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Repulsive-Levitation Control at Standstill Using Underwater ME02 as a Land Travelling ME Simulator

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Abstract : A unique linear synchronous motor (LSM) vehicle ME02 is designed to travel underwater based on the theory of new combined levitation and propulsion for the Marine-Express. This paper presents its stable levitation control in repulsive-mode underwater during standstill. The repulsive-mode levitation can be realized under a condition that the buoyancy of the water is smaller than the weight of the vehicle, which means that the ME02 can simulate the ME running on land. Because ME02 is a combined levitation and propulsion system, positioning control at a demand standstill-point is simultaneously carried out by the help of thrust force to levitate steadily at the standstill point. The experiment in our Laboratory has shown that ME02 vehicle had been controlled successfully to levitate underwater in repulsive-mode during standstill by applying the decoupled-control method of lift and thrust forces.

Keywords : Underwater marine-express, LSM, Repulsive-levitation, Decoupled-control, DSP

1. Introduction

The Marine-Express (ME) project, of which the basic concept is an amphibious linear motor (LM) train able to run both on land and under the water, was initiated in our University, in 1989. A theory of new combined levitation and propulsion for the ME was proposed by Yoshida[1)2)]. In the sea, the ME can levitate and travel simultaneously by controlling *force vector* of LSM in attractive-mode to compensate a buoyancy of the water. On land it does by controlling *force vector* of LSM in repulsive-mode. For an actual amphibious vehicle running undersea, a buoyancy of the water is generally much larger than vehicle weight. It is the best solution to make use of an electromagnetic attractive-force between the magnet on board and the iron-core LM guideway under the sea to compensate the large buoyancy, while on land there should be no iron-core in the LM guideway to produce large repulsive-force easily. The first underwater LM vehicle ME01 which is driven by linear induction motor has successfully travelled underwater in a repulsive-mode levitation along the canned LM guideway in a water tank[2)]. To simulate an actual ME vehicle driven by superconducting LSM, the second underwater LM vehicle ME02 with permanent magnet (PM) on board is designed and manufactured to levitate and run both in attractive- and/or repulsive-mode in the same water tank as shown in **Fig. 1**[3)]. The levitation experiment in attractive-mode during standstill and propulsion experiment in a mass-control mode have been realized

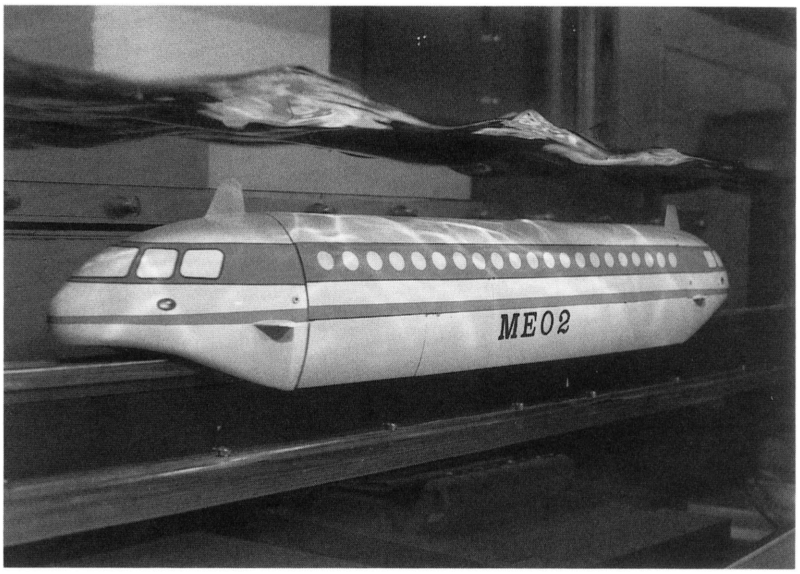

Fig. 1 ME02 running underwater in water tank

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successfully in our Laboratory[4)5)].

