https://doi.org/10.20965/jrm.2013.p1097

Paper:

Levitation Control of AEROTRAIN: The Design and System of Experimental Manned Wing-in-Ground Vehicle ART003R

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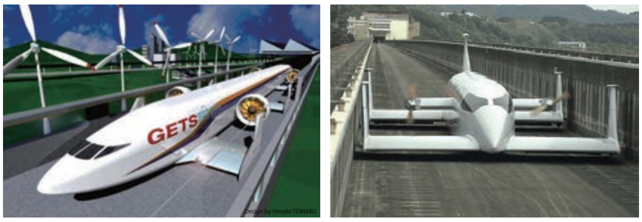
[Received September 28, 2011; accepted October 23, 2013]

The goal of this study was the development of a control method for the levitation stabilization of an aerodynamically levitated train called "Aero-Train," which is a high-speed and high-efficiency train system that levitates using the wing-in-ground effect acting on a U-shaped guideway. To achieve this goal, the authors have been developing the experimental manned vehicle ART003R. This paper provides an overview of ART003R and its control system. Moreover, a description is given of the results of preliminary levitation experiments using simple PD control, which confirmed the effectiveness of the developed control system hardware.

Keywords: aero-train, wing-in-ground effect, levitation control, aerial robotics and mechatronics



(a) Concept image [3] (b) ART002 prototype [13]

(c) ARTE01 prototype [15]

Fig. 1. Concept and prototypes of Aero-Train.

1. Introduction

The recent expansion of the range, scale, and types of activities undertaken by human beings has created global environmental problems. Thus, the realization of high-efficiency transportation systems is an important task that will benefit society. On the other hand, there has been a great demand for high-speed systems. Therefore, the next-generation transportation system should have both characteristics: high efficiency and high speed.

For this purpose, Kohama et al. [1–3] proposed an aerodynamically levitated high-efficiency and high-speed transportation system called "Aero-Train," as shown in **Fig. 1(a)**. Aero-Train has wings and levitates on a U-shaped guideway by utilizing the wing-in-ground (WIG) effect [4], in which the lift-to-drag ratio increases greatly as a result of the air cushion effect under the wings, when they approach the ground or a water surface. This system has several advantages: the wind drag of the vehicle body from the guideway is lower than that of a magnetically levitated train (MAGLEV), and it is safer and more efficient than WIG-effect crafts on a water surface [5–8] because of using a solid guideway. Kohama et al. studied the levitation height at which this phenomenon is effective, along with the lift-to-drag ratio under the WIG effect and the optimal design of the wing and vehicle [9–12]. Furthermore, actual levitation in manual operation has been achieved using the ART002 prototype shown in **Fig. 1(b)**.

To provide levitation stabilization control of Aero-Train, based on the distance between the guideway and vehicle body, a simple PD control [14] and PID control [13] have been studied using the ART002 prototype. However, the performance of this prototype has been unstable, because the low control frequency of 50 Hz and low accuracy and response of the hobby-use RC servo-actuators used to drive the moving blades have been insufficient, and the controller has not been based on a dynamical model of a WIG-effect vehicle. The authors de-

