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Fundamental Considerations on Noncontact Guide System Using Electromagnetic Forces for Changing Traveling Directions in High-Speed Traveling Steel Plate Process

by

Ken KASHIWABARA*1, Yoshihiko MITSUHASHI*2, Yasuo OSHINOYA*3 and Kazuhisa ISHIBASHI*4

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Abstract

Recently, along with high-end products, users demand steel plates with high quality and high added value manufactured by a continuous steel plate process. In the factory, the continuous thin steel plate subjected to iron and steel processes is supported by a series of rollers during processes such as rolling. In the plating process, the steel plate is conveyed 20-50 m in the vertical direction for drying, during which the steel plate is not supported by rollers and other mechanisms. Therefore, plating nonuniformity due to the generation of vibration and other factors prevents the increase in productivity. To solve this problem, we developed a noncontact guide system for fast traveling steel plates in which electromagnetic forces are applied at the edges of the steel plates in order to change the traveling direction. Efficacy of proposed system was verified by experiments.

Keywords: Steel Plate, Traveling, Noncontact Guide, Vibration Control, Elastic Vibration, High-Speed Traveling

1. Introduction

Recently, along with high-end products, users demand high quality and high added value of steel plates manufactured by the continuous steel plate process. In a factory, the continuous thin steel plate subjected to iron and steel processes is supported by rollers during processes such as rolling; the thin steel plate moves along the rollers at a speed of 10m/s or more. In the plating process, the steel plate is conveyed 20-50m in the vertical direction for drying, during which the steel plates are negligibly supported by rollers and other mechanisms. Therefore, plating nonuniformity due to the generation of vibration and other factors prevents the increase of productivity. Yanagi et al.[1] proposed a noncontact belt steel plate conveying system with a floater that lifts the conveyor belt of the steel plate by means of gas, and Okada et al.[2] and Kurita et al.[3] studied vibration suppression of a stationary long steel plate, however, their method did not completely solve the problem. The authors have designed a control system in which a thin steel plate conveyed in the horizontal direction is supported without contact using an electromagnet[4]. By controlling the electromagnetic attractive force applied to the surface of the conveyed steel plate, we experimentally confirmed the suppression effect of the elastic vibration in the steel plate being conveyed at 13m/s[5]. However, in this case, along with the instability of the control system, the electromagnet comes into contact with the conveyed steel plate, leading to the significant deterioration of the steel quality. In these studies, the control of a steel plate is attempted by applying an electromagnetic attractive force to the surface of the plate. In this case, improvement in the performance can be expected by bringing the electromagnet sufficiently close to the steel plate. However, in actual machines, this is difficult because the thin steel plate is traveling at a high speed and because of various other factors such as deformation and vibration. As one method of solving this problem, we have proposed a noncontact guide system which suppresses the vibration of a moving thin-steel plate by adding an electromagnetic force from the direction of the edge of the plate[6][7]. Furthermore, by applying the proposed noncontact guide system in a section where the transport direction of the steel plate is changed, we experimentally investigated the vibration—suppression characteristics of the system during low-speed transport (1-5 m/s) [8][9], and acceleration-deceleration transport[10]-[12]. In the current study, we applied the proposed noncontact guide system to a steel plate transported at high speed (6-10 m/s) in a section where the transport direction is changed, and experimentally examined the applicability of control using this system.

＊1 Graduate Student, Course of Mechanical Engineering
＊2 Graduate Student, Course of Mechanical Engineering
＊3 Associate Professor, Department of Prime Mover Engineering
＊4 Professor, Department of Mechanical Engineering, School of Engineering II

2. Noncontact guide system

2.1 Experimental apparatus

Figure 1 shows the schematic illustration of the noncontact guide experiment device for a traveling steel plate. A steel material for making carbon tool steels with a total length of approximately 7m is welded into a looped belt shape (width:150mm, thickness:0.3mm), and then suspended from a driving pulley used to rotate the belt. The pulley is driven with the DC servo motor. No pulley is installed at the bottom of the belt. Expected applications of this system include a section where a continuous steel plate traveling in the horizontal direction is moved in the vertical direction after passing through a plating tank, a section where a steel plate is moved back in the downward direction after the previous process and a direction-changing section in the loop.

