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Noncontact Guide for Traveling Continuous Steel Plates Using Electromagnets Placed Asymmetrically at the Positions Where Traveling Direction of Plate Changes

by

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Abstract

Recently, along with high-end products, users demand high quality and high added value manufactured by the continuous steel plate process. In the factory, the continuous thin steel plates are subjected to iron and steel processes is supported by a series of rollers during processes such as plating and rolling. However, because the rollers come in contact with the steel plates, the problem of surface quality deterioration arises. To solve this problem, we developed a non-contact guide system for parts of the steel plate at which its traveling direction changes in high-speed traveling by applying an electromagnetic force from the direction of the edge of the thin steel plate, and experimentally examined the effectiveness of the system. In this study, a basic examination of the technique for forming a guideway using asymmetric placement of electromagnets, in which the change in the uncontrolled loop shape is considered, was carried out. By comparing the results for guideways with several different arrangement of the electromagnets, the effect of the guideway shape on the vibration suppression performance of the steel plate was discussed experimentally. As a result, it was confirmed that the vibration suppression performance of the steel plate can be improved by adjusting the shape of the noncontact guide system that uses asymmetric placement of electromagnets to conform with that of the loop of the uncontrolled steel plate.

Keywords: Steel plate, Electromagnet, Traveling, Noncontact guide, Vibration control device

1. Introduction

The length of the production line of a continuous steel plate in iron mills can reach 2-3 km, and the continuous steel plate travels in contact with and supported by rollers. However, in contact-support traveling using rollers, many problems arise, for example, the deterioration of surface quality owing to contact between the steel plate and the roller. To find methods to solve this problem, research and development on the noncontact conveyance system of belt steel using a floater, whereby a belt steel is floated using a fluid, have been carried out[1)]. However, problems in the occurrence of wind ripples and irregularities on the surface of steel plates in processes such as plating are unavoidable. Meanwhile, as an application of magnetic technology to iron-making process lines, shape control and vibration-suppression control of strips[2,3)] and the suppression of the vibration of a long stationary steel plate using electromagnets [4,5)] have been studied. Researchers in our laboratory have examined noncontact edge control by applying an electromagnetic force near the edge of a continuous steel plate traveling along a straight line in order to suppress its vibration[6,7)]. We also confirmed the effectiveness of the noncontact guide that is used to change the traveling direction of the traveling continuous steel plate and that has functions similar to those of sink rolls, on the vibration suppression of the steel plate[8,9)]. However, to improve the surface quality, a more stable vibration suppression performance of the actual equipment is required in processes such as drying and plating.

In the previous studies, we have confirmed that the loop shape of the traveling steel plate under the condition without

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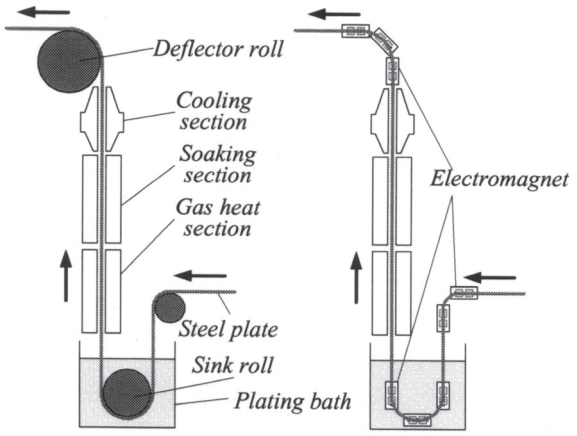

