical analysis

### 3.1 Discussion on steel plate

Figures 7 and 8 show apparent spring coefficient, $k_s$, and apparent damping coefficient, $c_s$, respectively, measured using the free vibration waveforms of steel plates in a system in which permanent magnets are included. The solid and dotted lines indicate the analytical results. Figure 9 shows one example of time histories of the steel plate when the gap is 45 mm and without magnet (experimental results). The ∞ symbol on the abscissa in Figs. 7 and 8 indicates that no permanent magnets were in place. The vertical line indicates the standard deviation of 30 experimental values. The finding that the experimental and analytical results are in good agreement for both $k_s$ and $c_s$ demonstrates that our analytical method is valid.

The apparent spring coefficient, $k_s$, decreases with decreasing gap; $k_s$ at a gap of 45 mm is approximately 20% less than that in the case when no permanent magnets were in place, which confirms that the attractive force of the permanent magnets act as a negative spring. At a gap of approximately 55 mm or less, $k_s$ of the NS arrangement is lower than that of the 4N arrangement by approximately 6% at maximum. This phenomenon is a result of the characteristics of the attractive force, as shown in Fig. 5.

The apparent damping force, $c_s$, or damping effect increases, with a decreasing gap. It is considered that with a decreasing gap, the amount of magnetic flux applied to the steel plate increases. Next, the damping force of the permanent magnets which is applied to the steel plate is discussed.

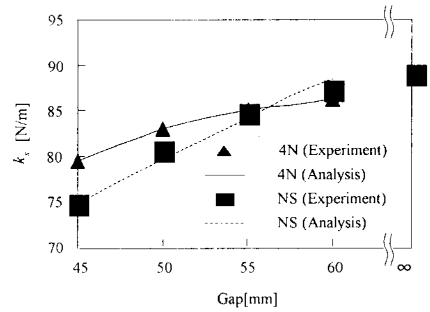



**Fig.7** Apparent parameters of spring coefficient(steel plate).

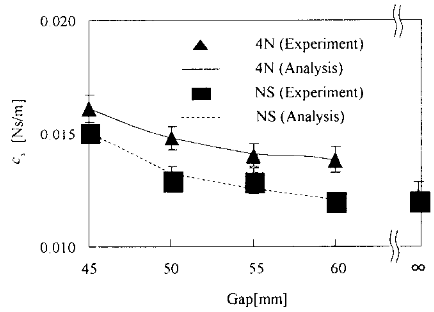
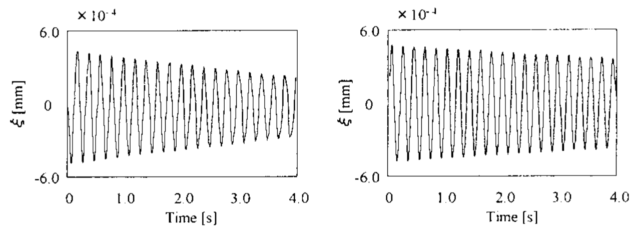



**Fig.8** Apparent parameters of damping coefficient (steel plate).




(a) Gap=45mm (b) Without magnet

**Fig.9** Time histories of the steel plate.

3.2 Results of aluminum plate in comparison with those of steel plate

In order to investigate the damping force of the permanent magnets applied to the steel plate, an experiment and analysis similar to those described in Section 3.1 are carried out using an aluminum plate on which the static attractive force of permanent magnets does not act. The results are shown in Figs. 10 and 11. Since the attractive force of permanent magnets does not act on the aluminum plate, the $k_x$ values remain almost constant for various gap values for both 4N and NS arrangements. In contrast, the change in $c_x$ with gap exhibits a similar tendency to that observed in the case of the steel plate; Lorentz force, $f_e$, which acts on both steel and aluminum plates, affects the increase in $c_x$. The change in $c_x$ is large for the 4N arrangement compared with that for the NS arrangement.

3.3 Polarity of permanent magnet and damping force

In this section, the effect of the polarity of the permanent magnets on the damping force is discussed. Figure 12 shows the eddy current observed on the rigid steel plate in translational motion with a maximum speed of 0.04 m/s when the gap is 45 mm.

