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Combined Levitation-Propulsion-Guidance Motion Control in a New PM LSM Controlled-Repulsive Maglev Vehicle

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Abstract: This paper proposes a new repulsive-Maglev vehicle in which a vertical type PM linear synchronous motor can levitate, propell and guide simultaneously from a standstill, independently of vehicle speeds. To verify experimentally the theory of a new repulsive Maglev vehicle, we have designed and constructed a model vehicle which has permanent magnet (PM) on board and armature coil on the ground. The PM's are mounted on both side surfaces of the vehicle and armature coils are installed along both side-walls of U-shaped guideway. In the Maglev system, propulsion and levitation forces are produced as two components of LSM tangential force and guidance force is also exerted as LSM normal force. We have verified experimentally the theory of new LSM controlled-repulsive Maglev vehicle which can control combined levitation-propulsion -guidance motion by using only LSM without any additional coils for levitation and/or guidance.

Keywords: PM LSM, Maglev vehicle, Repulsive force, Three-dimensional force, Zero-phase-current control, Guidance control

1. Introduction

As a superconducting (SC) linear synchronous motor (LSM) repulsive Maglev vehicle, JR Maglev vehicle is well-known all over the world[1]. Repulsive Maglev force is produced passively between SC magnets on board and the currents at levitation coils on the ground installed independently of LSM, which are induced depending strongly on vehicle speeds. At standstill and low speeds, any effective levitation force can not be expected due to no and small speed-emf inductions. In the speeds higher than about 150km/h, the Maglev system can levitate the vehicle.

From the viewpoint that LSM can produce three-dimensional force[2], the first author has proposed the theory of a new air-cored LSM repulsive Maglev vehicle which can levitate, propel and guide simultaneously from a standstill, independently of vehicle speeds[3]. We have verified experimentally the theory of combined levitation and propulsion by the help of another guidance control method[4][5].

We have designed and manufactured a new PM LSM controlled-repulsive Maglev model vehicle system which can control guidance motion as well as levitation-propulsion motion. For the first step of the study, a standstill levitation cantrol has succeeded[6] and then the combined levitation-and-propulsion motion has been accomplished experimentally in the center of the guideway with contacting softly by the help of guiderollers for guidance. In the basic experiments of combined levitation-and-propulsion with pitching control, the vehicle has been controlled very well to follow the low-speed demand patterns[7].

We verify experimentally the theory of new PM LSM controlled-repulsive Maglev vehicle which can control simultaneously three-dimensional forces of levitation, propulsion and guidance. Both side LSM's are driven and controlled by two independent controllers to realize guidance control.

2. Model for Analysis of the Vehicle

Fig. 1 shows a new PM LSM controlled-repulsive Maglev vehicle which is levitated, guided and propelled along a vertical guideway with armature coils.

Fig. 2 (a) and (b) show a model for analysis of the vehicle. A model vehicle which has permanent magnet (PM) on board and air-cored armature coil on the ground. The PM's are mounted on both side surfaces of the vehicle and armature coils are installed along the both side-walls of U-shaped guideway. In the Maglev system, the propulsion and levitation forces are produced as x-and y-components of the tangential force and guidance force is also exerted as the normal force in the z-direction.

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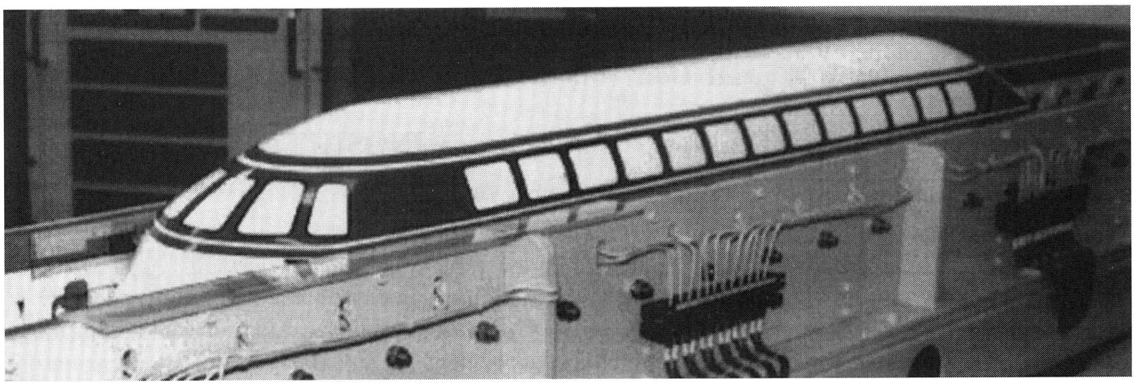