This paper presents a repulsive-mode levitation control at standstill using underwater ME02 as a land travelling ME simulator. Under the condition of a little smaller buoyancy than the vehicle weight, ME02 is controlled by lift and thrust forces to follow the demand standstill-levitation patterns according to the decoupled-control method which treats independently the two forces. In order to realize a stable levitation at standstill under the water in this combined levitation and propulsion system, positioning control at the demand point is simultaneously carried out by the help of thrust force. The experiment has shown that ME02 vehicle had been controlled successfully to levitate underwater as a land travelling ME simulator, following the demand standstill-levitation patterns in repulsive-mode.

2. ME02 and Its Characteristics

Figure 1 shows ME02 running underwater in the water tank. ME02 is 105 cm long, about 11 kg in weight, 17 cm in diameter and streamlined with dorsal and tail fins. **Figure 2** shows the cross-section of a 1/25-th scale model vehicle ME02. It has fifteen poles of PM's underneath the body and the LM guideway of iron-cored long stator is enclosed by stainless steel in the water tank. Vehicle is levitated and propelled by only one pair of armature on the guideway and PM on board.

The ME02 has four upper and four lower guide-rollers in the vertical direction and two side guide-rollers in the lateral direction on each side. In **Fig. 2**, when four upper guide-rollers are contacted simultaneously with the guideway, the airgap-lengths δ at the center of the vehicle, and δ_F, δ_R at the points of front and rear gap-sensors as shown in **Fig. 5** are all the same value, 9 mm. δ, δ_F and δ_R are 12 mm with four lower guide-rollers contacted at the same time with the guideway. It is thus possible that one end of the vehicle sinks down and another rises up.

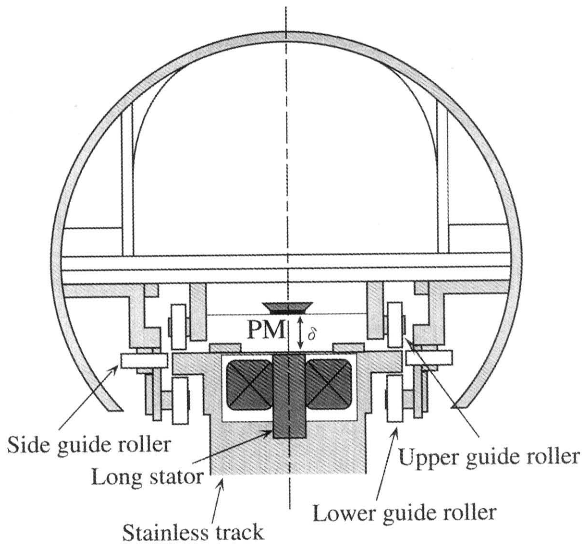


Fig. 2　Transvers cross-section of ME02

In this LSM system, the thrust force F_x and the lift force F_z can be given in the following analytical form by using Magnetic Vector Potential (MVP) transfer-matrix method[6)7)]:

$$F_x = K_{F0}(\delta_e) I_1 \sin\frac{\pi}{\tau} x_0 \tag{1}$$

$$F_z = -K_{zs}(\delta_e) I_1^2 - K_{zMs}(\delta_e) I_1 \cos\frac{\pi}{\tau} x_0 - K_{zM}(\delta_e) \tag{2}$$