As shown in Fig. 12(a) the four permanent magnets act as if they are a single permanent magnet in the 4N arrangement and one eddy current is formed. In contrast, in the NS arrangement, since the arrangement of polarities of N and S poles differ, the directions of eddy currents for each pole are in opposite directions. Figure 13 shows an example of the Lorentz force generated in this study. The Lorentz force of the 4N arrangement is larger by approximately 70% at maximum compared with the case of the NS arrangement; along with this, greater damping force is obtained with the 4N arrangement.

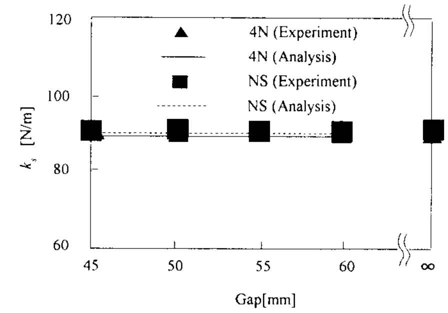



**Fig.10** Apparent parameters of spring coefficient(aluminum plate).

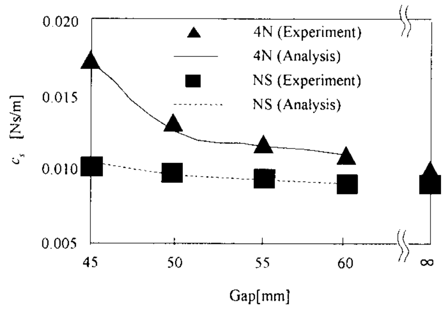
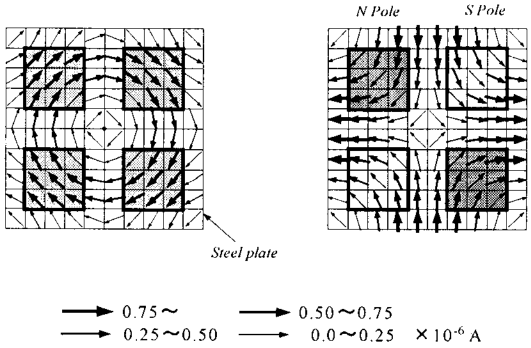
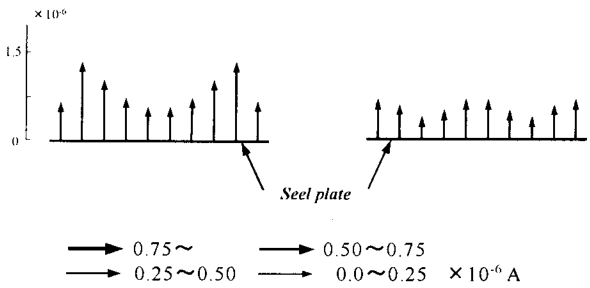



**Fig.11** Apparent parameters of damping coefficient (aluminum plate).




(a) 4N arrangement (b) NS arrangement

**Fig.12** Distribution of eddy current on steel plate(Top view).




(a) 4N arrangement (b) NS arrangement

**Fig.13** Distribution of Lorenz force on steel plate(Side view : Gap=45mm).

## 4. Conclusions

The ultimate goal of this study is to realize the stable levitation of thin steel plates in a magnetic levitation system in which electromagnets are used together with permanent magnets. In the primary stage of our research, the effect of the placement of permanent magnets on the vibration characteristics of the steel plate was examined theoretically and experimentally in this study, targeting steel plates under translational motion. The results indicate that when the strength of the obtained attractive force is of concern, the alternating arrangement of N and S poles, i.e., the NS arrangement, is more advantageous since the magnetic circuit is more effectively constructed. When damping effect is of concern, the arrangement of the permanent magnets with all N poles upward, i.e., the 4N arrangement, is necessary to effectively generate Lorentz force.

The results of this study indicate a trade-off between attractive force and damping force, which must be considered when designing a system. Based on the results of this study, we will widen the range of our research to include steel plates under elastic vibration, considering practical application. Furthermore, we plan to examine the optimal number of permanent magnets, the level of magnetic flux density and the optimal size of the permanent magnet with respect to the size of the steel plate, and to present fundamental data of permanent magnets used together with electromagnets in a magnetic levitation system for thin steel plates.

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