Fig. 1　New PM LSM Controlled-Repulsive Maglev Model Vehicle

3. Three-Dimensional Forces

3.1 Propulsion, Levitation and Guidance Forces

In the Maglev system, three-dimensional forces are produced independently at the left and right sides, respectively. As a result of analysis, three-dimensional forces of the left side LSM can be expressed in the following form:

$$F_{xL}(I_{1L},x_{0L},\delta_L)=K_{xL}(\delta_L)I_{1L}\sin\frac{\pi}{\tau}x_{0L} \tag{1}$$

$$F_{yL}(I_{1L},x_{0L},\delta_L)=-K_{yL}(\delta_L)I_{1L}\cos\frac{\pi}{\tau}x_{0L} \tag{2}$$

$$F_{zL}(I_{1L},x_{0L},\delta_L)=-K_{zL}(\delta_L)I_{1L}\cos\frac{\pi}{\tau}x_{0L} \tag{3}$$

where τ is the pole-pitch, and for the left side LSM I_{1L} is effective armature-current, x_{0L} mechanical loadangle, δ_L air-gap length, K_{xL}, K_{yL} and K_{zL} are coefficients of propulsion-, levitation- and guidance-forces.

Similarly, for the right side LSM, subscript R is applied instead of L for the left side LSM.

3.2 Equation of Motion

The equations of three-dimensional motions are simply described as follows:

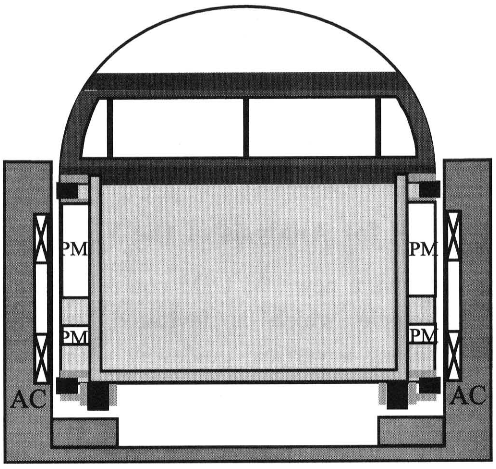
$$Ma_x=F_{xL}+F_{xR} \tag{4}$$
$$Ma_y=F_{yL}+F_{yR}-Mg \tag{5}$$
$$Ma_z=F_{zL}-F_{zR} \tag{6}$$

where a_x, a_y and a_z are the x-, y- and z-directed acceleration of the vehicle, g the acceleration of gravity, M the mass of the vehicle.

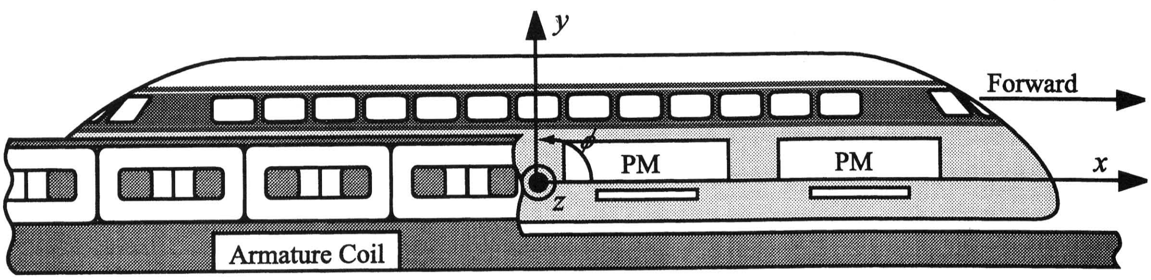
4. Control Method

4.1 Control Method for Levitation and Propulsion

A compact control method is developed which is based on the concept of controlling individually the



(a) Front view



(b) Side view

Fig. 2　Model for Analysis of the Vehicle levitation system by armature-current I_1 and the propulsion system by mechanical load-angle x_0.

The demand patterns of mechanical load-angle x_{00} and effective armature-current I_{10} are obtained for the demand propulsion-and-levitation motion pattern from (4) and (5) under the condition that δ_L is equal to δ_R.