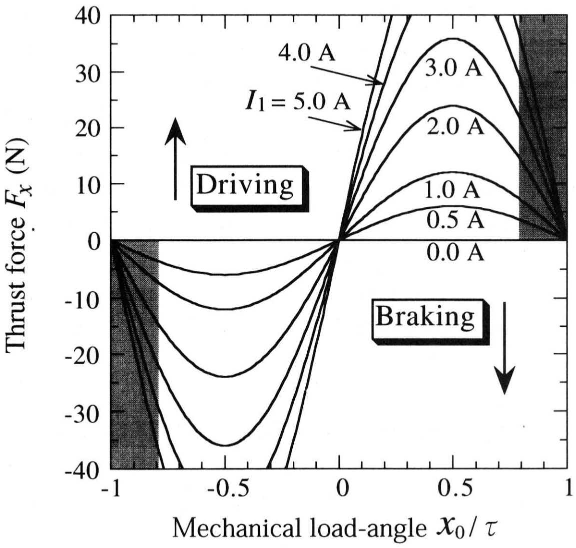
where K_{F0}, K_{zs}, K_{zMs}, K_{zM} are the coefficients of thrust and lift forces, I_1 effective value of armature current, τ the pole pitch, x_0 mechanical load-angle and $\delta_e = k_c \delta$ effective airgap length modified by Carter's coefficient.

Figures 3 (a) and (b) show the dependence of thrust force F_x and the lift force F_z on the mechanical load-angle x_0 when the airgap-length δ is 10 mm and the effective armature-current I_1 is given in the range of 0~5A by calculating Equ.(1) and (2). F_z shows a sinusoidal function including the offset which is varied with I_1. Heavily and lightly shaded regions in **Fig. 3** (b) illustrate the repulsive- and attractive-modes, respectively. From **Fig. 3** (b), it is known that the attractive force can be large enough to compensate easily the buoyancy of the water by regulating I_1 and x_0 due to the large attraction between PM on board and the stator iron in the LSM guideway. In addition, in the range of about $0.78\,\tau < |x_0| \leqq \tau$ for $0.8\text{A} \leqq I_1 < 4$ A, we can realize the repulsive-mode levitation with $0 < F_z < 1$ kg to compensate the vehicle weight about 11 kg together with the buoyancy of 10~11 kg. Although thrust force F_x is small in the range $0.78\,\tau < |x_0| \leqq \tau$ as shown in **Fig. 3** (a), it is available to drive and brake ME02 in repulsive-mode levitation because required F_x is also very small when ME02 run under the water. This repulsive-mode levitation under the water can simulate that of the actual ME running on the ground.

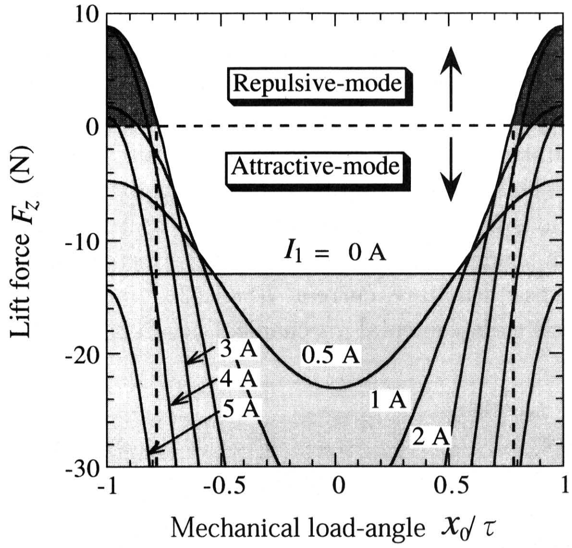
3. Decoupled-Control for ME02

The decoupled-control law of thrust and lift forces in combined levitation- and propulsion-motions is obtained as shown in **Fig. 4**[8)].

In order to control the ME, which runs under the water in repulsive-mode, the thrust and lift forces have to be controlled quickly without coupling for the