A pair of electromagnets, which are of the same type as those used in the previously proposed noncontact positioning control mechanism(5), is placed at each of the three locations which change the traveling direction of the steel belt at the lower part of the belt, as actuators. These locations are designated No. 1, No. 2 and No 3, as shown in Fig. 1. In Fig. 1, x_1, x_2 and x_3 indicate coordinates in the direction of the tangential line of the steel plate at the three electromagnet locations, and z_1, z_2 and z_3 indicate coordinates in the direction perpendicular to the steel plate surface at the three electromagnet locations. Similarly, y_1, y_2 and y_3 indicate coordinates of the lateral vibration in the plane of the steel plate direction at the three electromagnet locations. Figure 2 shows a photograph of the experimental apparatus.

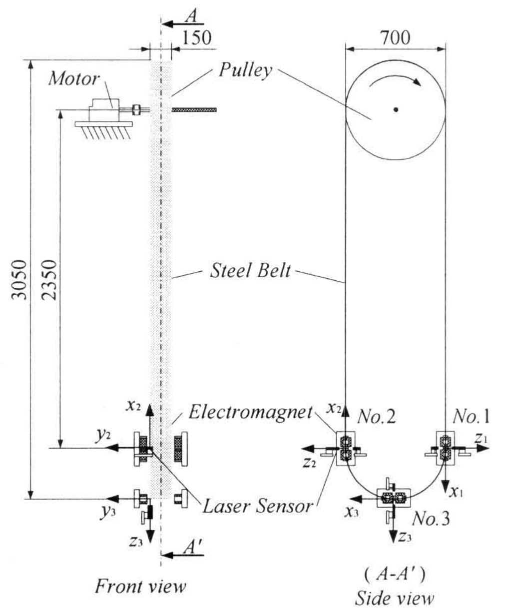


Fig.1 Noncontact guide system for a traveling steel belt.

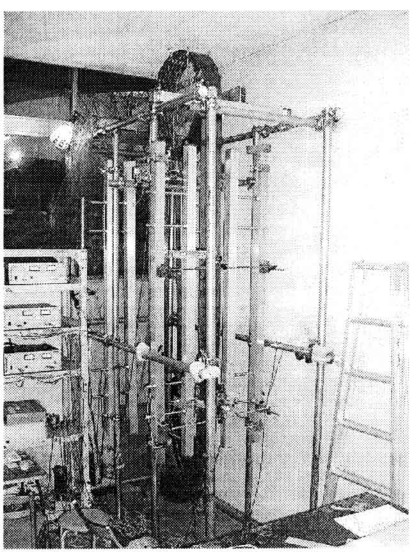


Fig.2 Photograph of the experimental apparatus.

2.2 Control system

In this study, electromagnets are placed at the three locations where the direction of travel is changed. Local feedback control, in which the displacement detected at the position of one electromagnet as well as the velocity of the steel sheet obtained by digital differentiation of the displacement are fed back to the same electromagnet, is carried out. Figure 3 shows the control system. Laser displacement sensors are placed at the three electromagnet locations to measure the displacement of the steel plate in the y_1, y_2 and y_3 directions. These displacements are input to the computer through the A/D converter. The controller keeps a 5mm clearance between the edge of the steel plate and the electromagnet surface. The velocity is differentiated by a discrete algorithm in the computer. The control forces are calculated in the DSP (Digital Signal Processor) and are fed to the two electromagnets through the D/A converter and two power amplifiers.

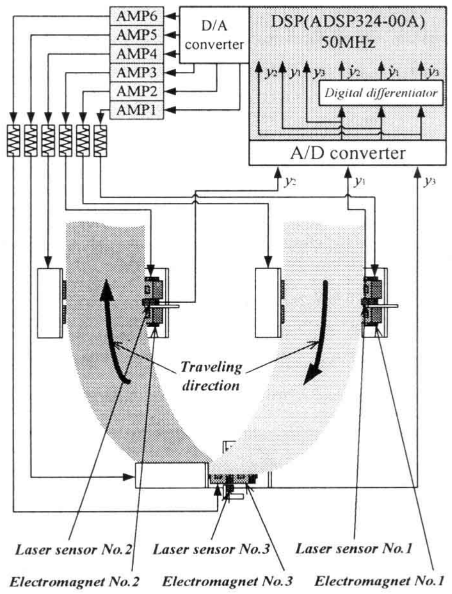


Fig.3 Control system of noncontact guide.