In order to follow the demand patterns in the x- and y-directions, the control law for x_0 and I_1 based on PID regulator becomes

$$x_0^* = G_{xD}\frac{d}{dt}(x_2 - x_{20}) + G_{xP}(x_2 - x_{20}) + G_{xI}\int(x_2 - x_{20})dt + x_{00} \tag{7}$$

$$I_1^* = G_{yD}\frac{d}{dt}(y_G - y_{G0}) + G_{yP}(y_G - y_{G0}) + G_{yI}\int(y_G - y_{G0})dt + I_{10} \tag{8}$$

where x_0^*, I_1^* are command mechanical load-angle and effective armature-current, respectively. x_2 and x_{20} are the x-directed position and its demand pattern of the vehicle, respectively. y_G and y_{G0} are levitation height of the center of the gravity (CG) of the vehicle and its demand pattern, respectively. G_{iD}, G_{iP} and G_{iI} are feedback gains ($i = x$, y).

4.2 Control Method for Guidance

When δ_L is not equal to δ_R, guidance motion can be controlled without active control from (6). To realize more stable guidance control, active guidance control method is developed which is based on the concept of controlling individually both side effective armature-currents and mechanical load-angles. Command mechanical load-angle x_{0L}^* and effective armature-current I_{1L}^* of the left side LSM are shown below

$$x_{0L}^* = G_{\psi D}\frac{d}{dt}\Psi + G_{\psi P}\Psi + G_{\psi I}\int\Psi dt + x_0^* \tag{9}$$

$$I_{1L}^* = G_{zD}\frac{d}{dt}\Delta z_G + G_{zP}\Delta z_G + G_{zI}\int\Delta z_G dt + I_1^* \tag{10}$$

where Ψ is yawing angle of the vehicle, Δz_G guidance displacement of the CG of the vehicle, G_{jD}, G_{jP} and G_{jI} are feedback gains ($j = \Psi$, z).

Similarly, the command values of the right side LSM x_{0R}^* and I_{1R}^* are expressed, but the sign of feedback gains must be changed.

4.3 Zero-phase-current Control Method for Pitching and Rolling

The demand pattern of zero-phase-current I_{0d} is obtained under the condition that all torque is zero around the CG of the vehicle. In order to restrain pitching motion, the feedback control law becomes as follows:

$$I_0^* = G_{\phi D}\frac{d}{dt}\phi + G_{\phi P}\phi + I_{0d} \tag{11}$$

where I_0^* is command zero-phase-current, ϕ pitching angle of the vehicle, $G_{\phi D}$ and $G_{\phi P}$ are feedback gains.

To control rolling motion, command zero-phasecurrents of left and right side LSM's I_{0L}^* and I_{0R}^* are shown below

$$I_{0L}^* = G_{\theta D}\frac{d}{dt}\theta + G_{\theta P}\theta + I_0^* \tag{12}$$

$$I_{0R}^* = -G_{\theta D}\frac{d}{dt}\theta - G_{\theta P}\theta + I_0^* \tag{13}$$

where θ is rolling angle of the vehicle, $G_{\theta D}$ and $G_{\theta P}$ are feedback gains.

4.4 Instantaneous Armature-current

From x_{0L}^*, I_{1L}^*, x_{0R}^*, I_{1R}^*, I_{0L}^*, I_{0R}^* and x_2, left- and right-side command values of instantaneous armature-current can be derived. Its instantaneous three phase armature-current i_{uL}^*, i_{vL}^*, i_{wL}^* in the left-side becomes

$$i_{uL}^* = \sqrt{2}\, I_{1L}^* \cos\theta_L + I_{0L}^* \tag{14}$$

$$i_{vL}^* = \sqrt{2}\, I_{1L}^* \cos\left(\theta_L - \frac{2}{3}\pi\right) + I_{0L}^* \tag{15}$$

$$i_{wL}^* = \sqrt{2}\, I_{1L}^* \cos\left(\theta_L - \frac{4}{3}\pi\right) + I_{0L}^* \tag{16}$$

$$\theta_L = \frac{\pi}{\tau}(x_2 + x_{0L}^*) + \frac{\pi}{2} \tag{17}$$

Similarly, for the right-side LSM, subscript R is applied instead of L for the left-side LSM.

Levitation, propulsion and guidance motions of the Maglev vehicle are controlled simultaneously by only these left and right armature-currents. In this Maglev system, both side LSM's are driven and controlled by two independent controllers to realize guidance control.