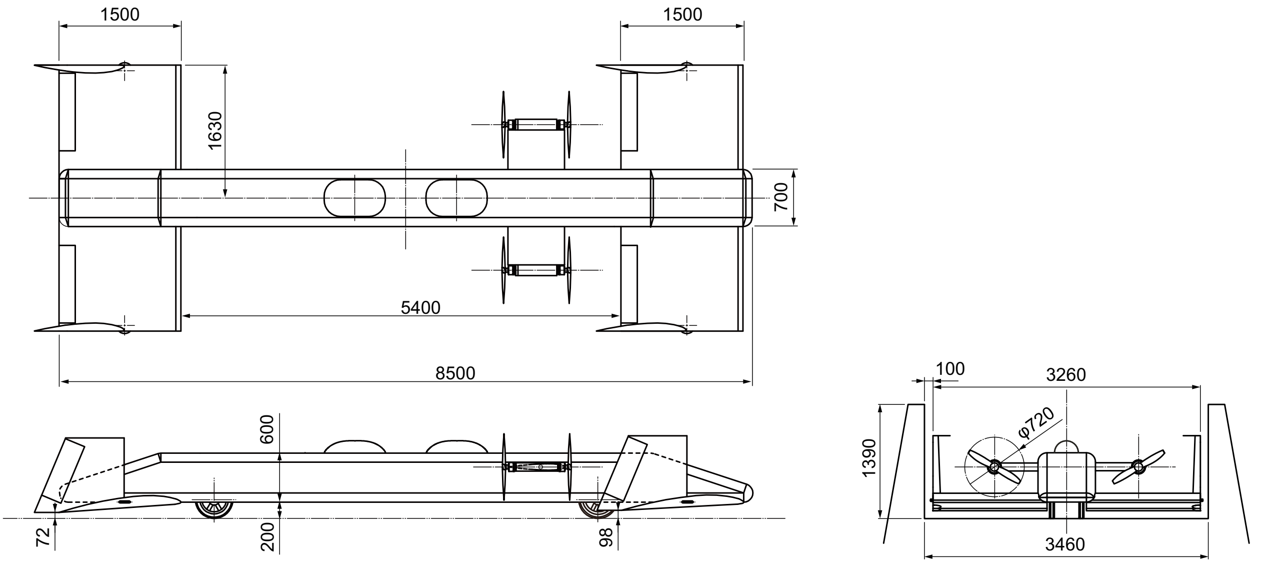


Fig. 2. Orthographic views of experimental manned WIG effect vehicle ART003R.

veloped a small and lightweight experimental WIG-effect vehicle (ARTE01) that can levitate at low speed, as shown in **Fig. 1(c)**, derived 6-DOF dynamic model that included the WIG effect, and designed a controller based on this model for the vehicle height, roll and pitch angles by using state feedback based on a linear quadratic regulator. Through experiments, its effectiveness at achieving stable levitation running under a WIG effect with strong nonlinearity was confirmed [15, 16].

Taking this knowledge into account, Kohama et al. started to develop an experimental manned prototype of Aero-Train (ART003R) that runs at speeds greater than 150 km/h, and the authors have been developing the levitation control system based on the controller of ARTE01.

A brief overview of this manned prototype (ART003R) was given in [17]. This paper describes the details of the experimental manned WIG-effect vehicle ART003R and its control system hardware. Furthermore, the results of a preliminary experiment to confirm the basic performances of the developed hardware are described.

2. Experimental Manned Wing-In-Ground Vehicle ART003R

2.1. Structure and Equipment

The orthographic views, the isometric views, a photograph, and the specifications of the experimental manned WIG-effect vehicle ART003R, are provided in **Figs. 2**, **3**, and **4** and **Table 1**, respectively.

ART003R has two levitation wings at the bottom of the front and rear of the vehicle body in a tandem configuration, along with four guide wings at the tips of these levitation wings. The cross section of the guideway is U-shaped, and the levitation wings generate the lift force for levitation using the WIG effect on the under-surface of the guideway, whereas the guide wings use the WIG effect to generate lift for repulsion from the sidewall of the guideway to maintain the straightness of the course. The dimensions of the wings were designed based on the