2.3 Modeling

The parts where the direction of travel is changed (indicated by curves) and the linear-traveling parts are divided into sections, as shown in Fig. 4. Each section is modeled as a target of control. For a model with one degree of freedom where the weight of each section is represented by m_n and the control force generated by the electromagnet is represented by f_n, the equation of motion is expressed as

$$m_n \ddot{y}_n = 2 f_n \qquad (1)$$

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

$$f_n = \frac{2F_0}{\Gamma_0} y_n + \frac{2F_0}{I_0 R} v_n \qquad (2)$$

Where

$$v_n = Ri_n$$

F_0: magnetic force in the equilibrium state (0.83N), Γ_0: gap between steel plate and electromagnet in the equilibrium state (59mm), I_0: current in the equilibrium state (0.5A), R: resistance of the coupled magnet coils (10Ω), y_n: horizontal displacement [m], v_n: dynamic voltage of the coupled magnets [V], i_n: dynamic current of the coupled magnets [A].

The state equation of the system is introduced from the from the equation of motion, that is,

$$\dot{y}_n = A_y y_n + B_y v_n \tag{3}$$

Where

$$y_n = \begin{bmatrix} y_n & \dot{y}_n \end{bmatrix}^T,$$

$$A_y = \begin{bmatrix} 0 & 1 \\ \dfrac{4F_0}{\Gamma_0} & 0 \end{bmatrix},$$

$$B_y = \begin{bmatrix} 0 \\ \dfrac{4F_0}{I_0 R} \end{bmatrix}.$$

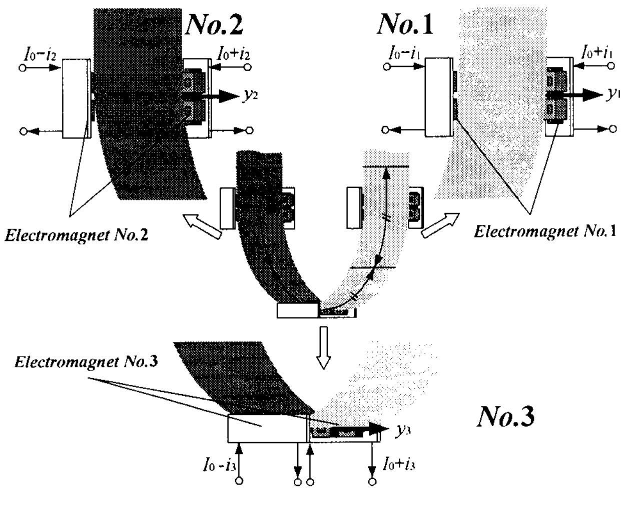


Fig.4 Model of noncontact guide system for a traveling steel belttraveling steel belt.

3. Design of discrete time optimal controller for electromagnetic levitation control system

The control voltages are calculated in the DSP, so we design the digital control system.

The discrete time system of equation (3) is

$$y_{dn}(i+1) = \boldsymbol{\Phi}_y y_{dn}(i) + \boldsymbol{\Gamma}_y v_{dn}(i). \tag{4}$$

The discrete optimal controller is obtained as follows:

$$J_{dn} = \sum_{i=0}^{\infty}\left[y_{dn}(i)^T Q_{yd} y_{dn}(i) + r_{yd} v_{dn}(i)^2\right]. \tag{5}$$

where Q_{yd} and r_{yd} are weighting coefficients.