5. System for Experiment

Fig. 3 shows system for experiment. The system consists of on-board and on-the-ground systems. These control systems are administered and measured by personal computer.

On-board system sends levitation heights y_1, y_2, y_3, y_4 at the four corners and guidance positions z_1, z_2 measured by gap sensors to on-the-ground system by

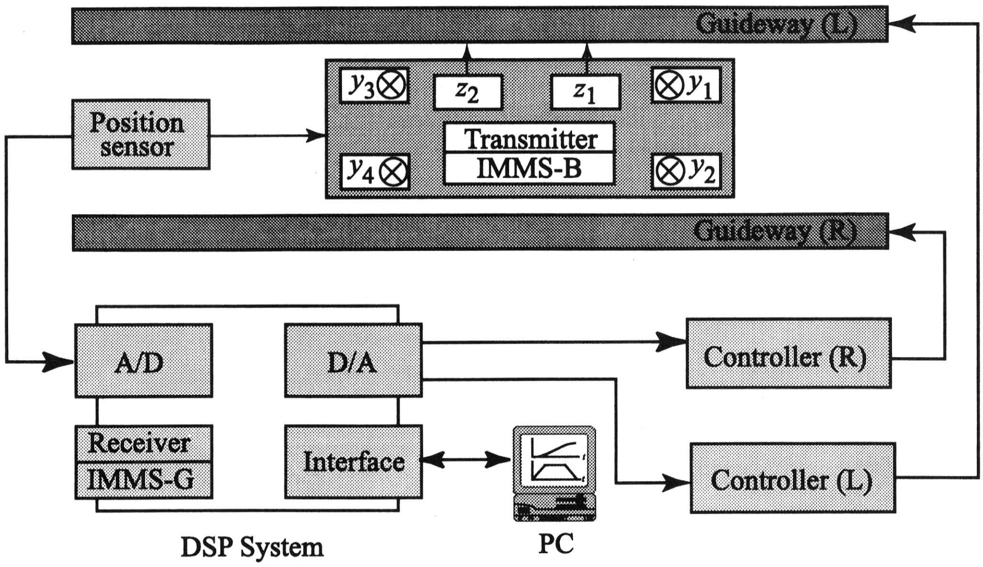


Fig. 3 System for Experiment

wireless through A/D converters, integrated Maglev measuring system on board (IMMS-B) and transmitter.

On-the-ground system controls Maglev vehicle on the basis of information of levitation height, guidance position and vehicle position sent to DSP through receiver and IMMS on the ground (IMMS-G). The DSP programed according to control method for levitation, propulsion and guidance calculates command values of instantaneous armature-current in both sides and sends them to the corresponding controllers through D/A converters, respectively.

6. Experimental Results

Levitation, propulsion and guidance motions have been simultaneously controlled successfully. The vehicle takes off from initial height (0mm) supported mechanically by rollers up to the rated height of 5mm, together with positioning and guiding at its starting point. It travels with going and returning along a distance of 9cm at the maximum speed of 9cm/s and the maximum acceleration and deceleration of 22.5cm/s^2.

Fig. 4 shows experimental results of combined levitation-propulsion-guidance motion control. **Fig. 4** (a), (c), (f), show the date measured directly by sensor. The shaded and shadeless regions in **Fig. 4** show the running and standstill periods, respectively. At standstill the levitation and guidance motions are controlled stably with rolling, pitching and yawing controls.

Fig. 4 (e) shows the pitching angle of the vehicle, which a relatively large acceleration has caused. **Fig. 4** (g) and (h) show the sway position and the yawing angle, respectively. From the **Fig. 4** (a), (b), (d), (g) it is found that the vehicle has followed very well the demand patterns of position, speed, levitation-height and guidance-position in the center of the guideway. As shown in **Fig. 4** (i), the rolling motion has been controlled satisfactory. **Fig. 4** (j) and (k) show the zero-phase-current of left- and right-side LSM's calculated for pitching and rolling controls. **Fig. 4** (l), (m), (n) and (o) show the command effective armature-current and mechanical load-angle of left- and right-side LSM's calculated for levitation, propulsion and guidance controls. It is found that the mechanical load-angles of both side LSM's have been τ because of repulsive control.

7. Conclusions

We have verified experimentally the theory of combined levitation-propulsion-guidance by using LSM only in the new PM LSM controlled-repulsive Maglev model vehicle. In the new vertical type Maglev system proposed here, levitation, propulsion and guidance motions have been controlled simultaneously by driving and controlling both side LSM's with two controllers which have enabled the guidance control to be realized. Zero-phase-current control method has compensated for pitching and rolling motion and also helped Maglev vehicle to control levitation-propulsion-guidance motion more stably.

