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Study on Noncontact Support and Transportation of a Rectangular Thin Steel Plate

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Abstract

Cold-rolled steel sheets, such as steel plates for automobiles, are conveyed on rollers to undergo many processes, such as rolling, plating, coating and drying and ultimately, the steel plates are rolled as products. In this type of continuous-web handling system, production lines are generally constructed for the purpose of improving production yield and productivity while suppressing energy loss, coating nonuniformity and flaws as much as possible. However, these problems have conventionally been tackled via experience-based techniques accumulated at each production site and systematic approaches to cope with these problems have not been sufficiently developed. 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. In this thesis, we discuss two aspects concerning the electromagnetic levitation control of a sheet steel which authors have been studying recently, that is, noncontact vibration control of a thin steel plate and noncontact horizontal positioning control of a transported thin steel plate.

Key Words: Optimal Control, Steel Plate, Electromagnetic Levitation, Noncontact Vibration Control, Elastic Vibration, Spillover, Suboptimal Control,Transportation, Positioning Control

1. *Introduction*

In recent years, innovative magnetic levitation techniques have been developed and applied to various contactless modes of transport. These techniques also make a large contribution toward promoting innovation in technology. For example, applications to contactless suspension of a traveling thin steel plate, which is widely used in the manufacture of various industrial products, especially steel works, are possible.

Cold-rolled steel sheets, such as steel plates for automobiles, are conveyed on rollers to undergo many processes, such as rolling, plating, coating and drying; ultimately, the steel plates are rolled as products. In this type of continuous-web handling system, production lines are generally constructed for the purpose of improving production yield and productivity while suppressing energy loss, coating nonuniformity and flaws as much as possible. However, these problems have conventionally been tackled via experience-based techniques accumulated at each production site; therefore, systematic approaches to cope with these problems have not been sufficiently developed, thus far. 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[1-4]. We experimentally examined noncontact support control of a continuous-web system by simulating a continuous heat-treatment process for steel plates actually performed at steel works, and reported the feasibility of noncontact support control [5,6]. Based on the study, we concluded that the suppressive effect of elastic vibration of the processed

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objects should be further improved to increase the performance of noncontact support control of thin steel plates. However, in practice, since the steel plates are very thin, elastic vibrations of the steel plates cannot be sufficiently suppressed using only a limited number of electromagnets. Needless to say we must eliminate, as much as possible, the elastic vibration of the processed objects by applying the control theory. Thus far, no experiment in which elastic vibration is actively generated and then suppressed in magnetic levitated steel plates has been carried out. Therefore, we fabricated equipment which enables the generation of elastic vibration via forced input of disturbance to a levitated thin steel plate, so that the suppressive effect on the elastic vibration could be examined. In chapter 2, the equipment was designed so that the electromagnets, which are used for magnetic levitation of a nonsupported steel plate with free edges, vibrate vertically. This mechanism may be realized as, for example, a robot arm with a magnetic levitation mechanism (noncontact grip mechanism) on its tip, where vibrations in the vertical direction are transmitted from the arm to the steel plate. Note that the motion of the steel plate in the horizontal direction, in other words, conveyance of the steel plate, was not taken into consideration in this chapter. Two models of the steel plate were considered: a single-degree-of-freedom model in which design of the control system is simplified through consideration of centralized control at the location of the electromagnet, and a continuous model which expresses the motion of the steel plate by means of equations in which the original elastic vibrations of the plate are considered. By applying the optimal control theory to these models, the superiority of the models with respect to the suppressive effect of elastic vibration was examined. Since only a limited number of elastic vibration modes, the number of which is equal to the number of sensors, can be considered in the optimal control system of a continuous model in which observers are not included, the excess elastic vibration modes may induce a spillover problem. We constructed a system which can control a mode that is difficult to control using the controller described above. Therefore, suboptimal control is applied in which spillover of elastic vibration is considered, the experimental results obtained using optimal control and suboptimal control are compared, and the applicability of the suboptimal control is discussed.

In chapter 3 ,the authors proposed a horizontal noncontact positioning control system for a magnetically levitated steel plate. A zinc-coated steel plate is levitated and positioned in a contactless manner by attractive forces of electromagnets which are controlled by feedback signals from gap sensors. For the basic examinations, sheet steel was reinforced by light carbon pipes in this chapter. The electromagnetic attractive control forces of the noncontact positioning control actuators are applied to the two forced edges of the levitated steel plate from the horizontal direction. By assuming that the interaction of levitation control with horizontal positioning control could be disregarded, each control system was independently designed as a one-degree-of-freedom system by applying the optimal control theory. To verify the usefulness of the proposed system, a digital control experiment was performed. Levitated steel plates subjected to horizontal random excitation and during transport were considered. The disturbance was found to be sufficiently suppressed and the offset displacement during transport to be reduced as a result of using the proposed horizontal positioning controller.

2. Noncontact vibration control of thin steel plate

2.1 Control System

A schematic illustration of the electromagnetic levitation control system is shown in Fig.1. A zinc-coated steel plate (length 800mm, width 600mm, thickness 0.3mm, material SS40 steel) is levitated in a contactless manner by attractive forces of electromagnets which are controlled by feedback signals from gap sensors. In this study , for the basic examinations, the steel plate was reinforced by three pipes in order to suppress the elastic vibrations in the y-axis direction. The dotted lines in the steel plate shown in Fig. 1 are the pipes made of light carbon fiber. The total weight of the carbon pipes is about 4% of the steel plate mass. It was confirmed that the influence of attaching a pipe to the steel is