(a) Thrust force vs. mechanical load-angle with a parameter of armature current



(b) Lift force vs. mechanical load-angle with a parameter of armature current

Fig. 3 Thrust and lift forces in PM LSM applied to ME02

vehicle to keep standstill stably and to levitate under the water. Therefore, the decoupled-control strategy for motions of levitation and propulsion is adopted into the robust control system of ME02. The equations of propulsion and levitation motion is simply described as follows:

$$M_x \ddot{x}_2 = F_x - K_{dx} \dot{x}_2 \quad (3)$$

$$M_z \ddot{z}_2 = F_z + F_L - Mg - K_{dz} \dot{z}_2 \quad (4)$$

where M is the mass of the vehicle, M_x the equivalent mass in the x direction and M_z the equivalent mass in the z direction, F_x the thrust force, F_z the lift force, F_L the buoyancy of the water, g the acceleration of gravity. K_{dx}, K_{dz} are the coefficients of running resistance in the x- and z- directions, $\dot{x}_2$, $\ddot{x}_2$, $\dot{z}_2$, $\ddot{z}_2$ the speeds and accelerations of vehicle in the x- and z-directions, respectively.

According to the optimal servo-control theory and the minimum error control method, demand forces $F_x{}^*$ and $F_z{}^*$ can be deduced as follows:

$$F_x{}^* = k_{xP}(x_{20} - x_2) + k_{xD}(v_{x20} - v_{x2}) + k_{xI}\int(x_{20} - x_2)dt + Ma_{x20} + F_{HD} \quad (5)$$

and

$$F_z{}^* = k_{zP}(z_{20} - z_2) + k_{zD}(v_{z20} - v_{z2}) + k_{zI}\int(z_{20} - z_2)dt + Mg - F_L + Ma_{z20} + F_{VD} \quad (6)$$

where x_{20}, x_2 denote the command and measured positions, v_{x20}, v_{x2} the command and measured speeds of propulsion motion, z_{20}, z_2 the command and the measured airgap-lengths, v_{z20}, v_{z2} the command and the measured speeds of levitation motion. k_{xP}, k_{xD} are the feedback gains for propulsion, k_{zP}, k_{zD} the feedback gains for levitation. k_{xI}, k_{zI} the integral gains for propulsion and levitation, respectively. F_{HD}, F_{VD} are the running resistances for propulsion and levitation motions, respectively.

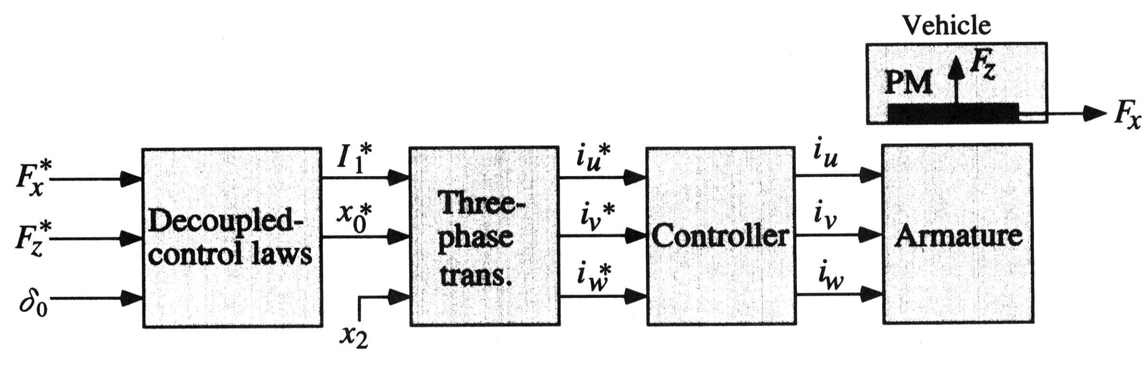


Fig. 4 Decoupled control system

In the control strategy as shown in **Fig. 4**, to realize a decoupled-control for levitation and propulsion, first we determine command force F_x^*, F_z^* required for the vehicle to follow the demand position, speed and acceleration patterns according to the control rule based on the optimal servo-control theoly. Then, we calculate the command armature current I_1^* and mechanical load-angle x_0^* from F_x^*, F_z^* and the demand airgap-length δ_0 by using a 2-dimensional interpolation method for Digital Signal Processor (DSP)[8]. Signals of the command 3-phase instantaneous currents are put into the power controller. Though the standstill levitation control is investigated, the positioning control in which the demand values for the vehicle position, speed and acceleration patterns in the x- direction are all zero is simultaneously carried out by the help of thrust force.