$$M = \boldsymbol{\Phi}^T M \boldsymbol{\Phi} + Q_{yd} - \boldsymbol{\Phi}^T M \boldsymbol{\Gamma}\left(r_{yd} + \boldsymbol{\Gamma}^T M \boldsymbol{\Gamma}\right)^{-1} \boldsymbol{\Gamma}^T M \boldsymbol{\Phi}, \tag{6}$$

$$F_{yd} = \left(r_{yd} + \boldsymbol{\Gamma}^T M \boldsymbol{\Gamma}\right)^{-1} \boldsymbol{\Gamma}^T M \boldsymbol{\Phi}, \tag{7}$$

where,

$$\boldsymbol{\Phi}(T_s) = \exp(A_y T_s),$$

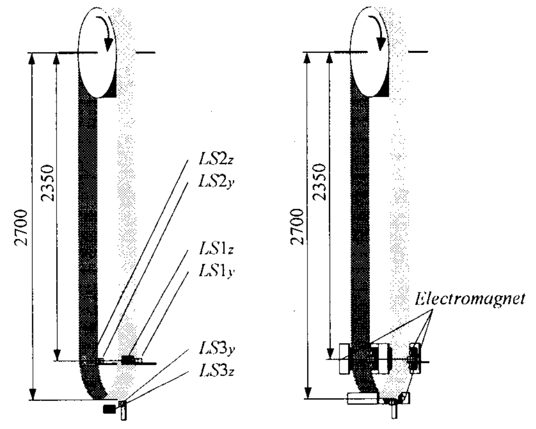
$$\boldsymbol{\Gamma}(T_s) = \int_0^{T_s}\left[\exp(A_y \tau)\right] d\tau\, B_y.$$

where T_s is a sampling interval (= 1 ms in the experiment). The MATLAB command "lqrd" was used to solve equation (7) and the digital controller was designed by using SIMULINK in the DSP.

4. Driving experiment

4.1 Experimental conditions

In this study, experiments were performed under two conditions (Fig.5): (a) without control, (b) with control using electromagnets. The location and shape of the steel plate without control at the locations where the direction of travel is changed are indicated by dotted lines in Fig. 6. In this experiment, to obtain the target location and shape of the steel plate, indicated by solid lines, a noncontact transport route is designed. We investigated the suppression of vibration while the traveling high-speed ranged from 6m/s to 10m/s. Similarly, as described in Section 4, displacement of the steel plate at three locations, No. 1, No. 2 and No. 3 was measured in the y and z-directions.



(a) Noncontrol (b) With electromagnets

Fig.5 Layout of electromagnets.

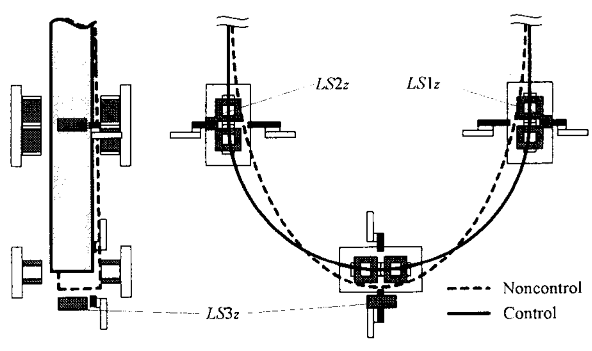


Fig.6 Position of steel plate before / after the positioning control.

4.2 Considerations

4.2.1 Examination concerning *y* direction vibration

Figures 7-10 show examples of time histories of *y*-direction displacement of the steel plates traveling at either 6m/s or 10m/s, with or without control by electromagnets. The zero point on the vertical axis in these figures represents the target guide position after control for sensors Nos. 1-3. While moving at a relatively high-speed of 6m/s, the half-maximum amplitude of close to 30mm is generated without control (Fig.7). In contrast, when the control is applied, the half-maximum amplitude is suppressed to approximately 2mm (Fig.9). When the traveling speed was increased to 10m/s, similar effects were observed (Figs. 8 and 10). Compared to the values of the experiment without control, a maximum of 7% suppression of vibration is obtained by means of control using electromagnets.

