Levitation Control Experiment at Standstill in PM LSM Controlled-Repulsive Maglev Vehicle

Kinjiro YOSHIDA, Hiroshi TAKAMI, Chiyuki JOZAKI, Shizuo KINOSHITA
Dept. of Electrical and Electronic Systems Engineering,
Graduate School of Information Science and Electrical Engineering,
Kyushu University,
10-1 6-chome Hakozaki Higashi-ku Fukuoka 812-8581,JAPAN
Phone +81-92-642-3905, Fax +81-92-633-2710

ABSTRACT - This paper proposes a new repulsive-Maglev vehicle in which a vertical type PM linear synchronous motor (LSM) can levitate and propel simultaneously, independently of the vehicle speeds. A compact control method is developed which is based on the concept of controlling individually the levitation system by armature-current and the propulsion system by mechanical load-angle. The levitation-motion control experiments have carried out successfully together with positioning at standstill. The pitching motion has been compensated for very well by using the zero-phase-current control method proposed here.

1 . INTRODUCTION

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

We have proposed and verified experimentally the theory of a new repulsive Maglev vehicle which can levitate and propel simultaneously from a standstill, independently of the vehicle speed [2] [3]. The controlled-repulsive Maglev vehicle system, which we call, has the SCM's or permanent magnets (PM) on board and air-cored armature coils on the ground which compose SC LSM or PM LSM. From the viewpoint that LSM can produce three-dimensional force [4], we have been studying on new controlled-repulsive Maglev vehicle system [5] [6].

This paper presents levitation control experiments with positioning at standstill which contain pitching control in newly proposed PM LSM vehicle. A repulsive levitation-force produced in the tangential direction is controlled stably in a vertical construction of PM on board and armature coils on the guideway. The zero-phase-current control method is proposed to compensate for the pitching motion.

2 . EQUATION OF MOTION

Figure 1 shows a new controlled-repulsive Maglev vehicle which is levitated at standstill on a vertical guideway with armature coils. The corresponding PM on board is arranged on both sides of the vehicle, as shown in Fig. 2.