4. Control System for ME02

Figure 5 shows the sensing system on board and vehicle control system on the ground for experiment[9]. The position-sensor target with periodic strip wide about 3 mm and the white tape for airgap sensors are pasted on the surface along the guideway.

In the control system for ME02, the airgap- and position-sensors on board are used to detect the vehicle states, respectively as shown in **Fig. 5**. The detected state-signals of the vehicle are collected by Integrated Vehicle Instrument System (IVIS) and transmitted to on-the-ground control system through water and air by high speed modem and transmitters. Receivers catching the transmitted signals, position-and-speed calculation and control units, A/D and D/A converters, a host computer sending the demand patterns, a current-source power controller supplying the command 3-phase currents to LSM armature winding, and so on, are included in the on-the-ground control system. To carry out the real-time calculation-and-control at high speed, DSP (TMS320C25) is applied in the experimental control system.

5. Experimental Results and Discussions

In this experiment, to simulate an ME running on land, the vehicle weight is regulated to the condition that it is larger than the buoyancy ($Mg-F_L=0.03Mg$). The initial airgap-length δ_i is 9 mm with the vehicle supported by upper guide-rollers on the guideway, due to the large attractive force (F_z=16.2N) between the on-board PM and the stator laminated-iron at δ_i=9 mm and $I_1=0$, as well as $Mg-F_L=0.03Mg$ (about 3N).

Figure 6 shows the experimental results of levitation in repulsive-mode including position control. The levitation control is started from 0.3s and ended at 10.4s. This is the levitation control period. During the periods from 0 to 0.3s and from 10.4 to 11s as shown with shaded regions, the command effective-value of 3-phase armature current $I_1^*=0.62$A and the command complemental mechanical load-angle $x_0'^*=\tau$,