4.2.2 Examination concerning *z* direction vibration

Figures 11-14 show examples of *z*-directional displacements under the same conditions as shown in Figs.7-10. For the thin steel plate without control, large vibrations are generated in the low-frequency region, as shown in Figs. 11 and 12, and the guidance of the plate within the transport route indicated by the bold line in Fig. 6 is unsuccessful. However, by installing the noncontact guide system in the y direction to the plate, vibrations are controlled within the range centering around the zero point on the vertical axis, as shown in Figs. 13 and 14, indicating successful guidance along the transport route set in the z direction. Compared to the values of the experiment without control, a maximum of 40% suppression of vibration is obtained by means of control using electromagnets. These results demonstrate that the attractive force from the *y* direction was very effective in suppressing vibration in the *z* direction. In the results shown in Figs. 13 and 14, the displacement amplitude of position No. 3 is smaller than those of Nos. 1 and 2 by approximately 30%. The following reason for this is considered. Disturbance generated due to transport in the contact section of the pulley and elastic vibration of the thin steel plate generated in the linear-transport section were suppressed by the electromagnets placed at Nos. 1 and 2, and therefore it is thought that the disturbance and vibration did not reach position No. 3.

5. Conclusion

In this study, we experimentally investigated the effect of the suppression of vibration by the use of the noncontact guide system using electromagnets, placed in the edge direction of a thin steel plate transported at high speed. As a result, we clarified that even when the thin steel plate is transported at a high speed of 6-10 m/s in a curved section where the transport direction changes, noncontact control by the proposed system is sufficiently effective against vibration in the edge direction of the steel plate. Furthermore, we were able to confirm that the action of the electromagnetic attractive force from the edge direction is also effective for suppressing the vibration in the planar direction of a steel plate that is not actively controlled.

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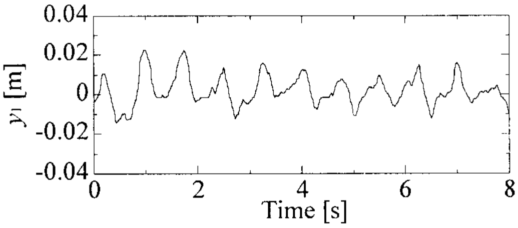

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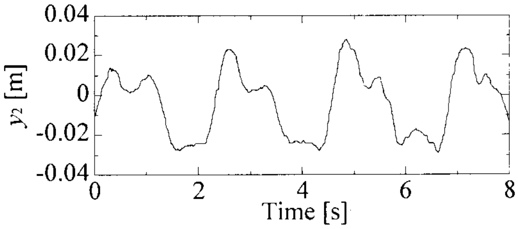

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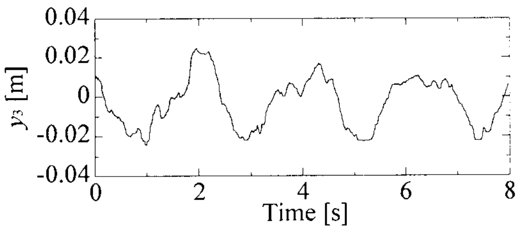
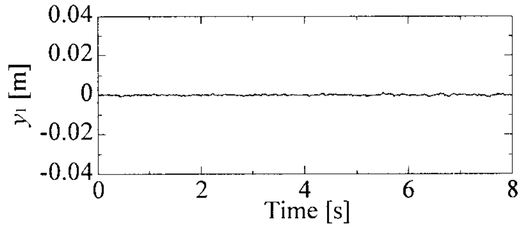


(c) Position No.3

Fig.7 Time histories of y-direction displacement at traveling speed 6m/s(Noncontrol).



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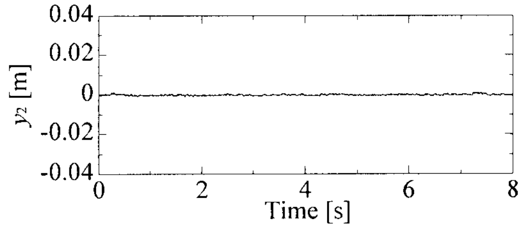

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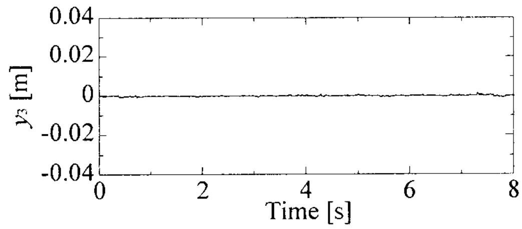
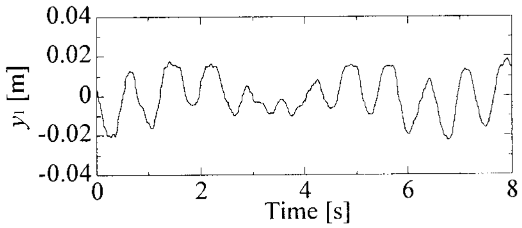


(c) Position No.3

Fig.9 Time histories of y-direction displacement at traveling speed 6m/s(with electromagnets).