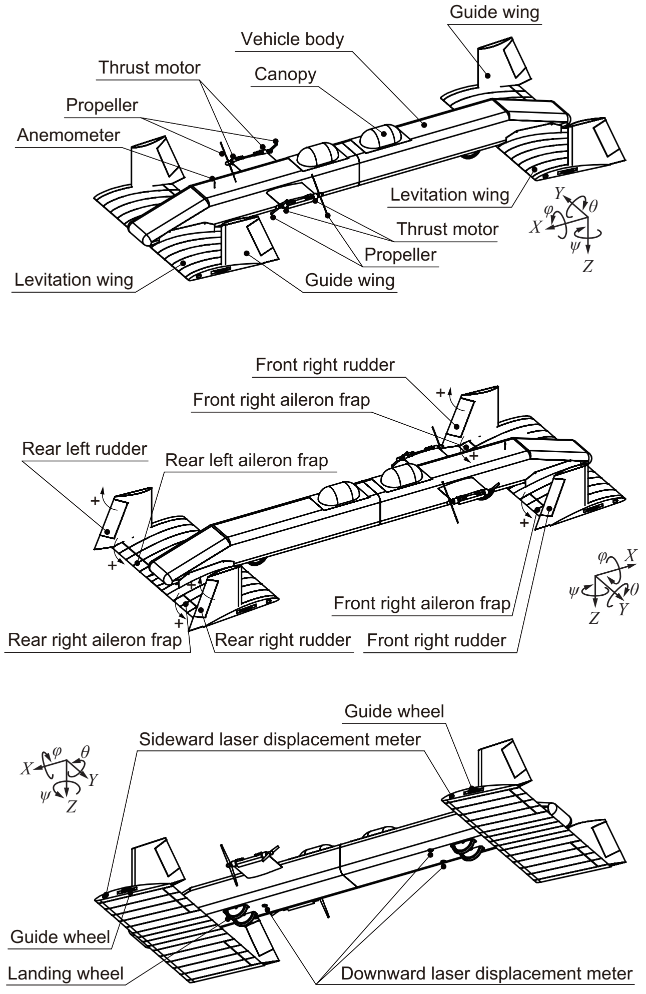


Fig. 3. Overview of ART003R [17].

Fig. 4. Photograph of ART003R running on guideway.

Table 1. Specifications.

Model No.	ART003R
Dimension / Weight	
Height	950 mm
Width	3260 mm
Length	8700 mm
Weight	474 kg
Material	Incombustible magnesium
Levitation wing	
Wing number	2
Airfoil	NACA4408 modified
Chord length	1500 mm
Wing span	3260 mm
Angle of attack (front)	2°
Angle of attack (rear)	2.5°
Guide wing	
Wing number	4
Airfoil	NACA4408 modified
Mean chord length	900 mm
Wing span	950 mm
Angle of attack (front)	3°
Angle of attack (rear)	3°
Moving blade	
Aileron flap	4
Rudder	4
Thruster	
Number	4
Model No.	A200-6
Maximum Power	15 kW
Speed Controller	MasterSpin 220 OPTO
Actuator	
Number	10
Model No.	RSF-14B-100
Rated power	18.9 W
Maximum torque	28 Nm
Maximum speed	60 rpm
Computer	
CPU	Intel Pentium M 1.8 GHz
CPU board	PCI-6881F-00A2E
AD converter board	PCI-3135
DA converter board	PCI-3346A
Pulse counter board	PCI-6205C
OS	QNX 6.1.0
Control frequency	1 kHz
Sensors	
Laser displacement meter	LD-1300L-200 ×5
Air speedometer	6332D + 0964-02
Revolution meter	E3C-LR + E3C-LDA + K3HB-RNB ×2

guideway in Miyazaki prefecture, which is used for MAGLEV experiments conducted by the Railway Technical Research Institute, where the experiments with ART003R have also been conducted. The levitation wings and guide wings employed a NACA 4408 modified airfoil, which is considered to be effective at utilizing the WIG effect. To provide thrust, each side of the vehicle body was equipped with two by two motors and propellers of the type used for model aircraft.

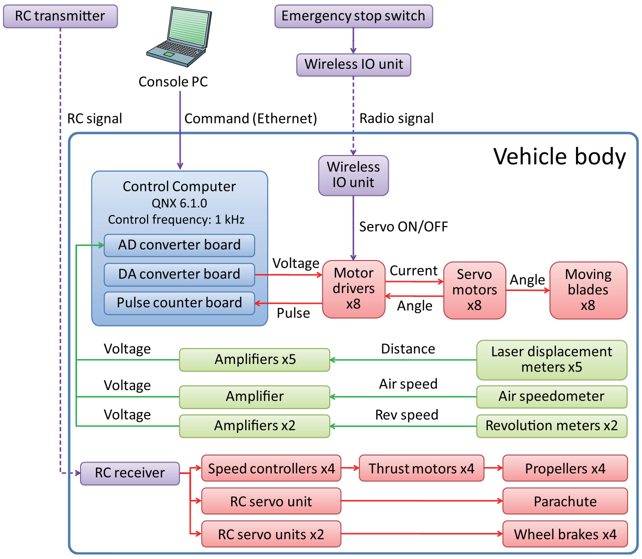


Fig. 5. Control system configuration [17].