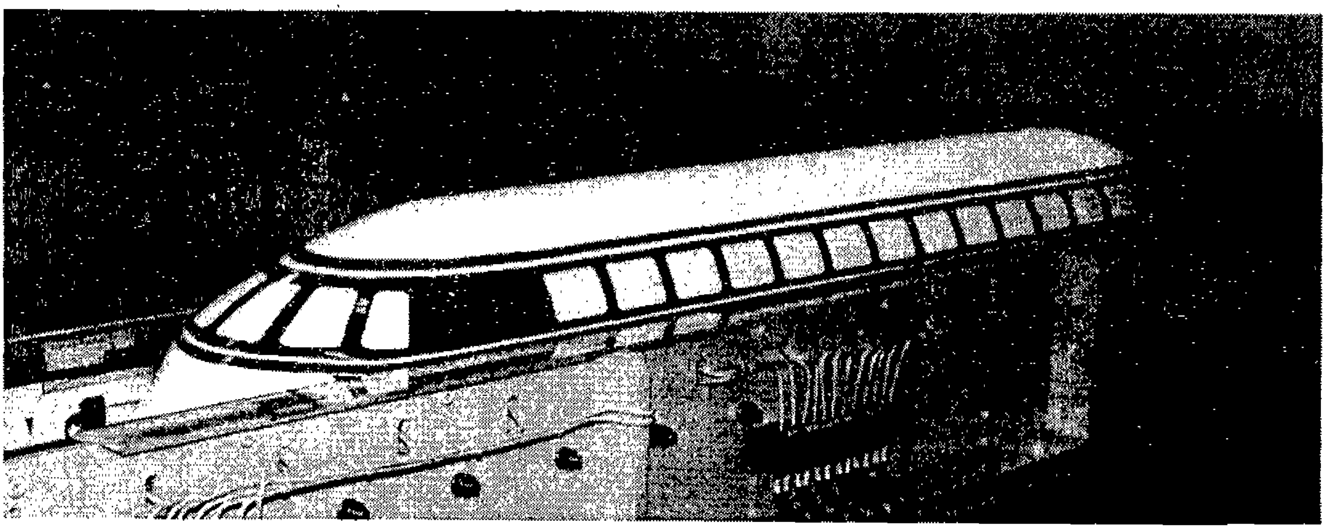


Fig. 1 New repulsive Maglev model vehicle levitated on vertical guideway

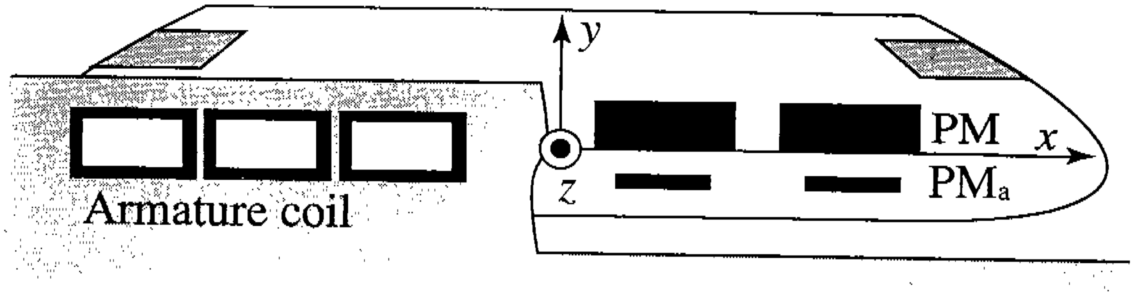


Fig. 2 An analytical model of the Maglev vehicle

Levitation and propulsion forces

The vehicle is assumed to be running in the center of both sides of armature coils. The propulsion and levitation forces are analyzed as the x- and y-components of tangential forces produced between PM and current-carrying armature coils.

As a result of analysis, propulsion-force F_x can be expressed in the following simple form :

$$F_x(I_1, x_0) = K_{Fx} I_1 \sin\frac{\pi}{\tau} x_0 \tag{1}$$

where τ = pole-pitch
K_{Fx} = coefficient of propulsion-force
I_1 = effective armature-current
x_0 = mechanical load-angle

Levitation-force F_y can be also expressed in the following form :

$$F_y(I_1, x_0) = -K_{Fy} I_1 \cos\frac{\pi}{\tau} x_0 \tag{2}$$

where K_{Fy} = coefficient of levitation-force

Equation of motions

The equations of propulsion and levitation motions are simply described as follows :

$$Ma_x = F_x \quad \text{(for propulsion)} \tag{3}$$

$$Ma_y = F_y - Mg \quad \text{(for levitation)} \tag{4}$$

where M = mass of the vehicle
a_x = x-directed acceleration of the vehicle
a_y = y-directed acceleration of the vehicle
g = acceleration of gravity

3 . CONTROL METHOD

A compact control method is developed which is based on the concept of controlling individually the levitation system by armature-current and the propulsion system by mechanical load-angle.

Control method for levitation at standstill

The demand pattern of mechanical load-angle x_{00} is obtained as shown in (5) by applying $F_x = 0$ in (1) in repulsive-mode.

$$x_{00} = \tau \tag{5}$$

For y-directed acceleration pattern of the vehicle a_{y0}, the demand effective armature-current I_{10} is derived from (2), (4) and (5), as follows :

$$I_{10} = \frac{M(a_{y0} + g)}{K_{Fy}} \tag{6}$$

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

$$x_0^* = G_{xD}(\dot{x}_2 - \dot{x}_{20}) + G_{xP}(x_2 - x_{20}) + G_{xI}\int(x_2 - x_{20})dt + x_{00} \tag{7}$$

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

where x_0^* = command of mechanical load-angle
I_1^* = command of effective armature-current
x_2 = x-directed position of the vehicle
x_{20} = x-directed position pattern of the vehicle
y_G = y-directed position of the vehicle
y_{G0} = y-directed position pattern of the vehicle
G_{iD} , G_{iP} , G_{iI} = feedback gains ($i = x , y$)

Zero-phase-current control method for pitching [7]