(a)With roll (b) With electromagnet

Fig. 1 Manufacturing process of continuous steel plates

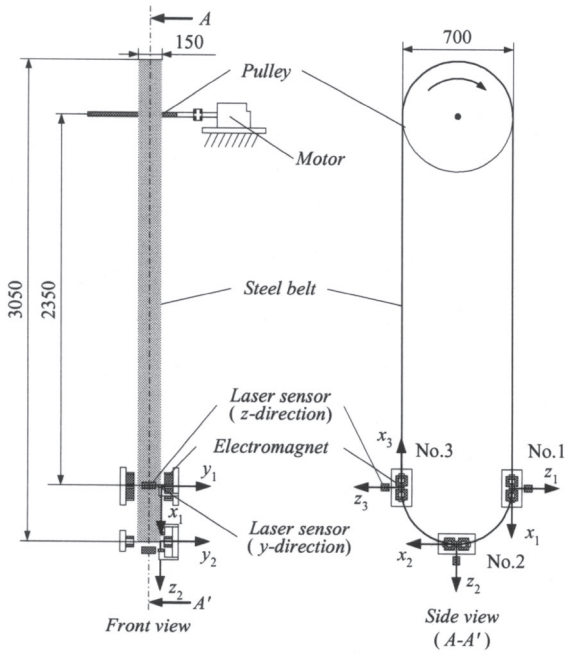

Fig. 2 Schematic illustration of noncontact guide system

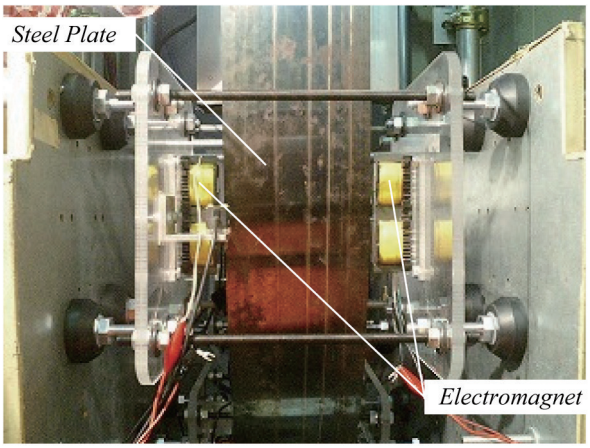

Fig. 3 Photograph of noncontact guide system

control changes at the section where the traveling direction of the steel plate changes[10-12].

In this study, we constructed the guideway using electromagnets taking into consideration the loop shape, and examined the effect of the difference in the guideway shape on vibration suppression.

2. Noncontact Guide System

2.1 *Experimental apparatus*

As shown in Fig. 1(a), in the plating process for continuous steel plates in a production line, a steel plate is contact-supported by a deflector or sink rolls. In this study, we aim to form a noncontact guide path using electromagnets at the roll sections as shown in Fig. 1(b). We prepared an experimental setup that simulates the plating bath through which the continuous steel plate passes, as shown in Fig. 2. A continuous steel plate produced by welding a quenched steel plate (SK3) with the dimensions of 6,894 mm (length) × 150 mm (width) × 0.3 mm (thickness) into a belt shape is suspended by a pulley with a diameter of 700 mm and a width of 154 mm, as shown in Fig. 2. The width of the steel plate is set at 150 mm in this experiment to reduce deformation and elastic vibration in the direction perpendicular to the traveling direction on the plane of the steel plate and to clarify the effects of the edge control system on loop-shaped sections. The pulley is driven by a DC servomotor, enabling endless traveling of the continuous steel plate. The electromagnets were placed at the three positions (Nos. 1, 2, and 3) indicated in the figure. x_1, x_2, and x_3 indicate the coordinates of the traveling direction of the steel plate at the three electromagnet positions. Similarly, y_1, y_2, and y_3 indicate the coordinates perpendicular to the traveling direction and on the same plane as the steel plate at the three electromagnet positions (hereafter, this direction is called the y direction). z_1, z_2, and z_3 indicate the coordinates perpendicular to the plane of the steel plate at the three electromagnet positions (hereafter, this direction is called the z direction).

Electromagnets are pressed in place from inside the system, using two acrylic plates and anti-vibration pads against the two plates outside the continuous steel plate. The electromagnets can be placed arbitrarily along the surface of the acrylic plates, as shown in Fig. 3.

2.2 *Noncontact edge control system*

A displacement in the y direction of the traveling steel plate is subjected to active control by electromagnets. The control system is shown in Fig. 4. In this experiment, a pair of serially connected electromagnets[7] is placed facing each