The vehicle body is primarily made of a non-combustible magnesium alloy [18] developed by Sakamoto et al. The vehicle body was designed as a monocoque construction and has spaces for two passenger seats. The landing wheels have disk brakes on the undersurface and wheels on the side of the guide wings to prevent collisions with the sidewall of the guideway. It is also equipped with a parachute for braking at high speed.

Each levitation wing has aileron flaps on its posterior border on the right and left sides, and each guide wing has a rudder. In contrast to a normal airplane, each moving blade can be controlled independently using a servomotor with a harmonic drive reduction gear.

This prototype has three laser displacement sensors on the undersurface, with two at the tips of the levitation wings to measure the distance between the guideway and the vehicle body. In addition, it is equipped with an anemometer to measure the air speed and rotational speed meters for the propellers.

2.2. Control System Configuration

The control system configuration of ART003R is shown in **Fig. 5**.

The control computer works with a control cycle of 1 ms. It computes the position along the Y- and Z-axes and the orientation about the roll, pitch, and yaw axes of the vehicle based on the distance between the guideway and the vehicle body measured using laser displacement meters. It also computes the moving blade angles based on the control law, and controls them. This control computer also measures the air speed and rotational speed of the thrust propellers.

In the experiment, a car for surveillance followed the ART003R. From the point of view of safety, the thrust propellers, disk brakes, and parachute were manually operated via a radio control signal from the car. In the future, a feedback system will be configured for the running speed, including the control of the thrust propellers. In addition, an emergency stop switch for the controller could be operated from the surveillance car via a wireless IO unit.

3. Preliminary Experiment

As a preliminary step in the control system design of ART003R based on its dynamic model and state equation, a preliminary levitation running experiment using a simple PD controller was conducted.

3.1. Controller

In the case of a normal airplane, in consideration of small disturbances during steady horizontal flight, the relationship between the moving blade angle and the variation in the lift force is usually considered to be a simple proportional relation [19]. Ishizuka investigated this relationship under the WIG effect using several angles of attack and distances from the ground in wind tunnel experiments [20]. **Fig. 6** shows the relationship between the moving blade angle δ and the lift coefficient C_L under several angles of attack α, cord lengths c, and heights for the rear edge of the wing from the ground h. It can be seen that the relationship is also proportional under the WIG effect.

Based on this knowledge, in this preliminary controller, the control variable of each state variable was computed based on a simple PD control, and the moving blade angles were computed as these summations.

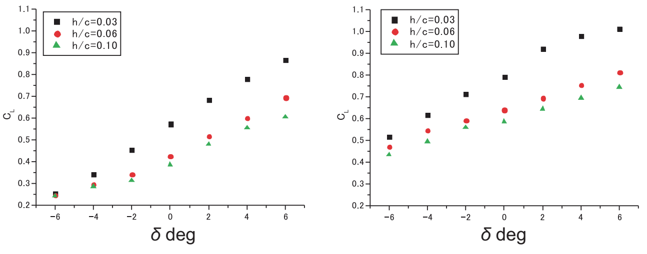
$$\left.\begin{array}{l}\boldsymbol{\delta}=\boldsymbol{A}\boldsymbol{u}\\ \boldsymbol{u}=\boldsymbol{K}_P\Delta\boldsymbol{x}+\boldsymbol{K}_D\Delta\dot{\boldsymbol{x}}\end{array}\right\}\quad\cdots\cdots\cdots\cdots \tag{1}$$

where $\boldsymbol{\delta}$ is a moving blade angle vector, $\boldsymbol{A}$ is a matrix that is specific for the vehicle structure, $\boldsymbol{u}$ is a control vector, $\boldsymbol{K}_P$ and $\boldsymbol{K}_D$ are the proportional and velocity gain matrices, and $\Delta\boldsymbol{x}$ is a state vector.