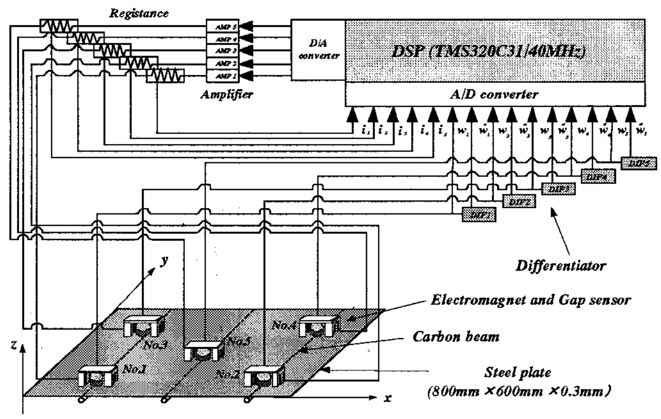


Fig.1 Electromagnetic levitation control system

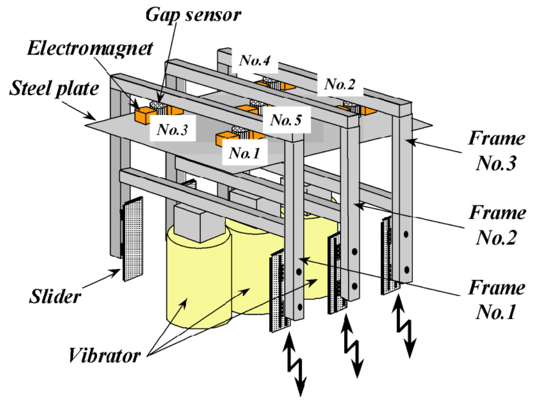


Fig.2 Experimental apparatus of noncontact vibration control

negligible when low-order modes, such as first- and second-order modes, are considered.

The vertical displacement of the plate, its velocity and the current through the magnet are acquired using five eddy-current-type displacement sensors, five differentiators and five resistors connected in series to the magnetic circuit, respectively. The total number of acquired values is fifteen. These values are converted from analog to digital in the sampling interval of 0.2ms to be processed in a digital signal processor. The control forces (voltage) are calculated in the DSP and are fed to the five electromagnets through the D/A converter and five power amplifiers. These sensors and electromagnets are installed in the frame shown in Fig.2. At the start of control, the steel plate is levitated to the equilibrium position, that is, its clearance between each electromagnet and the steel plate is 5mm (z=0mm)

2.2 Single -degree- of -freedom model

Single-degree-of-freedom model in which design of the control system is simplified through consideration of centralized control at the location of the electromagnet is considered. The steel plate is imaginarily divided into five parts, and each is modeled as a single-degree-of-freedom electromagnetic levitation model, as shown in Fig. 3. Consequently, the displacement, the velocity and the coil current detected at one electromagnet position are used for the control of the electromagnet. In this study, eddy current sensors are used to detect vertical displacements of the steel plate. There is the possibility of error in measurement due to the effect of electromagnetic field caused by electromagnets. In order to prevent measurement error an electromagnet is made, as shown in Fig.3, and each sensor is positioned at the

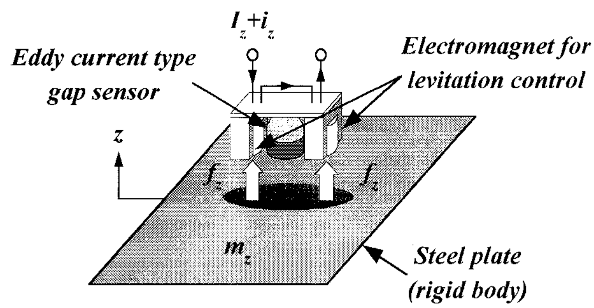


Fig.3 Single-degree-of-freedom model of the magnetic levitated steel plate

center of coupled magnets which generate the same attractive force f_z . It was confirmed that the influence for the control performance is negligible.

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

$$m_z\ddot{z} = 2f_z \tag{1}$$

where z: vertical displacement [m], f_z : dynamic magnetic force [N].

The number of turns of electromagnet coil is 1005 (diameter of wire is 0.5mm), and the sectional area passing the magnetic flux of the E-type core, which was made from ferrite, is 225mm^2. Characteristics of the electromagnet are estimated on the following assumptions:

(1) the permeability of a core is infinity; (2) the eddy current inside core is neglected; (3) the inductance of the electromagnetic coil is expressed as a sum of the component inversely proportional to the gap between the steel plate and magnet and the component of leakage inductance.

If deviation around the static equilibrium state is very small, the characteristic equations of the electromagnet are linearized as

$$f_z = \frac{F_z}{Z_0}z + \frac{F_z}{I_z}i_z \tag{2}$$

$$\frac{d}{dt}i_z = -\frac{L_{eff}}{L_z}\cdot\frac{I_z}{Z_0^2}\dot{z} - \frac{R_z}{2L_z}i_z + \frac{1}{2L_z}v_z \tag{3}$$

$$L_z = \frac{L_{eff}}{Z_0} + L_{lea} \tag{4}$$

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

2.3 Continuous model

Continuous model which expresses the motion of the steel plate by means of equations in which the original elastic vibrations of the plate is considered. At an equilibrium levitation state. magnetic forces are determined so as to balance with an elastic force and gravity. The equation of small vertical motion around the equilibrium state of the steel plate subjected to magnetic forces is expressed as follows

$$\rho h\frac{\partial^2}{\partial t^2}w+\frac{Ch^3}{12}\frac{\partial}{\partial t}\nabla^4 w+D\nabla^4 w$$
$$=\sum_{n=1}^{5} f_n(t)\{\delta(x-x_{a1n})\delta(y-y_{a1n})+\delta(x-x_{a2n})\delta(y-y_{a2n})\} \quad (5)$$

$$\nabla^4=\frac{\partial^4}{\partial x^4}+2\frac{\partial^4}{\partial x^2\partial y^2}+\frac{\partial^4}{\partial y^4}$$

where C : internal damping coefficient [Ns/m^2], D : $Eh^3/12(1\text{-}v^2)$ [Nm], E : Young's modulus [N/m^2],$f_n(t)$: dynamic magnetic force at the n-th coupled magnets [N], h : thickness [m]. $w(x,y,z)$: vertical displacement [m], x, y, z : coordinate axes indicated in Fig.1[m], x_{a1n}, x_{a2n}, y_{a1n}, y_{a2n} : location of the n-th coupled magnets (n=1,2,3,4,5) [m], $\delta()$: Dirac delta function [l/m], v : Poisson ratio, ρ: density [kg/m^3].