Acknowledgments

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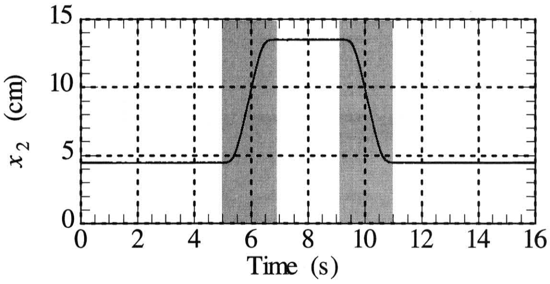
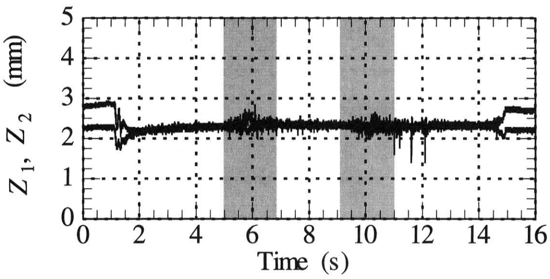
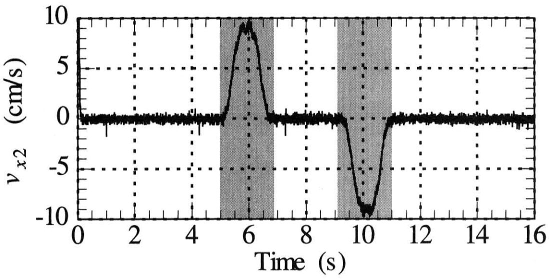


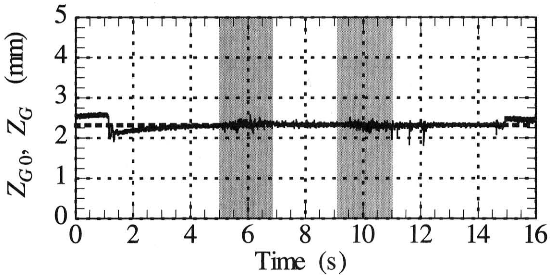
(a) x-directed running position of the Vehicle



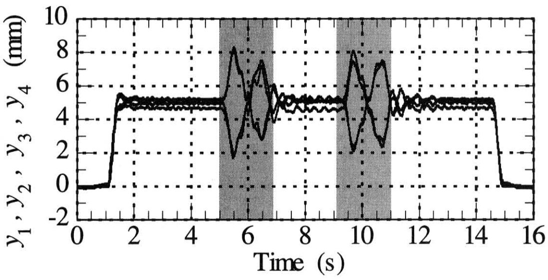
(f) z-directed position of the Vehicle



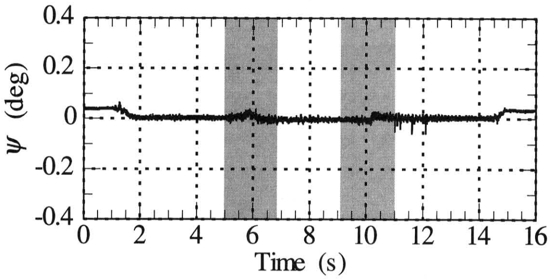
(b) x-directed running speed of the Vehicle



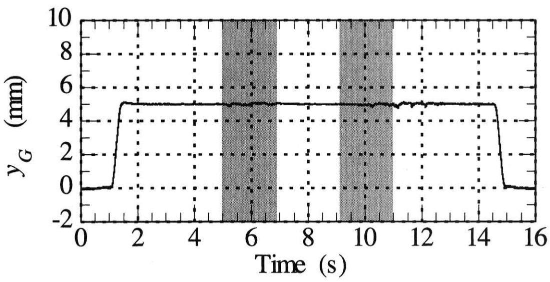
(g) z-directed sway position of the Vehicle



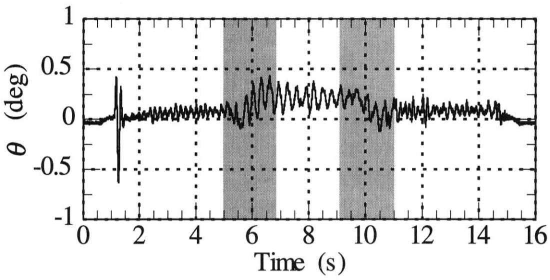
(c) Levitation height at four corners of the Vehicle