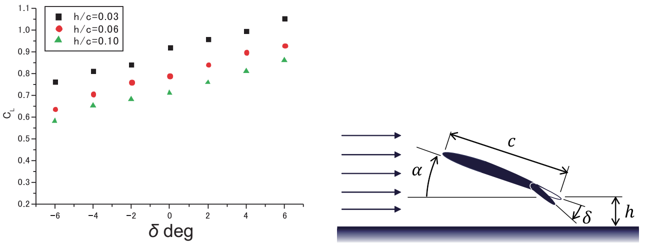
The elements of each matrix are as follows:

$$\left.\begin{array}{l}\boldsymbol{\delta}=\begin{bmatrix}\delta_{fraf} & \delta_{flaf} & \delta_{rraf} & \delta_{rlaf} & \delta_{frd} & \delta_{rrd}\end{bmatrix}^T\\ \boldsymbol{A}=\begin{bmatrix}1 & -1 & 1 & 0 & 0\\ 1 & 1 & 1 & 0 & 0\\ 1 & -1 & -1 & 0 & 0\\ 1 & 1 & -1 & 0 & 0\\ 0 & 0 & 0 & 1 & 1\\ 0 & 0 & 0 & 1 & -1\end{bmatrix}\end{array}\right\} \tag{2}$$

$$\left.\begin{array}{l}\boldsymbol{u}=\begin{bmatrix}u_z & u_\phi & u_\theta & u_y & u_\psi\end{bmatrix}^T\\ \Delta\boldsymbol{x}=\begin{bmatrix}\Delta z & \Delta\phi & \Delta\theta & \Delta y & \Delta\psi\end{bmatrix}^T\\ \boldsymbol{K}_P=\mathrm{diag}\begin{bmatrix}K_{Pz} & K_{P\phi} & K_{P\theta} & K_{Py} & K_{P\psi}\end{bmatrix}\\ \boldsymbol{K}_D=\mathrm{diag}\begin{bmatrix}K_{Dz} & K_{D\phi} & K_{D\theta} & K_{Dy} & K_{D\psi}\end{bmatrix}\end{array}\right\} \tag{3}$$



(a) $\alpha = 2°$ (b) $\alpha = 4°$



(c) $\alpha = 6°$ (d) Symbols

Fig. 6. Experimental results of lift coefficient [20].

where u_z, u_ϕ, u_θ, u_y, and u_ψ are control variables along the Z- and Y-axes and about the roll, pitch and yaw axes; Δz, $\Delta\phi$, $\Delta\theta$, Δy, and $\Delta\psi$ are the errors from the desired value along the Z- and Y-axes and about the roll, pitch, and yaw axes; and δ_{fraf}, δ_{flaf}, δ_{rraf}, δ_{rlaf}, δ_{frd}, and δ_{rrd} are the angles of the front right, front left, rear right, and rear left aileron flaps and the front and rear rudders, respectively.

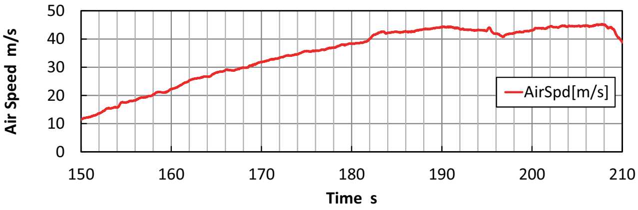
The purpose of the experiment was to evaluate the hardware, including its integrated control system, as a preliminary step toward a 6-DOF controller design based on the dynamic model. Therefore, in this step, a simple PD control law without integral action was used, which has relatively high robustness.

The $\boldsymbol{K}_P$ and $\boldsymbol{K}_D$ components were tuned heuristically, with attention given to safety.

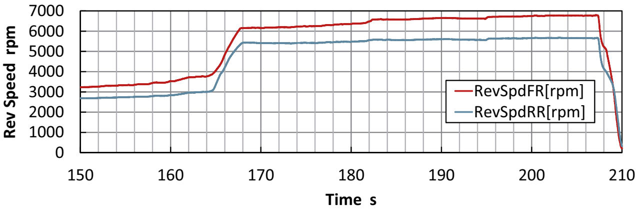
3.2. Experiment

Using the developed ART003R and control system, a levitation experiment in the described guideway was conducted. In this experiment, ART003R was pushed by a car until its speed reached 100 km/h (28 m/s). It then accelerated using its thrust propellers. Because of the length limitation of the guideway, the levitation time was approximately 30 s in this experiment. The desired height of the COG was set at 450 mm. In this case, the desired levitation height was 50 mm, because the COG height when the wheels were landing was 400 mm.