The characteristic equations of the electromagnets can be derived in much the same as the single-degree-of freedom model, that is

$$f_n=\frac{F_n}{Z_0}w(x_{sn},y_{sn})+\frac{F_n}{I_n}i_n \quad (6)$$

$$\frac{d}{dt}i_n=-\frac{L_{eff}I_n}{L_zZ_0^2}\frac{d}{dt}w(x_{sn},y_{sn})-\frac{R_z}{2L_z}i_n+\frac{1}{2L_z}v_n \quad (7)$$

where F_n : magnetic force of the coupled magnets in the equilibrium state[N], I_n : current of the coupled magnets in the equilibrium state[A], x_{sn}, y_{sn} :position of the n-th sensor[m], v_n : dynamic voltage of the n-th coupled magnets[V], i_n : dynamic current of the n-th coupled magnets[A]

2.4 State equation and controller for single-degree-of-freedom model

Using the state vector. the eqs. (1)-(4) are written as the following state equations:

$$\dot{z}=A_z z+B_z v_z \quad (8)$$

$$z=[z \ \ \dot{z} \ \ i_z]^T$$

$$A_z=\begin{bmatrix} 0 & 1 & 0 \\ \frac{2F_z}{m_zZ_0} & 0 & \frac{2F_z}{m_zI_z} \\ 0 & -\frac{L_{eff}}{L_z}\cdot\frac{I_z}{Z_0^2} & -\frac{R_z}{2L_z}\end{bmatrix}$$

$$B_z=\begin{bmatrix}0 & 0 & \frac{1}{2L_z}\end{bmatrix}^T$$

To design the controller based on the optimal control theory. the following criterion functions is chosen.

$$J=\lim_{t_f\to\infty}\int_0^{t_f}\left(z^TQ_zz+r_zv_z^2\right)dt \quad (9)$$

$$Q_z=diag\left(q_z \ q_{\dot{z}} \ q_{i_z}\right)$$

where q and r are weighting coefficients.

According to the optimal control theory, the optimal state feedback gain is determined by solving the Riccati equation. The optimal voltage of electromagnet is obtained as

$$v_z=-F_zz \quad (10)$$

2.5 State equation and controller for continuous model

The vertical displacement of the plate can be expanded to an infinite series of a space-dependent eigenfunction $\phi(x,y)$ as shown in Fig.4 multiplied by the time-dependent normal coordinate. The eigenfunctions of the plate are assumed to be products of the elastic beam eigenfunctions of the x- and y-coordinates. The function of x-coordinate $X_{mm}(x)(mm$=1,2, ⋯) satisfies the free-free boundary condition. and the function of the y-coordinate is expressed in rigid modes(parallel and rotational motions) $Y_1(y)$,$Y_2(y)$ only. The following eigenfunctions are chosen in this study:

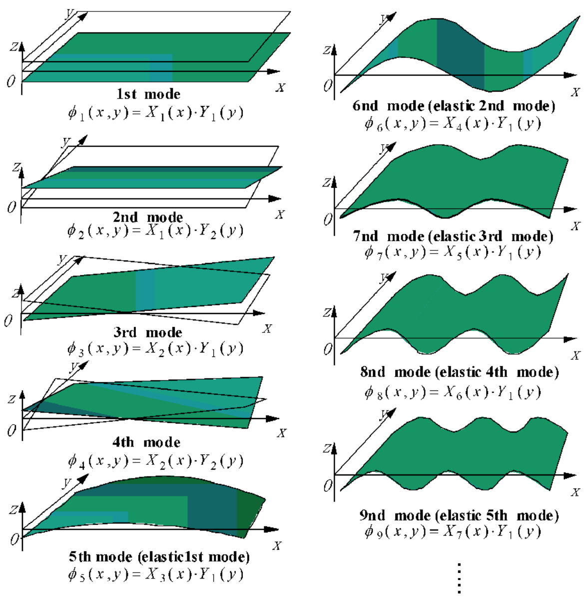


Fig.4 Mode shape for the continuous model of the magnetic levitated steel plate

$$w(x,y)=\sum_{i=1}^{M}\phi_i(x,y)W_i(t) \tag{11}$$

$$\phi_i(x,y)=X_{mm}(x)\cdot Y_{nn}(y)$$

$$(mm,\ nn=1,2,\cdots) \tag{12}$$

$$X_1(x)=1 \tag{13}$$

$$X_2(x)=\frac{\sqrt{3}}{a}(2x-a) \tag{14}$$

$$X_{mm}(x)=\cos\frac{\lambda_{xmm}}{a}x+\cosh\frac{\lambda_{xmm}}{a}x$$

$$+\frac{\sin\lambda_{xmm}+\sinh\lambda_{xmm}}{\cos\lambda_{xmm}-\cosh\lambda_{xmm}}\left(\sin\frac{\lambda_{xmm}}{a}x+\sinh\frac{\lambda_{xmm}}{a}x\right) \tag{15}$$

$$\cosh\lambda_{xmm}\cdot\cos\lambda_{xmm}=1$$

$$(mm=3,4,\cdots) \tag{16}$$

$$Y_1(y)=1 \tag{17}$$

$$Y_2(y)=\frac{\sqrt{3}}{b}(2y-b) \tag{18}$$

$$f_{xmm}=\frac{1}{2\pi}\left(\frac{\lambda_{xmm}}{a}\right)^2\sqrt{\frac{D}{\rho h}} \tag{19}$$

where a: length of the plate, b: width of the plate.

State variables of the system are normal coordinates of vertical displacement of the plate $W_i(t)(i=1,\cdots,M)$, their differential values and dynamic currents of the coupled magnet coils $i_n(t)$ $(n=1,2,3,4,5)$. The control input of the system is the dynamic voltages of the magnets $v_n(t)(n=1,2,3,4,5)$. Output variables of the system are vertical displacements $w_n(x_{sn},y_{sn},t)$ $(n=1,2,3,4,5)$ detected by the noncontact displacement sensor, their differential values and dynamic currents of the coupled magnet coils $i_n(t)$. Using the state, control and output vectors, the forgoing eqs. (4)~(7) are written as following state and output equations:

$$\dot{W}=AW+Bv \tag{20}$$

$$w=CW \tag{21}$$

$$W=\left[W_1\cdots W_M\dot{W}_1\cdots\dot{W}_M\,i_1\cdots i_5\right]^T$$

$$v=\left[v_1\cdots v_5\right]^T$$

$$w=\left[w_1,\cdots w_5\ \dot{w}_1\cdots\dot{w}_5 i_1\cdots i_5\right]^T$$

2.6 *Optimal control theory*

The optimal control theory is applied to the continuous model in the same manner as the single-degree-of freedom model. The number of elastic vibration modes which is equall to the number of sensors (M=5) can be considered in the optimal control system of a continuous model in which observers are not included.