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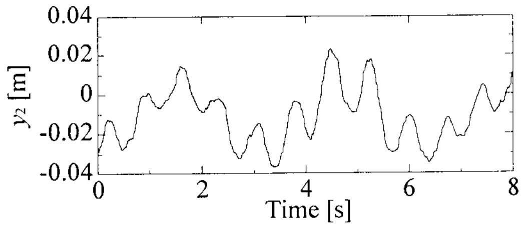

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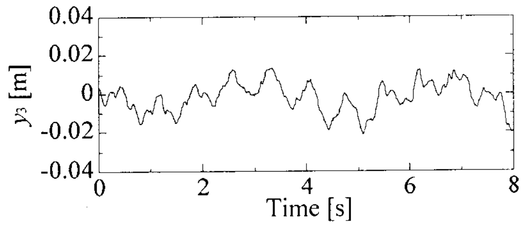
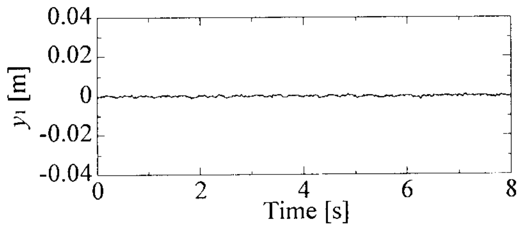


(c) Position No.3

Fig.8 Time histories of y-direction displacement at traveling speed 10m/s(Noncontrol).



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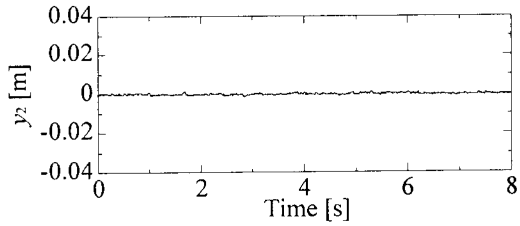

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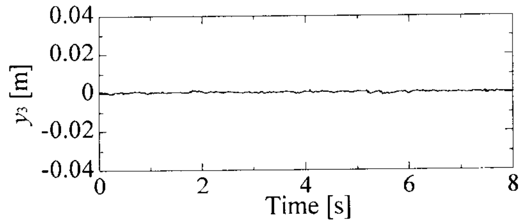
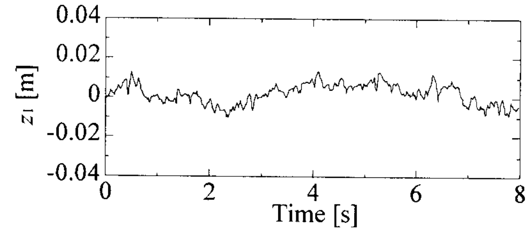


(c) Position No.3

Fig.10 Time histories of y-direction displacement at traveling speed 10m/s(with electromagnets).



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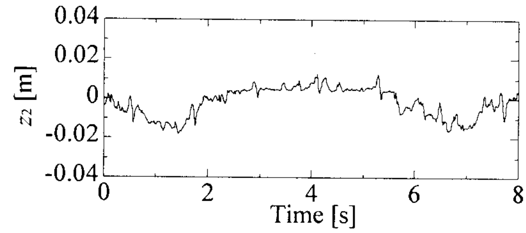

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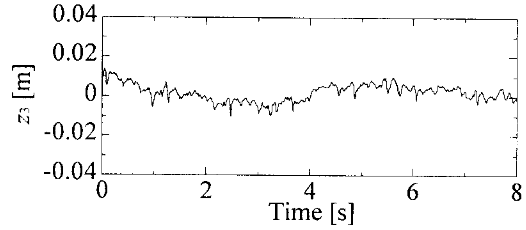
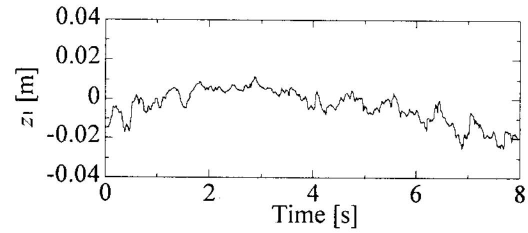


(c) Position No.3

Fig.11 Time histories of z-direction displacement at traveling speed 6m/s(Noncontrol).