The demand pattern of zero-phase-current I_{0d} is obtained under the condition that all torque is zero around the center of gravity (CG) of the vehicle, as shown in (9).

$$I_{0d} = \sum_{n=1}^{6} c_{3n} \sin\frac{3n\pi}{\tau} x \tag{9}$$

where c_{3n} = coefficient for harmonics

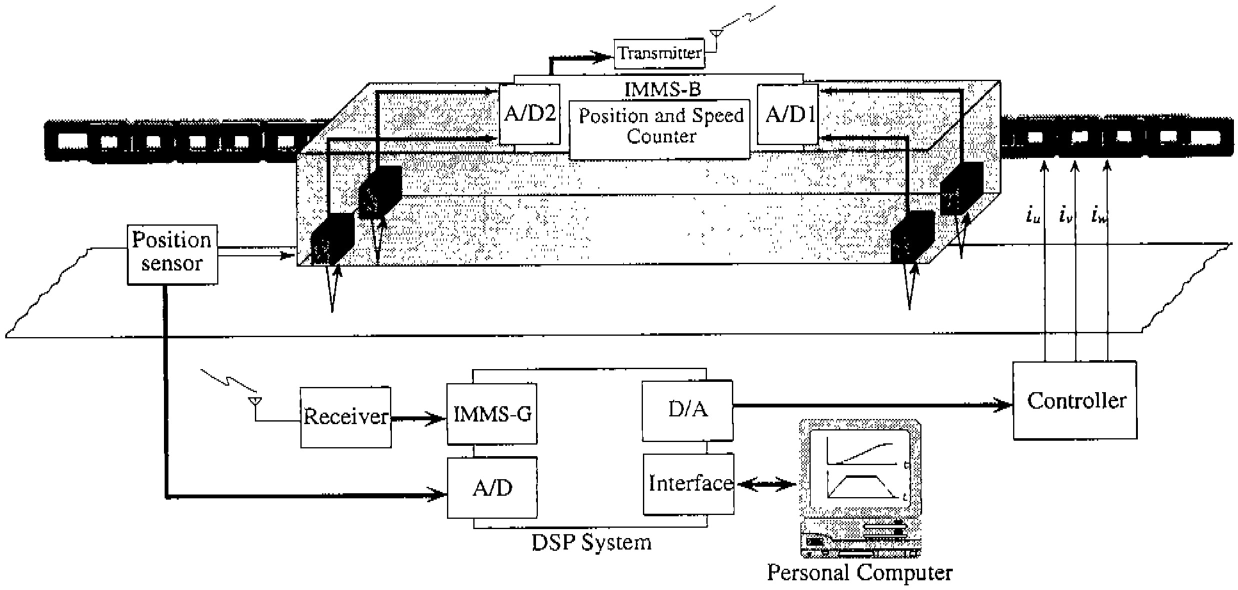


Fig. 3 System for experiment

IMMS-B : Integrated Maglev Measuring System on Board
IMMS-G : Integrated Maglev Measuring System on the Ground

In order to restrain pitching motion, the feedback control law for (9) becomes

$$I_0^* = I_{0d} + G_{\phi P}\phi \quad (10)$$

where I_0^* = command pattern of zero-phase-current
ϕ = pitching-angle of the vehicle
$G_{\phi P}$ = feedback gain

Instantaneous armature-current

The command of instantaneous armature-current i_u^*, i_v^*, and i_w^* are expressed as follows :

$$i_u^* = \sqrt{2}I_1^* \cos\theta + I_0^* \quad (11)$$

$$i_v^* = \sqrt{2}I_1^* \cos\left(\theta - \frac{2}{3}\pi\right) + I_0^* \quad (12)$$

$$i_w^* = \sqrt{2}I_1^* \cos\left(\theta - \frac{4}{3}\pi\right) + I_0^* \quad (13)$$

$$\theta = \frac{\pi}{\tau}\left(x_2 + x_0^*\right) + \frac{\pi}{2} \quad (14)$$

Note that $\pi/2$ in (14) is used for a starting position of the vehicle to coincide with u-phase coil.

4 . SYSTEM FOR EXPERIMENT

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

On-board system sends levitation heights (y_1, y_2, y_3, y_4) at four corner measured by sensors to On-the-ground system by wireless.