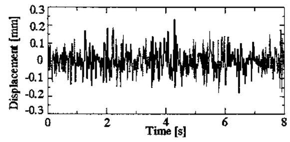
2.7 *Suboptimal control theory in consideration of spillover of residual modes*

When designing an optimal controller taking 5 elastic modes (M=5) equal to the number of the sensors into consideration, the system may become spillover unstable owing to the effects of higher-order residual modes. In order to suppress the spillover of residual modes, a control technique suggested by Yoshida [7,8] is applied to this magnetic levitation control system.

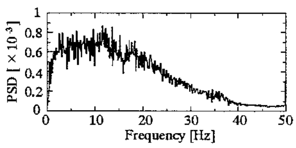
2.8 *Specifications of the experimental apparatus*

The length of the plate a=800mm, the width b=600mm, the thickness h=0.3mm, x_{s1}= x_{s3}=180mm, x_{s2}= x_{s4}=620mm, x_{s5}=400mm, y_{s1}= y_{s2}=85mm, y_{s3}= y_{s4}=515mm, y_{s5}=300mm, ρ =7500kg/m^3, ν = 0.3, E=2.17×10^{11}N/m^2, C=2.49×10^{8}Ns/m^2, m=1.08kg, m_z=0.188kg (for magnet No.1-4), 0.327kg (for magnet No.5), Z_0=5mm, F_z=1.85N (for magnet No.1-4), 3.21N (for magnet No.5), F_1~F_4=1.85N, F_5=3.21N, R_z=20.6Ω, L_z=0.204H, L_{eff}=0.762×10^{-5}Hm.

We confirmed the natural frequencies of the mode when non-supported (Fig.4) by the following experiments. The position of the nodes of elastic 1st mode was supported with the knife-edge (cutter is used), and the natural frequency was

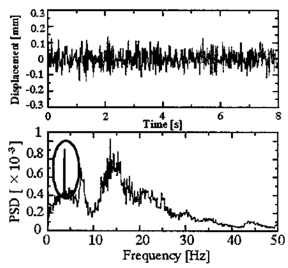


(a) Time history

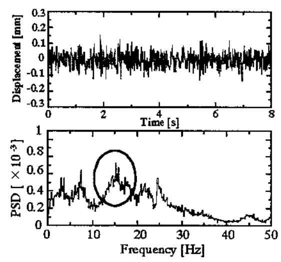


(b) Power spectrums

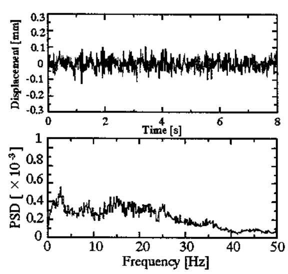
Fig.5 Time history and power spectrum of absolute displacement of frame No.3



(a) Control result in the case of using optimal control for 1 DOF model



(b) Control result in the case of using optimal control for continuous model



(c) Control result in the case of using suboptimal control for continuous model

Fig.6 Time histories and power spectrums of gap between the steel plate and the electromagnet at the sensor No.2 under random excitation

approximately measured by impulse excitation.

Similar experiments were carried out for elastic 2nd to 4th modes respectively. As a result, the error between calculated values and the measurement values were less than 7 percent. Natural frequency (calculated value) of elastic 1st mode = 2.72Hz, 2nd mode = 7.49Hz, 3rd mode = 14.69Hz, 4th mode = 24.28Hz.

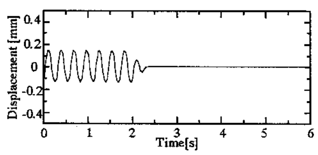
2.9 Consideration on suppression of the elastic vibration caused by random excitation

In the preliminary experiments, various disturbance patterns were experimentally input; among them we adopted the disturbance pattern of exciting only frame No. 3 using a random wave, since the vibration mode can be most clearly observed in this case. Figure 5 shows the absolute displacement and power spectral density of the frame No.3 shown in Fig. 2.

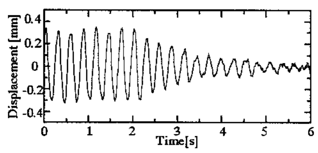
Figure 6 shows the displacement of the levitated plate and its power spectral density of sensor No.2 at the frame No.3, where 6(a) shows the results for the single-degree-of-freedom model, 6(b) for the continuous model in which the optimal control is adopted and 6(c) for the continuous model in which the suboptimal control is adopted. Zero displacement in the figures indicates the equilibrium position of the levitated plate, that is, gap between the plate and the electromagnet is 5mm. Under any control system, the steel plate can be levitated without any slippage or drop due to excitation. As shown in Fig. 6, in the single-degree-of-freedom model, the vibration mode which corresponds to the 3.5 Hz first-order elastic vibration (in the circle in Fig. 6 (a)) is suppressed when the continuous model is used and the first-order elastic vibration mode is taken into consideration (Fig. 6 (b), (c)). In other words, the superiority of modeling the steel plate as a continuous body is demonstrated. However, in the continuous model in which optimal control is adopted (Fig. 6 (b)), since no consideration is given to any vibration mode above the second-order elastic vibration in the system, no distinct difference was found in the spectrum of the frequency range above the second-order mode between a single-degree-of-freedom model (Fig. 6 (a)) and the continuous model (Fig. 6 (b)). Therefore, the amplitude of the two models with respect to time course are comparable (Fig. 6 (a) standard deviation = 0.044 mm, 6 (b) standard deviation = 0.045 mm). By adopting the suboptimal control theory and thus including the spillover mode in the continuous model (Fig. 6 (c)), the mode corresponding to second-order elastic vibration (15 Hz), which was observed in the model in which the optimal control theory was adopted (in the circle in Fig. 6 (b)), is suppressed; this indicates the superiority of the suboptimal control theory. Furthermore, when the suboptimal control theory is adopted, the difference in the control performance is clear at frequencies higher than that of the second-order elastic vibration mode.