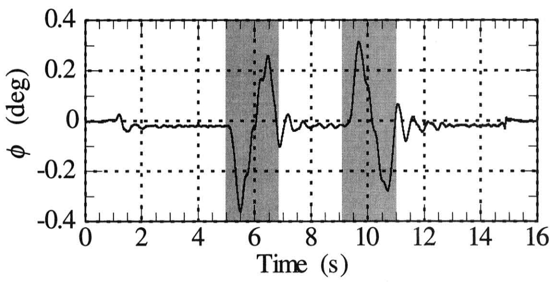
(h) Yawing-angle of the Vehicle



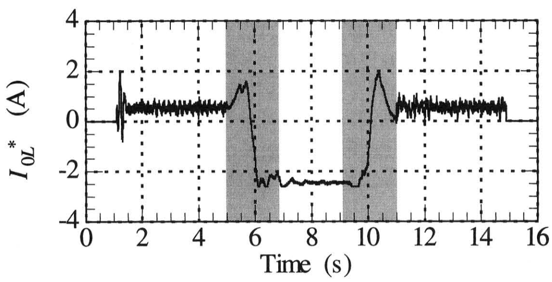
(d) Levitation height of the CG of the Vehicle



(i) Rolling-angle of the Vehicle

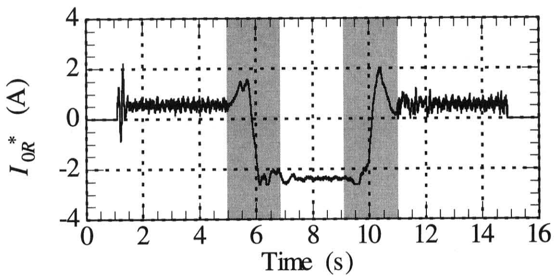


(e) Pitching-angle of the Vehicle

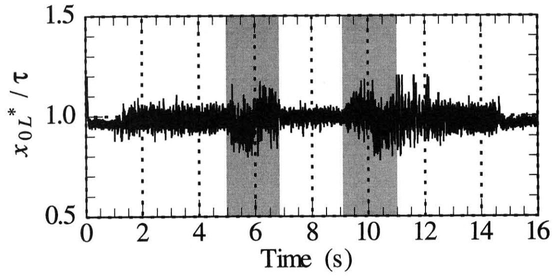


(j) Zero-phase-current of left side LSM

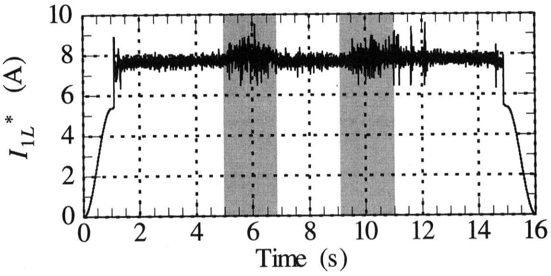
Fig. 4 Experimental Results



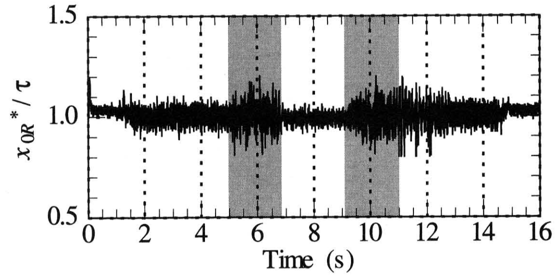
(k) Zero-phase-current of right side LSM



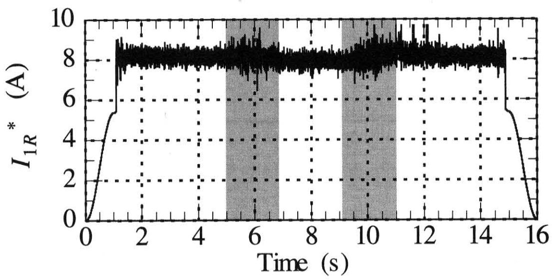
(n) Mechanical load-angle of left side LSM



(l) Effective armature-current of left side LSM



(o) Mechanical load-angle of right side LSM



(m) Effective armature-current of right side LSM

Fig. 4　Experimental Results

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