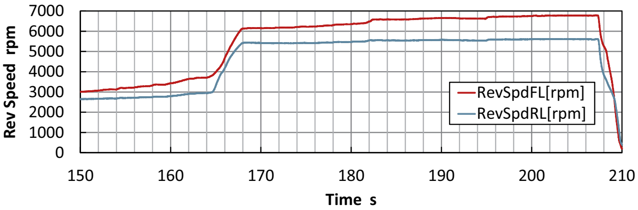
The experimental results are shown in **Figs. 7**, **8**, and **9**. **Fig. 7(a)** shows the air speed. **Figs. 7(b)** and **(c)** show the revolution speed of the thrust propellers. **Figs. 8(a)** and **(b)** show the position of the COG with respect to the center line of the surface of the guideway, and **Figs. 8(c)**, **(d)**, and **(e)** show the orientation of the vehicle body. The levitation height is the value left when 400 is subtracted from Z, as shown in **Fig. 8(b)**. **Figs. 9(a)**, **(b)**, **(c)**, and **(d)**



(a) Air speed



(b) Revolution speed of right propellers



(c) Revolution speed of left propellers

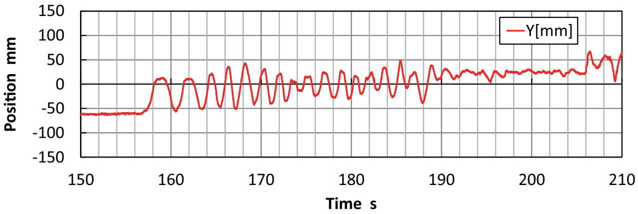
Fig. 7. Experimental results (1 of 3).

shows the blade angles of aileron flaps and rudders.

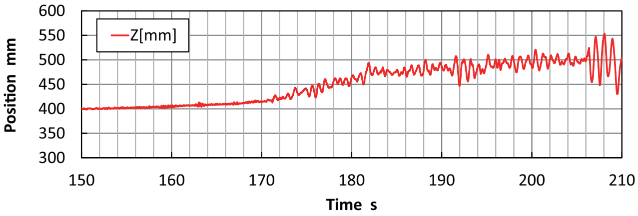
As shown in **Fig. 7(a)**, the revolution speeds peaked at 168–207 s, and the air speed was accelerating in this period. After 183 s, the vehicle was in the cruise condition with a maximum speed of 43–45 m/s (155–162 km/h). **Fig. 10** shows snapshots of the vehicle during this period. After 207 s, braking was started by the halt of the thrust propellers and parachute.

As shown in **Fig. 8(b)**, the levitation height increased with the acceleration of the air speed, and it was maintained at 80–100 mm in the cruise condition. In this period, although a small vibration with an amplitude of 20 mm was seen, it can be said that stable levitation was realized. However, considering the desired height of 50 mm, the 30–50 mm error seen here is a stationary error. From **Figs. 9(a)** and **(b)**, all the aileron flaps maintained negative angles to decrease the lift in this cruise condition. In particular, considering that the desired levitation height is 50 mm and the unevenness of the road surface of the guideway is about 10 mm, the desirable vibration amplitude is considered to be approximately 10 mm. These results show that there is still room for improvement in the gain and offset value of the blade angle.

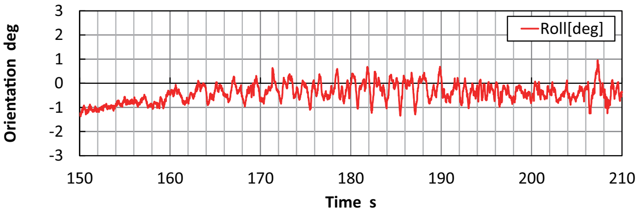
The pitch angle shown in **Fig. 8(d)** is stable without a large pitch-up under the increase in air speed and levitation height during the acceleration phase from the start of levitation to the start of the cruise period. In contrast, the roll angle shown in **Fig. 8(c)** has a small vibration and stationary error. It was mainly affected by the extremely low S/N ratio because the distance between the right and left laser sensors, which was used to compute the roll angle, was a tenth of the distance between the front and rear sensors used to compute the pitch angle. In addition, as shown in **Fig. 10**, no large vibration could be visually confirmed.