2.10 Consideration on suppression of the elastic vibration caused by sine excitation

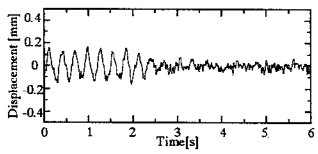
Thus far, we have discussed the suppression of the elastic vibration caused by random excitation, and clarified the suppressive effect. Next, the suppressive effects on modes corresponding to first-order and second-order elastic vibration are individually considered. Figure 7 shows the result for the first-order elastic vibration mode, where (a) shows the absolute displacement (sine wave, 3.5 Hz) of the central frame No.2 shown in Fig. 2. Figures 7(b), 7(c) and 7(d) show the time histories of displacement (sensor No.5) of the first-order elastic vibration mode of the single-degree-of-freedom model (in which optimal control theory is applied), of the continuous model (in which optimal control theory is applied) and of the continuous model (in which suboptimal control theory is applied), respectively. Note that excitation is stopped at approximately 2 s in these models. Similar to the results for peak height of the first-order mode with random excitation shown in Fig. 8, the single-degree-of-freedom model is approximately twice that amplitude of the first-order mode of the of the continuous model. Considering elastic vibration by modeling a steel plate as a continuous body was confirmed to impart a clear advantage in terms of vibration convergence. Based on the comparison of the results in Figs. 7(c) and 7(d), the control performances of the two models (horizontal axis, 0-2 s) with respect to the amplitude of the vibration of a steel plate in the first-order mode are similar. These results are obtained by taking the first-order elastic vibration mode into model (in which suboptimal control theory is applied),respectively. The results in Figs. 8(b), 8(c) and 8(d) reveal consideration



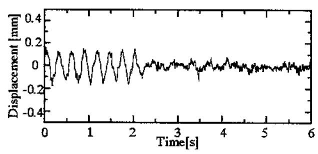
(a) Forced input of disturbance at the frame No.2



(b) Control result in the case of using optimal control for 1 DOF model

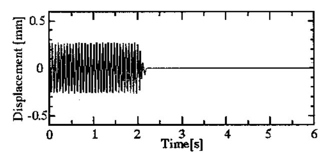


(c) Control result in the case of using optimal control for continuous model

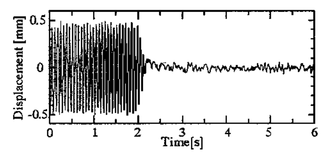


(d) Control result in the case of using suboptimal control for continuous model

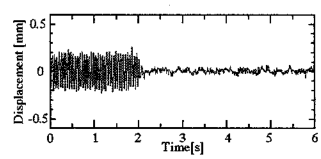
Fig.7 Time histories of displacement of the frame and gap between the steel plate and the electromagnet at the sensor No.5 under sinusoidal excitation (frequency=3.5Hz)



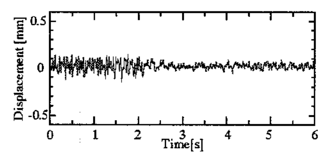
(a) Forced input of disturbance at the frame No.3



(b) Control result in the case of using optimal control for 1 DOF model



(c) Control result in the case of using optimal control for continuous model



(c) Control result in the case of using suboptimal control for continuous model

Fig.8 Time histories of displacement of the frame and gap between the steel plate and the electromagnet at the sensor No.2 under sinusoidal excitation (frequency=15Hz) in both optimal control and suboptimal control systems.

Figure 8 shows the result for the second-order elastic vibration mode, where (a) shows the absolute displacement (sine wave, 15.0 Hz) of the frame No.3 shown in Fig. 2. Figures 8(b), 8(c) and 8(d) show the time histories of displacement (sensor No.2) of the second-order elastic vibration mode of the single-degree-of-freedom model (in which optimal control theory is applied), of the continuous distinct differences in the control performance between the suboptimal control, in which spillover of the second- or higher order elastic vibration is considered, and other forms of control.

3. Noncotact positioning control of transported thin steel plate

3.1 Control System

A schematic illustration of the electromagnetic levitation control system with a horizontal positioning controller is shown in Fig.9. A zinc-coated steel plate (length 800mm, width 600mm, thickness 0.3mm, material SS40 steel) is levitated and positioned in a contactless manner by attractive forces of electromagnets which are controlled by feedback signals from gap sensors. The dotted lines in the steel plate shown in Fig. 9 are pipes made of light carbon fiber. The total weight of the carbon pipes is about 8% of the steel plate mass = 1.2kg.

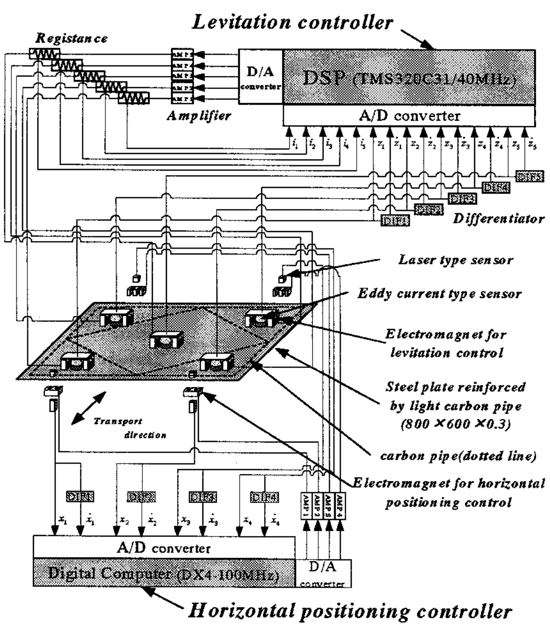


Fig.9 Electromagnetic levitation control system with horizontal positioning controller.