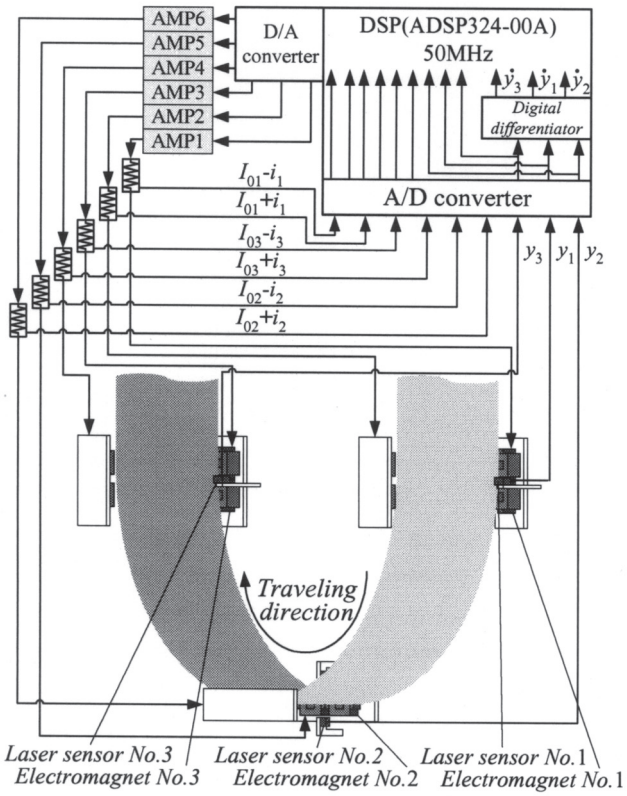

Fig. 4 Control system of noncontact guide

other near the two edges of the continuous steel plate in order to supplement the lack of attractive force. At the three electromagnet positions, the distance between the electromagnet surface and the edge of the continuous steel plate is maintained at 5 mm using two pairs of electromagnets. The information on displacement, traveling speed, and current are only fed back to the local electromagnets.

Moreover, in the z direction, the steel plate is guided from the initial position at the time of being stationary (represented by the dotted line in Fig. 3, right figure) toward the center of the electromagnet coil (solid-line position). This is because a magnetic field generated by y-directional positioning control acts as an attractive force toward the coil force acting on the steel plate in the z direction is center in the z direction[13]. Here, the range of this attractive experimentally confirmed to be approximately the outermost circumference of the electromagnetic coil used in this experiment.

3. Modeling

Figure 5 shows a model diagram at an arbitrary electromagnet position. In this study, the same modeling is applied at all the three positions. The mass of the continuous steel plate passing between two electromagnets placed near

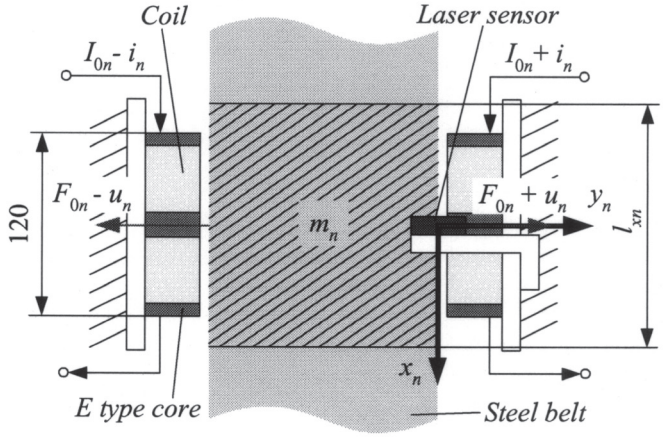

Fig. 5 Model of noncontact guide

the two edges of the steel plate is represented by m_n [kg], thelength of the corresponding area of the steel plate in the traveling direction is represented by l_{xn} [m], and n (n = 1, 2, 3) represents the locations of the electromagnets. A translation model in the y_n direction with one degree of freedom, where the controlling force applied from the electromagnets is assumed to be u_n as shown in Fig. 5, was developed. Here, an equilibrium state exists, in which the distance between the edge of the steel plate and the surface of the electromagnet is maintained constant because the steel plate is drawn by the attractive force generated by the stationary electric current I_{0n} that flows in the electromagnets positioned at both sides of the steel plate. The equation of motion in the y_n-axis direction from this equilibrium state is expressed as

$$m_n \ddot{y}_n = 2u_n \quad . \tag{1}$$

Here, u_n is the variation [N] in the total attractive force of the two electromagnets positioned at one side near the edge of the steel plate. In addition, the characteristic equations of the electromagnet are linearized as[7]

$$u_n = \frac{F_{0n}}{\Gamma_{0n}} y_n + \frac{F_{0n}}{I_{0n}} i_n \quad , \tag{2}$$

where F_{0n}: total stationary attractive force [N] in the equilibrium state generated by two electromagnets, Γ_{0n}; gap between steel plate and electromagnet in the equilibrium state [m], I_{0n}; current in the equilibrium state [A], and i_n: dynamic current of the coupled magnets [A].