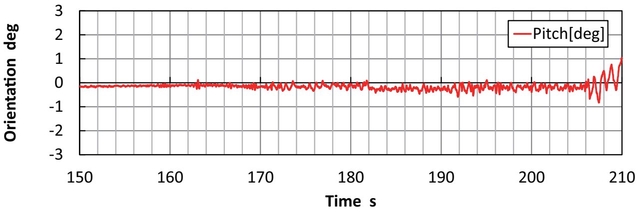
(a) Sideward position of COG



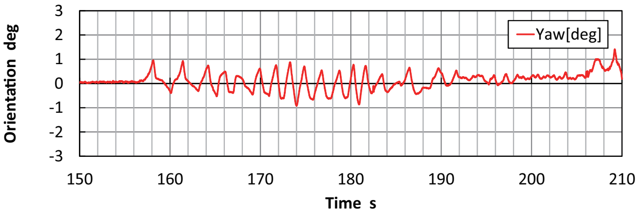
(b) Height of COG



(c) Roll angle



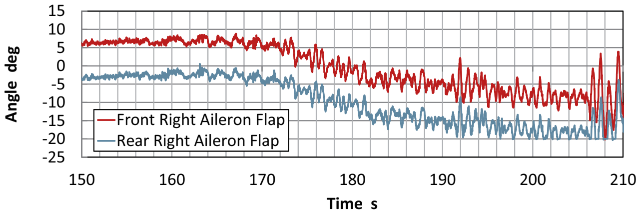
(d) Pitch angle



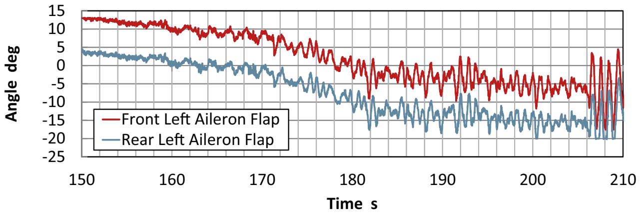
(e) Yaw angle

Fig. 8. Experimental results (2 of 3).

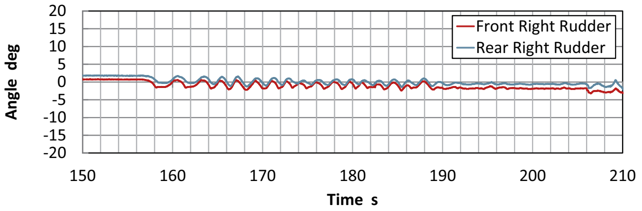
In relation to the lateral-directional motions, as shown in **Fig. 8(a)**, although the motion along the Y-axis shows a continuous vibration from the acceleration phase to the start of the cruise period, it is relatively stable in the cruise condition. In the same way, as shown in **Fig. 8(e)**, the yaw motion also has a large vibration until the cruise condition but is then stable in the cruise condition. Although it is necessary to discuss the characteristics of the guide wings based on additional experimental results, it can be said that a sufficient lift force for guiding and vibration suppression using guide wings with shorter spans than the levitation wings requires a higher air speed than that re-



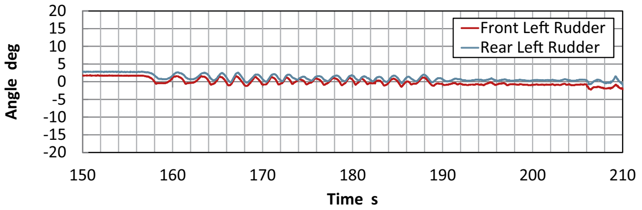
(a) Aileron flap angles (right)



(b) Aileron flap angles (left)



(c) Rudder angles (right)



(d) Rudder angles (left)

Fig. 9. Experimental results (3 of 3).

quired for levitation.

From these results, although the control performance left much room for improvement, it could be confirmed that ART003R could levitate when running at 160 km/h, and the developed hardware could control the levitation height and orientation of the vehicle during levitation.