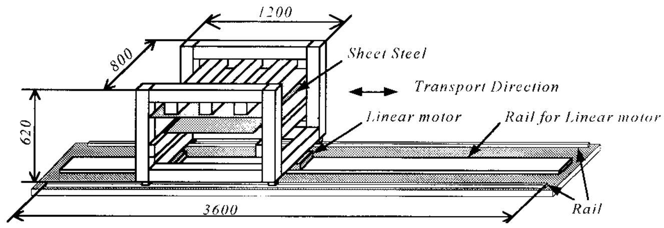


Fig.10 Transport system of the plate.

The vertical displacement of the plate, its velocity and the current through the magnet are acquired using five eddy-current-type displacement sensors, five differentiators and five resistors connected in series to the magnetic circuit, respectively. The total number of acquired values is fifteen. These values are converted from analog to digital in the sampling interval of 0.2ms to be processed in a digital signal processor. The control forces (voltage) are calculated in the DSP and are fed to the five electromagnets through the D/A converter and five power amplifiers. The horizontal displacement of the plate and its velocity are acquired using four laser-type displacement sensors and four differentiators, respectively. The control forces are calculated on a computer using these eight values (sampling interval is 0.2ms). These sensors and electromagnets are installed in the frame shown in Fig.10. The steel plate is carried about 1.9m with this frame, using the linear motor.

3.2 Electromagnetic levitation control system

In this study, the displacement, the velocity and the coil current detected at one electromagnet position were used for the control of the electromagnet. Consequently, the electromagnetic levitation system was modeled as a one-degree-of-freedom system, as shown in Fig. 11.

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

$$m_z \ddot{z} = 2 f_z \tag{22}$$

where m_z $=m/5$ [kg], z: vertical displacement [m], $f_z(t)$: dynamic magnetic force [N].

The inductance of the electromagnetic coil is expressed as a sum of the component inversely proportional to the gap between the steel plate and magnet and the component of leakage inductance. If deviation around the static equilibrium state is very small, the characteristic equations of the electromagnet are linearized as where F_z: magnetic force in

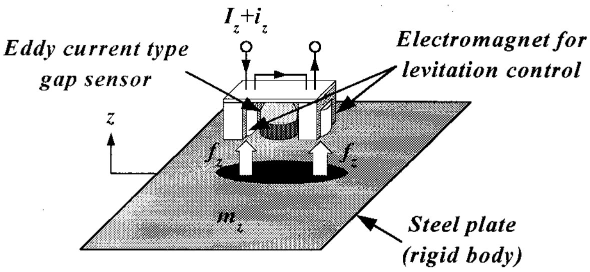


Fig.11 Theoretical model of levitation control of the steel plate.

the equilibrium state [N], Z_0: gap between steel plate and electromagnet in the equilibrium state [m], I_z : current in the equilibrium state [A], i_z: dynamic current of the coupled magnets [A], L_z: inductance of the magnet coil in the

$$f_z = \frac{2F_z}{Z_0} z + \frac{2F_z}{I_z} i_z \tag{23}$$

$$\frac{d}{dt} i_z = -\frac{L_{eff}}{L_z} \cdot \frac{I_z}{Z_0^2} \dot{z} - \frac{R_z}{2L_z} i_z + \frac{1}{2L_z} v_z \tag{24}$$

$$L_z = \frac{L_{eff}}{Z_0} + L_{lea} \tag{25}$$

equilibrium state [H], R_z: resistance of the coupled magnet coils [Ω], v_z: dynamic voltage of the coupled magnets [V] , L_{lea}: leakage inductance of the magnet coil.

3.3 Horizontal positioning control system

Horizontal positioning control was carried out using the electromagnets installed at two edges of the steel plate. The horizontal displacement was measured by the banded laser beam sensor, keeping 5mm of clearance between the edge of the steel plate and each electromagnet surface.

For the basic examination, the horizontal motion of the steel plate was modeled to have one-degree-of-freedom in the transport direction, as shown in Fig. 12. Therefore, the same attractive forces were generated from two electromagnets placed at one side of the steel plate. The equation of small horizontal motion around the equilibrium state of the steel plate subjected to the same static magnetic forces from the electromagnets at two edges is expressed as

$$m_x \ddot{x} = f_1 - f_2 + f_w = f_x + f_w \tag{26}$$

$$f_x = \frac{4F_x}{X_0} x - \frac{4F_x}{I_x} i_x \tag{27}$$

where mx =m/2 [kg], x: horizontal displacement [m], fx(t): dynamic magnetic force [N], fw(t): disturbance [N], F_x: magnetic force in the equilibrium state [N], X_0: gap between steel plate edge and electromagnet in the equilibrium state [m], I_x: current of the magnet in the equilibrium state [A], i_x: dynamic current of the magnet [A].

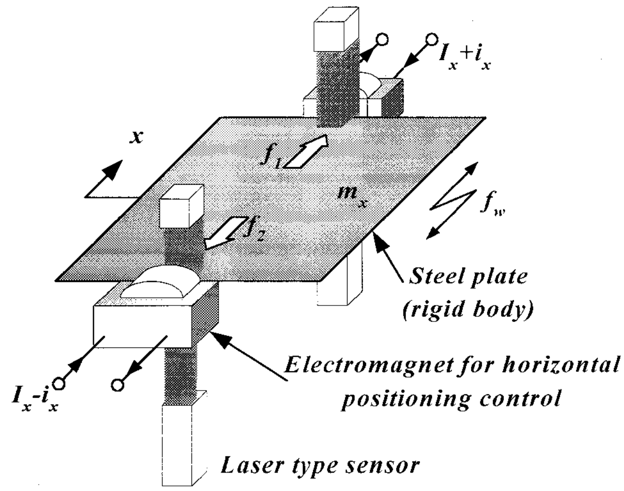


Fig.12 Theoretical model of horizontal positioning control of the steel plate.