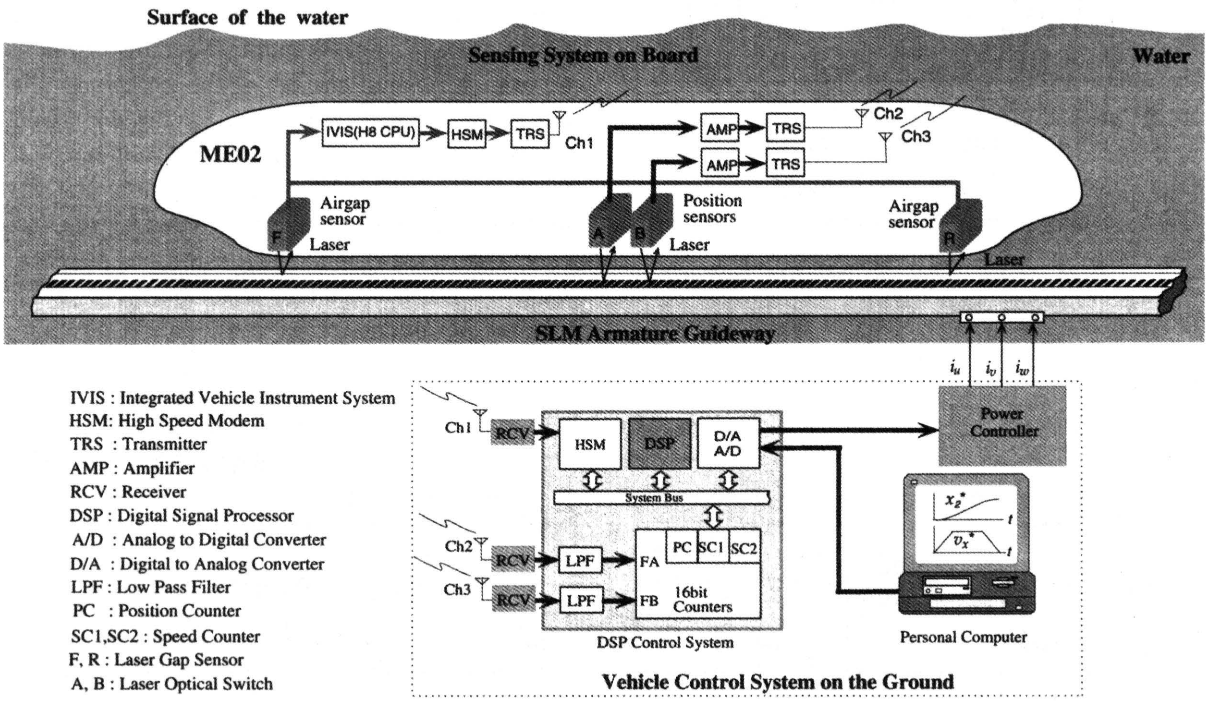


Fig. 5　Vehicle control system with no contact

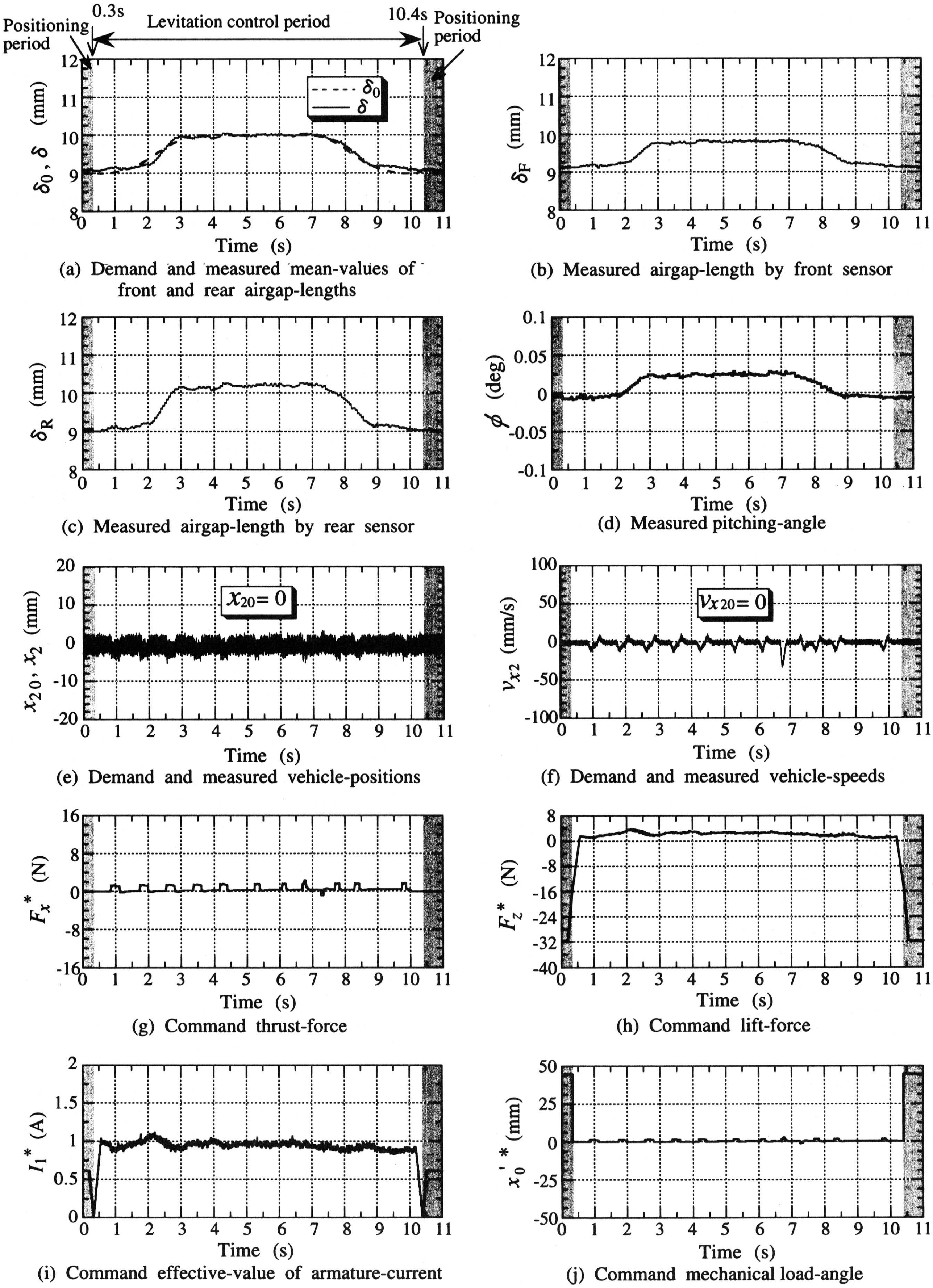


Fig. 6 Experimental results for standstill-levitation control in repulsive-mode under the water

which is defined by $x_0'^* = \tau - x_0^*$, are input into the controller to bring the vehicle to the starting position. These are the positioning periods before and after the levitation period.

From 0.3 to 10.4s, the vehicle is levitated at standstill. **Figure 6** (a) shows the measured mean-value of the front and rear airgap-lengths, meanwhile the demand pattern of airgap is also shown with broken line. **Figure 6s** (b) and (c) show the airgap-lengths measured by the front and rear gap-sensors. **Figure 6** (d) shows the pitching angle calculated from **Figs.6** (b) and (c). All these show that the vehicle had been levitated following the demand levitation patterns satisfactorily. The oscillations of vehicle position and speed as shown in **Figs. 6** (e) and (f) are mainly due to a relatively large width (about 3 mm) of the periodic strip of a position-sensor target on the surface of the guideway. But it is clear that these oscillations are very smalll as compared with the pole pitch $\tau = 44.7$ mm.

When vehicle deviated from standstill-point as shown in **Figs. 6** (e) and (f), the command thrust force F_x^* was produced as shown in **Fig. 6** (g) to keep the vehicle at the standstill-point. The command lift force F_z^* shown in **Fig. 6** (h) is positive to levitate the vehicle, which means that the levitation is realized in repulsive-mode. The command effective-value of the armature-current I_1^* shown in **Fig. 6** (i) is changed gradually from positioning