4. Conclusions and Future Work

In this paper, an overview was given of the hardware, the control system configuration, and the results of a preliminary experiment for the experimental manned WIG-effect vehicle ART003R. This prototype has two levitation wings and four guide wings with aileron flaps and rudders, and it utilizes the WIG effect for levitation and guiding. Its body is made of a non-combustible magnesium alloy, and it has four thrust propellers, landing wheels, a parachute, etc. The control system measures the distance of the vehicle from the guideway, along with the air speed and rotational speeds, and controls the moving blades. The results of a preliminary experiment using a simple PD control law for the purpose of confirming the

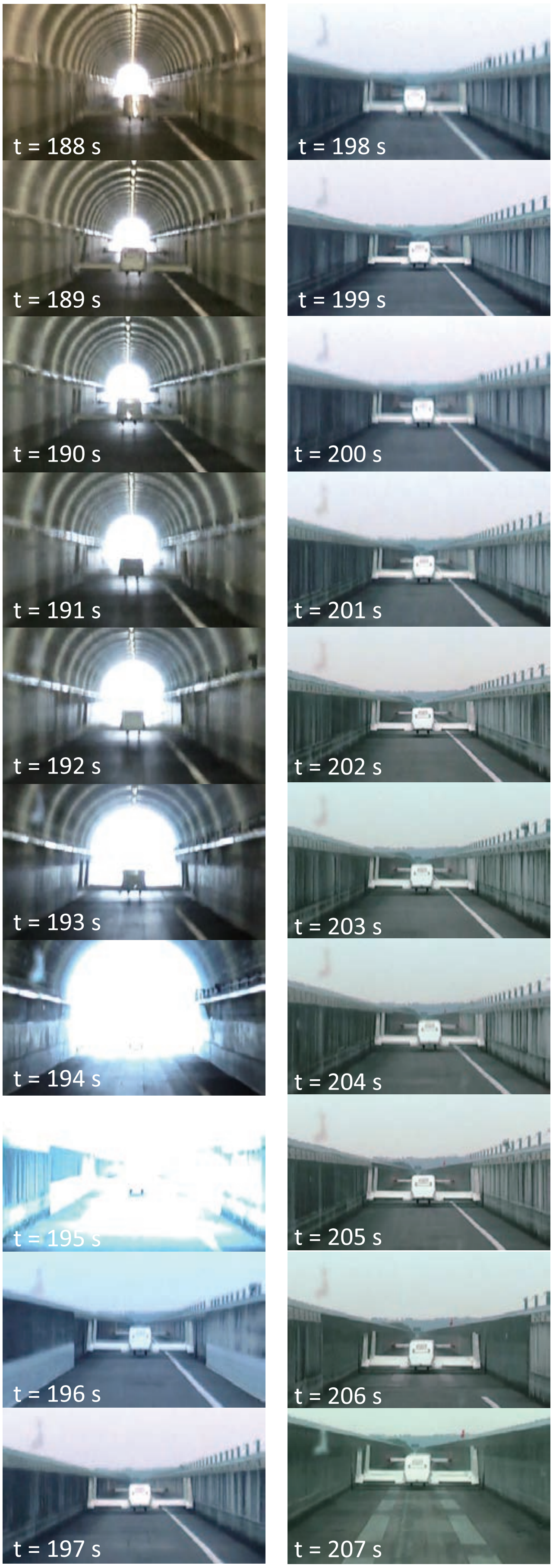


Fig. 10. Snapshots of experiment.

basic performances of the developed hardware confirmed that ART003R could levitate at 160 km/h, and the developed hardware could control the levitation height and orientation of the vehicle.

Our next report will discuss a 6-DOF dynamic model that extends the model described in [15], as well as a controller design based on this model, which was briefly shown in [21].

In parallel, the authors will develop a control system for the traveling speed by using air speed feedback for ART003R. Future work will also include investigations on the stability and the modeling and control of the vehicle motion on a curved and banked guideway, during the acceleration and deceleration phases, and at higher speeds. In addition, a controller will also be designed that takes advantage of the nonlinearity of the WIG effect. Studies on appropriate WIG vehicle structures for a train system are also interesting from the design and control points of view.

Acknowledgements

This work was performed in part under the New Energy and Industrial Technology Development Organization (NEDO) Research and Development “Strategic Development of Energy Conservation Technology Project.” We thank Masao Harada and Toshiyuki Haraguchi at Sunrise Beach Research Facility, Tohoku University and Masanobu Matsuda at Ota Engineering Co., Ltd. for their technical support in manufacturing the vehicle body and conducting the experiments, and Shinji Suzuki and Naoaki Yonezawa for their technical support in the implementation of the control system.

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