3.4 Design of controller

In this study, by assuming that the interaction of the levitation system with the horizontal positioning system could be disregarded, each control system was independently designed. Using the state vector, the equations. (22)~(25) and (26), (27) are written as the following state equations:

$$\dot{\boldsymbol{z}} = \boldsymbol{A}_z \boldsymbol{z} + \boldsymbol{B}_z v_z \tag{28}$$

$$\boldsymbol{z} = \begin{bmatrix} z & \dot{z} & i_z \end{bmatrix}^T$$

$$\boldsymbol{A}_z = \begin{bmatrix} 0 & 1 & 0 \\ \frac{4F_z}{m_z Z_0} & 0 & \frac{4F_z}{m_z I_z} \\ 0 & -\frac{L_{eff}}{L_z} \cdot \frac{I_z}{Z_0^2} & -\frac{R_z}{2L_z} \end{bmatrix}$$

$$\boldsymbol{B}_z = \begin{bmatrix} 0 & 0 & \frac{1}{2L_z} \end{bmatrix}^T$$

$$\dot{x} = A_x x + B_x v_x + D_x f_w \tag{29}$$

$$x = [x \quad \dot{x}]^T, \quad A_x = \begin{bmatrix} 0 & 1 \\ \dfrac{4F_x}{m_x X_0} & 0 \end{bmatrix}$$

$$B_x = \begin{bmatrix} 0 & -\dfrac{4F_x}{m_x I_x R_x} \end{bmatrix}^T, \quad D_x = \begin{bmatrix} 0 & \dfrac{1}{m_x} \end{bmatrix}^T.$$

To design their controllers based on optimal control theory, the following criterion functions are chosen.

$$J_z = \lim_{t_f \to \infty} \int_0^{t_f} \left(z^T Q_z z + r_z v_z^2 \right) dt \tag{30}$$

$$J_x = \lim_{t_f \to \infty} \int_0^{t_f} \left(x^T Q_x x + r_x v_x^2 \right) dt \tag{31}$$

$$Q_z = \begin{bmatrix} q_z & 0 & 0 \\ 0 & q_{zs} & 0 \\ 0 & 0 & q_{zi} \end{bmatrix}, \quad Q_x = \begin{bmatrix} q_x & 0 \\ 0 & q_{xs} \end{bmatrix}$$

q and r are weighting coefficients.

According to the optimal control theory, the optimal state feedback gain is determined by solving the Riccati equation. The optimal voltages of electromagnets are obtained as

$$v_z = [-f_{bz} \quad -f_{bzs} \quad -f_{bzi}] z \tag{32}$$

$$v_x = [-f_{bx} \quad -f_{bxs}] x \tag{33}$$

3.5 Specifications of the experimental apparatus

Levitation system: m=1.2kg, Z_0=5mm, I_z=0.45A, F_z=1.18N, R_z=20.6Ω, L_z=2.21×10^{-1}H, L_{eff}=1.16×10^{-4}Hm. Horizontal positioning system: X_0=5mm, I_x=0.50 A, F_x=0.40 N, R_x=9.50Ω.

The characteristics of electromagnetic attractive forces used for levitation and horizontal positioning control are shown in Fig.13.

3.6 Consideration for random excitation in nontransport

To verify the usefulness of the proposed system, a digital control experiment for a nontransported steel plate was performed. The steel plate levitated using feedback gain values shown in Table 1 was subjected to horizontal random excitation by a shaker. The disturbance is transferred to the plate through a soft coil spring connected by a universal joint. The experimental results are shown in Fig.14. In Fig.14(a), the horizontal displacement and its spectrum in the case of no horizontal positioning control are shown. Fig.14 (b) shows control results. The validity of modeling was confirmed, because the horizontal disturbance was sufficiently suppressed upon using horizontal positioning control in the steady state.

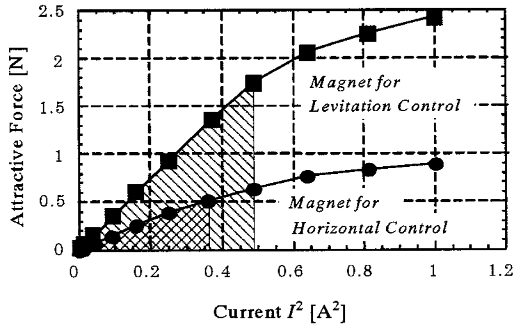
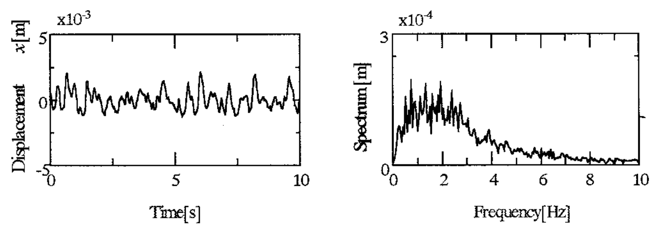


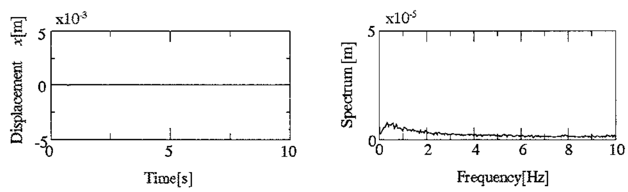
Fig13 Characteristics of electromagnetic attractive forces for levitation and horizontal positioning control.

Table 1 Weighting coefficient and feedback gain for levitation control.

Weighting coefficient			Feedback gain		
q_z	q_{zs}	r_z	f_{bz}	f_{bzs}	f_{bzi}
1	1	1	-11239	-187	-43