period to levitation control period dependence on the airgap pattern to avoid high voltage induced in armature coils because of the sharp variation of armature current. Mechanical load-angle changed from positioning period to levitation control period at the point of armature current $I_1^* = 0$. **Figure 6** (j) shows the command complemental mechanical-load-angle $x_0'^*$, which variation is also very small around 0 and agreement with the variation of thrust force in the repulsive-mode levitation control period.

The experimental results of armature current and mechanical load-angle are identical on the whole to the analysis for **Fig. 3** (b).

6. Conclusions

We can simulate easily the operation of ME running under the water in attractive-mode levitation and on land in repulsive-mode levitation, by using ME02 running under the water of which the vehicle weight is regulated with respect to the buoyancy. Repulsive-mode levitation control at standstill using ME02 as a land travelling ME simulator has been realized successfully by experiment, under the condition of a little less buoyancy than the vehicle weight.

The decoupled control strategy, which are necessary in combined levitation and propulsion, and control system with DSP have enabled ME02 to realize a stable levitation in repulsive-mode, following very well the demand patterns including the positioning-control at a standstill-point.

This has verified experimentally the theory of new combined levitation and propulsion for the amphibious LM vehicle ME which travels under the water and/or on land.

Repulsive-mode levitation and propulsion test of ME02 are being carried out now.

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