Then, we obtain the state equation below by using the displacement and velocity of the steel plate as state variables and organizing eqs. (1) and (2). Where v_n: voltage of the electromagnet coil [V] and R_n: voltage of the electromagnet coil [Ω].

$$\dot{\boldsymbol{y}}_n = \boldsymbol{A}_{yn}\boldsymbol{y}_n + \boldsymbol{B}_{yn}v_n \tag{3}$$

$$\boldsymbol{y}_n = \begin{bmatrix} y_n \\ \dot{y}_n \end{bmatrix}, \quad \mathbf{A}_{yn} = \begin{bmatrix} 0 & 1 \\ \dfrac{2F_{0n}}{m_n \Gamma_{0n}} & 0 \end{bmatrix},$$

$$\mathbf{B}_{yn} = \begin{bmatrix} 0 \\ \dfrac{2F_{0n}}{m_n I_{0n} R_n} \end{bmatrix}$$

4. Control Theory

With the optimal control theory, we obtain the control voltage ${}^{\circ}v_{\mathrm{fd}n}$ that minimizes the quadratic-form evaluation function $J_{\mathrm{d}n}$ shown below. Here, the subscript d indicates discretization, and its sampling frequency is set to be 1.0 x 10^{-3}s.

$${}^{\circ}v_{\mathrm{fd}n}(k) = -\boldsymbol{K}_{\mathrm{d}n}\boldsymbol{y}_{\mathrm{d}n}(k) \tag{4}$$

$$\left.\begin{aligned} J_{\mathrm{d}n} &= \sum_{k=0}^{\infty}\left\{\boldsymbol{y}_{\mathrm{d}n}(k)^{\mathrm{T}}\,{}^{\circ}\boldsymbol{Q}_n\boldsymbol{y}_{\mathrm{d}n}(k) + {}^{\circ}r_n\,{}^{\circ}v_{\mathrm{fd}n}(k)^2\right\} \\ {}^{\circ}\boldsymbol{Q}_n &= \mathrm{diag}\left({}^{\circ}q_{yn} \quad {}^{\circ}q_{vn}\right) \end{aligned}\right\} \tag{5}$$

Here, $\boldsymbol{K}_{\mathrm{d}n}$: Feedback matrix, ${}^{\circ}q_{\mathrm{yn}}$: weighting factor regarding displacement, ${}^{\circ}q_{\mathrm{vn}}$: weighting factor regarding velocity, and ${}^{\circ}r_{\mathrm{n}}$: weighting factor regarding control input.

The parameter about an experimental device and each control theory is shown in Table 1.

Table 1 The symbols and values

Symbol	Value	Symbol	Value
m_n	0.042kg	L_n	2.3×10^{-2}H
F_{0n}	1.7N	${}^{\circ}q_{yn}$	$14..5\times10^{6}\mathrm{m}^{-2}$
Γ_{0n}	5.0×10^{-3}m	${}^{\circ}q_{vn}$	$16.7\times10^{5}\mathrm{s}^{2}/\mathrm{m}^{2}$
I_{0n}	0.5A	${}^{\circ}r_n$	$1.0\times10^{4}\mathrm{V}^{-2}$
R_n	20Ω		

(n =1, 2, 3)

5. Traveling Experiment

5.1 *Experimental conditions*

To examine the effect of the shape of the guide at the positions where the traveling direction changes and the placement of the electromagnets on the suppression of vibration of the continuous steel plate in the z direction, the following three conditions in terms of guide shape and placement of electromagnets were examined; namely, (A) electromagnets were placed along the semicircular shape at positions θ = 0, 90, and 180°, similar to the case of using a roller, (B) electromagnets were placed asymmetrically at positions θ = 0, 85, and 165°, along the loop of a steel plate when it is traveling at a high speed of approximately 1000 m/min, and (C) electromagnets were placed asymmetrically at positions θ = 10, 110, and 180°, along the loop of a steel plate when it is traveling at a high speed of approximately 1000 m/min, as shown in Fig. 6. The reasons for placing the electromagnets at θ = 0, 85, and 165° under condition (B) are as follows: for electromagnet No. 1, the position is the same as that of No. 1 in arrangement (A); electromagnet No. 2 is placed at the lowest position of the plate when it is not traveling; position No. 3 in arrangement (B) is far from that in arrangement (A). The positions of the electromagnets under arrangement (C) are determined considering the experimental results obtained under arrangements (A) and (B). The traveling speed of the steel plate was set at 1000 m/min in this experiment, at which the uncontrolled steel plate travels with the shapes shown in Figs. 6(B) and 6(C). Then, the effect of the difference in the arrangement of the electromagnets on the vibration suppression of the plate is examined. The displacement of the steel plate in the z direction is measured in the range of θ = 0 - 180° at 15° intervals in the three arrangements (A)-(C).