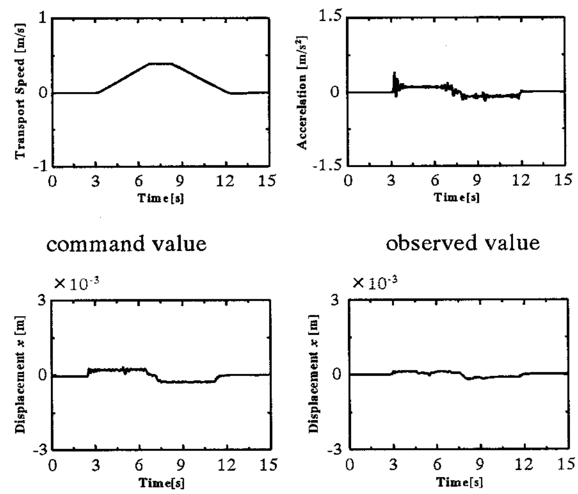


(a) Noncontrol



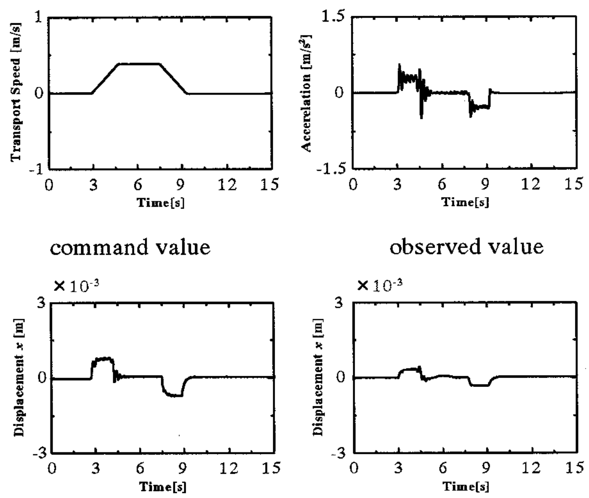
(b) With control

Fig.14 Time response and spectrum of horizontal displacement of the steel plate subjected to random excitation.



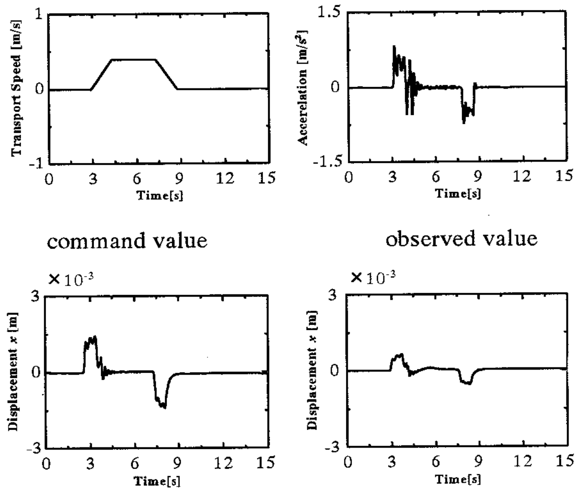
in the case of using gain No.1 in the case of using gain No.2

(a) Transport acceleration and deceleration = ±0.1m/s^2



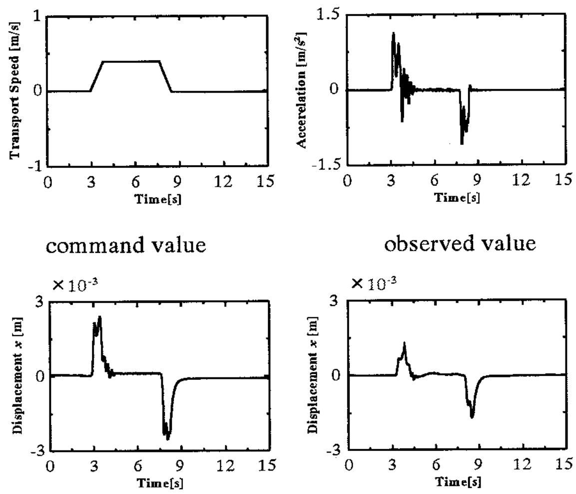
in the case of using gain No.1 in the case of using gain No.2

(b) Transport acceleration and deceleration = ±0.3m/s^2



in the case of using gain No.1 in the case of using gain No.2

(c) Transport acceleration and deceleration = ±0.5m/s^2



in the case of using gain No.1 in the case of using gain No.2

(d) Transport acceleration and deceleration = ±0.7m/s^2

Fig.15 The command values of transport speed, its observed acceleration and horizontal displacements of the plate.

3.7 Consideration during transport

The experimental results in the case of the transport mode are shown in Fig.15. The command values of the transport speed of the linear motor, its observed accelerations and the horizontal displacements of the steel plate when using two different feedback gains, No.1 and 2 in Table 2, are shown. Each figure indicates the results for the maximum transport speed of the steel plate of 0.4m/s, with the transport acceleration and deceleration of (a) ±0.1m/s^2, (b) ±0.3m/ s^2, (c) ±0.5m/ s^2, and (d) ±0.7m/ s^2 (command all). Zero horizontal displacement x indicates the equilibrium position. When the transport acceleration and deceleration increase as

Table 2 Weighting coefficient and feedback gain for horizontal positioning control.

	Weighting coefficient			Feedback gain	
	q_x	q_{xs}	r_x	f_{bx}	f_{bxs}
No.1	1	100	1.0×10^{-3}	-1857	-322
No.2	100	10	1.0×10^{-5}	-3831	-887

from (a) to (d), the offset horizontal displacement increases in the case of using feedback gain No.1. However, there is a marked difference in the control effect when using feedback gain No.2. It is possible to reduce the horizontal displacement by adjusting the feedback gains. Consequently, it was shown that the present noncontact horizontal positioning control system for the levitated steel plate was very effective.

4. Conclusions

Noncontact vibration control of a levitated plate with forced input of disturbances and noncontact horizontal positioning control of a transported plate were performed. To summarize our interpretation of the results, we can explain as follows:

1. Using the equipment developed by us (chapter 2), elastic vibration is forcibly induced in a levitated steel plate, by means of which various examinations of the elastic vibration of magnetically levitated steel were achieved which had conventionally been impossible.
2. We confirmed that magnetic levitation of the steel plate, which was the target of levitation in this study, was possible in the single-degree-of-freedom control model for which the modeling is relatively easy.
3. Although the continuous model includes a somewhat complicated mathematical treatment, the suppressive effect of the control system on the elastic vibration mode was confirmed to be sufficient.
4. By adopting suboptimal control, it is possible to solve the spillover problem of elastic vibration of the magnetically levitated steel plates.
5. Using noncontact horizontal control system proposed by us, good positioning control performance for the traveled steel plate was obtained.

In the future, we aim to adopt the control theory which suppresses elastic vibration more efficiently, and to develop a noncontact support system with high robustness, which is tolerable to factors such as disturbance with respect to control signals and variation of parameters of the system.

Acknowledgments

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