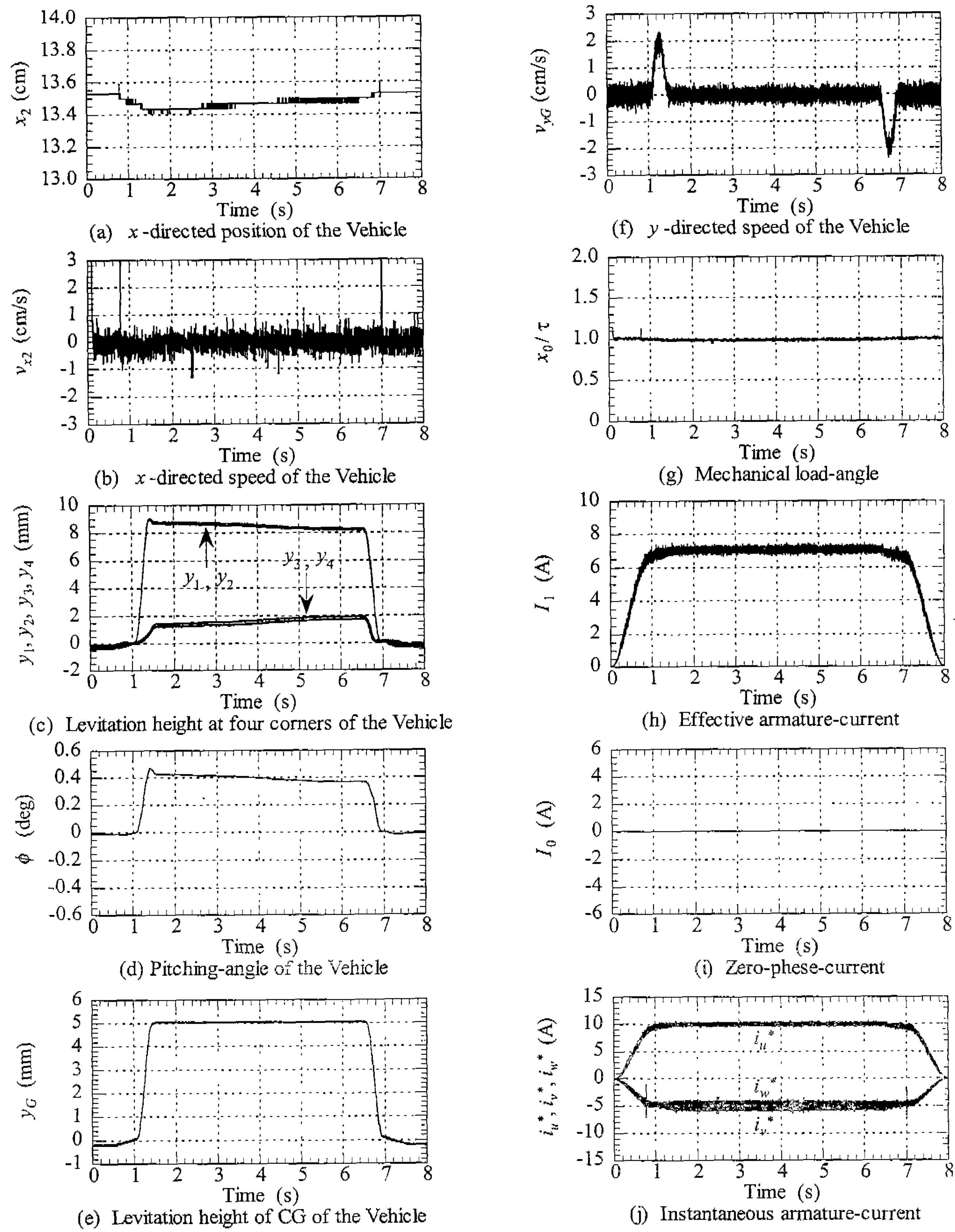
On-the-ground system controls Maglev vehicle on the basis of information of levitation height and vehicle position sent to DSP. DSP programed according to control method for levitation and propulsion calculates command values of instantaneous armature-current i_u^*, i_v^*, i_w^*, and sends these to Controller. Controller gives i_u, i_v, i_w to armature-coil. Levitation and propulsion motions of the vehicle is controlled by only armature currents on the ground.