5.2 *Experimental results and discussion*

Figure 7 shows the relationship between θ and the standard deviation of displacement in the z direction at each measurement point when the continuous steel plate is controlled under the conditions explained in 5.1.1. The standard deviation of displacement observed under arrangement (B) is smaller than that observed under arrangement (A) at all measurement points. At θ = 180°, where the difference in the standard deviation between arrangements (A) and (B) is the largest, the standard deviation under arrangement (B) is 24% smaller than thatunder arrangement (A). The standard deviations observed under arrangement (C) are smaller than those observed under arrangement (B) at 11 of 13 measurement points. Furthermore, at θ = 180°, the standard deviation under arrangement (C) is 23% smaller than that under arrangement (B), and 41% smaller than that under arrangement (A).

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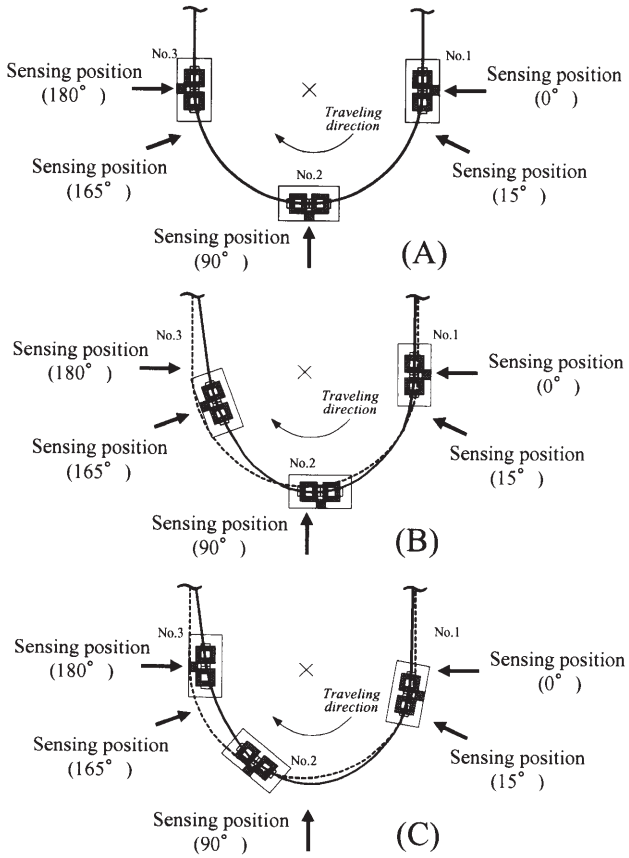

Fig. 6 Arrangement of electromagnets

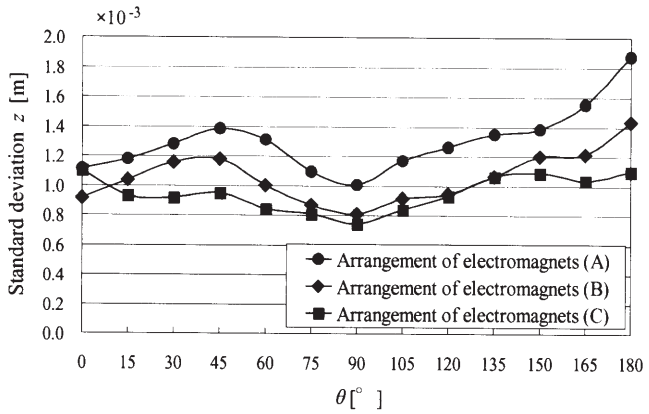

Fig.7 Standard deviation of displacement z

arrangements (A) and (B) is the largest, the standard deviation under arrangement (B) is 24% smaller than that under arrangement (A). The standard deviations observed under arrangement (C) are smaller than those observed under arrangement (B) at 11 of 13 measurement points. Furthermore, at θ = 180°, the standard deviation under arrangement (C) is 23% smaller than that under arrangement (B), and 41% smaller than that under arrangement (A).

As discussed above, we can confirm the effect on the suppression of vibration in the z direction by placing the electromagnets asymmetrically, as shown in Fig. 6(C), so that the shape of the noncontact guide using electromagnets conforms to that of the loop of the uncontrolled traveling steel plate.

6. Conclusions

In this study, we examined the effect of electromagnets placed asymmetrically at positions where the traveling direction changes on the suppression of the vibration of the traveling steel plate by considering the shape of the uncontrolled traveling steel plate.

The results indicate that the suppression of the vibration in the z direction, in which no active control is performed, was confirmed using electromagnets under arrangement (C), compared with those under arrangements (A) and (B), by positioning the electromagnets asymmetrically so that the shape of the noncontact guide conforms to the shape of the uncontrolled traveling steel plate.

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