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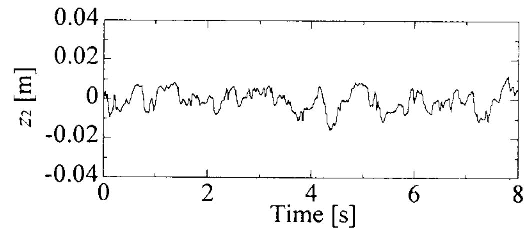

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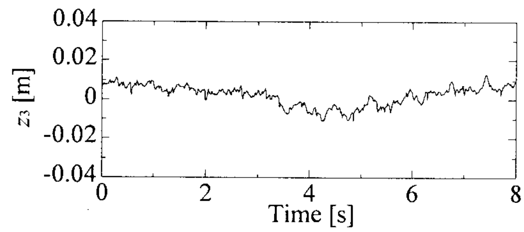
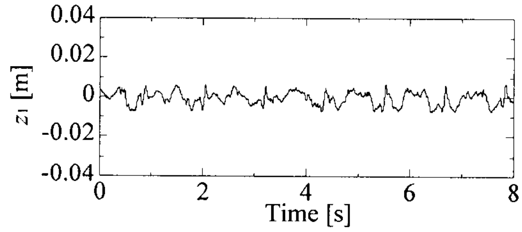


(c) Position No.3

Fig.12 Time histories of z-direction displacement at traveling speed 10m/s(Noncontrol).



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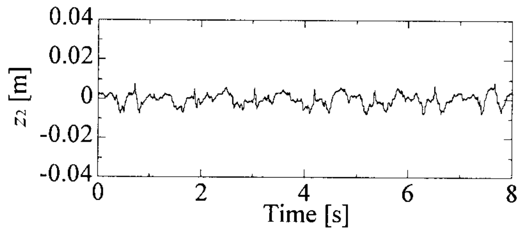

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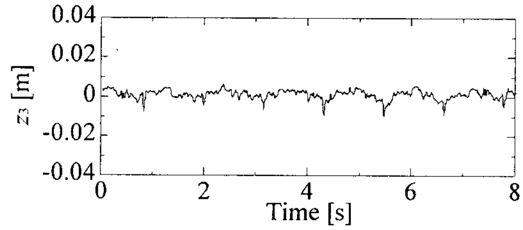

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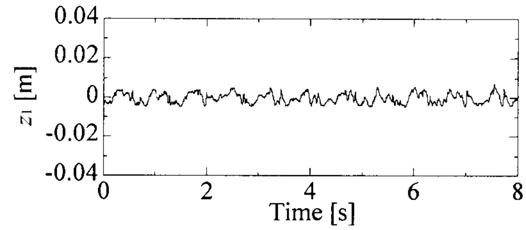
Fig.13 Time histories of z-direction displacement at traveling speed 6m/s(with electromagnets).



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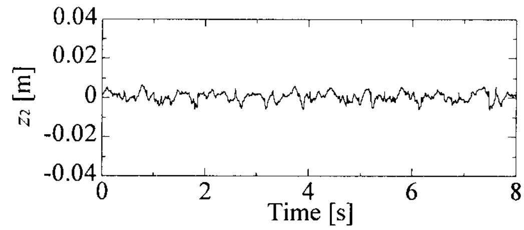

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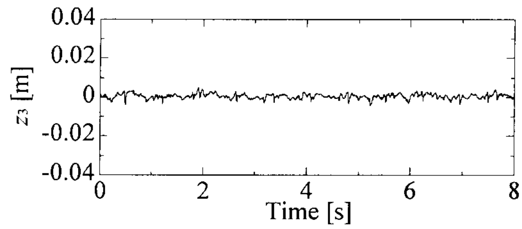

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Fig.14 Time histories of z-direction displacement at traveling speed 10m/s(with electromagnets).