5 . EXPERIMENTAL RESULTS

Standstill levitation-motion is controlled in which the vehicle takes off from 0 mm (initial height supported mechanically by rollers) to the rated height of 5mm, together with positioning at starting point of the vehicle. In order to analyse only the levitation and propulsion motions, the vehicle is guided in the center of the guideway with soft contact by the help of guide-rollers.

Figure 4 shows experimental results without any pitching control. Levitation and positioning at standstill have been controlled very well simultaneously. But a relatively large pitching-motion has been caused, and can not be neglected.

Figure 5 shows experimental results obtained by applying the zero-phase-current control method to pitching-control. Figure 5(d) shows that the pitching-motion has been almost compensated for. As compared with Fig.4, it is also found that the proposed pitching-control method do not almost have a bad influence on levitation and positioning motions.



(a) x-directed position of the Vehicle

(b) x-directed speed of the Vehicle

(c) Levitation height at four corners of the Vehicle

(d) Pitching-angle of the Vehicle

(e) Levitation height of CG of the Vehicle

(f) y-directed speed of the Vehicle

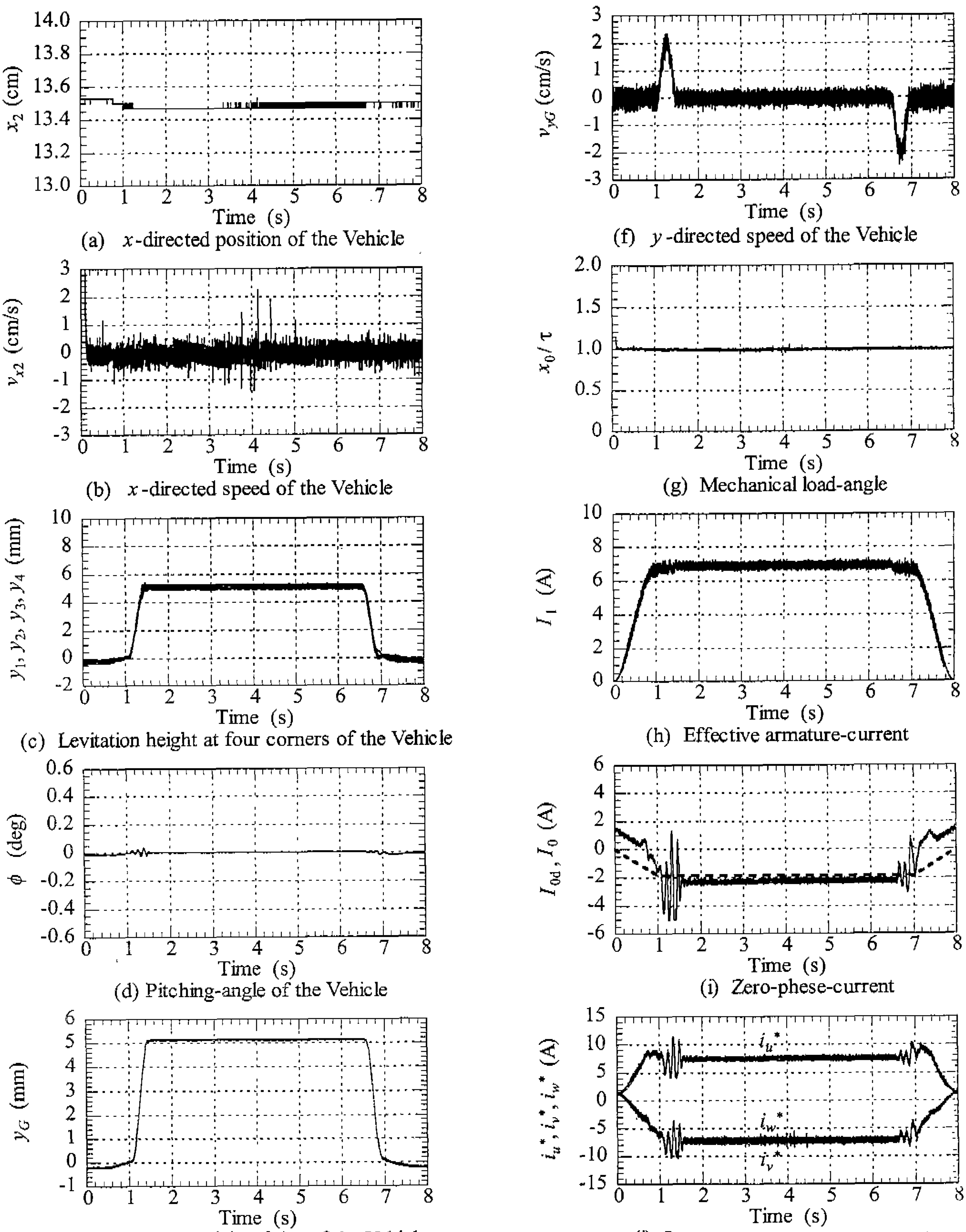
(g) Mechanical load-angle

(h) Effective armature-current

(i) Zero-phese-current

(j) Instantaneous armature-current

Fig.4 Experimental results without pitching control



(a) x-directed position of the Vehicle

(b) x-directed speed of the Vehicle

(c) Levitation height at four corners of the Vehicle

(d) Pitching-angle of the Vehicle

(e) Levitation height of CG of the Vehicle

(f) y-directed speed of the Vehicle

(g) Mechanical load-angle

(h) Effective armature-current

(i) Zero-phese-current

(j) Instantaneous armature-current

Fig.5 Experimental results using pitching control

6 . CONCLUSIONS

Levitation control experiment at standstill has succeeded in repulsive-mode in a vertical type PM LSM Maglev vehicle. Positioning-motion at standstill has been controlled very well, especially with pitching-motion controlled by using zero-phase-current control method proposed here. The proposed method can compensate for the pitching motion without any influence on levitation and positioning motions.

Controlled-repulsive Maglev vehicle could levitate and propel stably and smoothly from a standstill by using the proposed pitching-control method.

7 . ACKNOWLEDGMENT

This research was supported by Grant-in Aid for Scientific Research A(2), Japan.

8 . REFERENCES

[1] H. Soejima, K. Isoura, "Development of the Maglev system in Japan : Past, Present and Future --," in Proc. of The 15th Inter. Conf. on Magnetically Levitated Systems and Linear Drives, MAGLEV'98, pp.8-11, 1998

[2] K. Yoshida, H. Takami and L. Shi, "Decoupled-Control Method for Levitation and Propulsion in Amphibious Train Marine-Express,:" Memories of the Faculty of Engineering Kyushu University, vol.**55**, no.4, pp.476 - 489, Dec., 1995.

[3] K. Yoshida, H. Takami, Y. Nagano and A. Sonoda, "A New Combined Levitation-and-Propulsion Control in Repulsive-Mode of a Land Travelling Marine-Express Model Train ME03," in Proc. of the 1996 Inter. Conf. on Electrical Machines, pp.242-247.

[4] K. Yoshida, "Magnetic Levitation and Linear Motor,:" Science of Machine, vol.**42**, No.4, pp.468-474, 1990

[5] K. Yoshida and T. Egashira, "Running simulation in SCM LSM controlled-Repulsive Maglev Vehicle," in Record of 1996 Joint Conference of Electrical and Electronics Engineers in Kyushu, p.443.

[6] K. Yoshida and C. Jozaki, "Simulation of Lvitation Control at Standstill in PM LSM controlled-Repulsive Maglev Vehicle," in Record of 1997 Joint Conference of Electrical and Electronics Engineers in Kyushu, p.683.

[7] K. Yoshida, H. Takami, C. Jozaki and S. Kinoshita, "Zero-phase-current Method for Pitching Control in PM LSM controlled-Repulsive Maglev Vehicle," in Record of 1998 Joint Conference of Electrical and Electronics Engineers in Kyushu, (to be published) .