CRITERIA OF BOW-DIVING PHENOMENA FOR PLANING CRAFT

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Abstract

The purpose of this paper is to clarify the cause of Bow-Diving occurrence of planing craft. First, model experiments are carried out in order to reproduce Bow-Diving and it is confirmed that Bow-Diving occurs in calm water and in wave. From the experimental results, the relative position of the hull to the water surface at Bow-Diving occurrence is shown. Next, the hydrodynamic forces acting on the model are measured by fully captive model tests with wide range of attitudes including the running attitude at Bow-Diving occurrence to obtain the restoring forces acting on the model, and the characteristic of them are investigated. Consequently, it is shown that the restoring forces play an important role to Bow-Diving occurrence and a method of obtaining the criteria of Bow-Diving occurrence based on the restoring forces is proposed. Furthermore, the estimation methods of Bow-Diving occurrence are proposed.

1. INTRODUCTION

It is known with a kind of unstable phenomena[1] of high-speed planing craft that a planing craft, which runs at high speed in waves and accelerates rapidly, downs its bow and sinks into water immediately. This phenomenon is called Bow-Diving. This phenomenon rarely occurs under a special situation, however, when Bow-Diving occurs, the possibility that a crew are exposed to danger is high. Therefore, in order to secure safety, the elucidation of the cause of occurrence of this phenomenon, the development of the estimation method in a design stage and the proposal of the evasion method are desired.

In this study, Bow-Diving is simulated by a model test and the fundamental causes of Bow-Diving are investigated from the view point of the hydrodynamics. Moreover, a prediction method of occurrence of Bow-Diving is proposed.

2. MEASUREMENT OF BOW-DIVING

2.1 Outline of experiment

In this study, a 1/4 scale model which is a simplified hull based on a PWC (Personal Water Craft) is used. The body plan and the principle particulars of the model are shown in Figure 1 and Table 1.

In this experiment, the model is free in heaving and pitching motions. Model is accelerated at constant acceleration to the target speeds by a towing carriage [2] and the heaving and pitching motions of the model are measured while the towing carriage is moving. In Figure 2, the directions of motions are shown.

Table 1: Principle particulars of model.

ship condition	A	B
ship length of over all: L_{OA}	0.625m	
ship length (s.s.0 to s.s.10): *Lpp*	0.600m	
draft (even keel): *d*	0.059m	0.064m
ship weight: *W*	4.28 kgf	4.94 kgf
height of centre of gravity: *KG*	0.111m	0.075m
longitudinal position of centre of gravity from transom: *LCG*	0.285m	
initial trim angle (bow up +): θ_0	-3.4 degree	

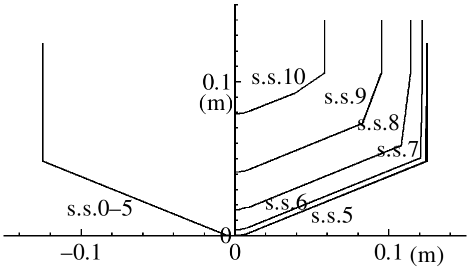


Figure 1: Body plan of model.

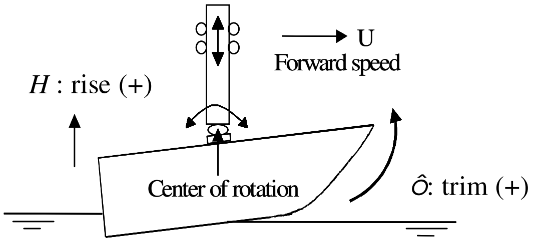


Figure 2: Schematic drawing of experimental setup and coordinates system.

2.2 Results of experiments

In Figures 3 and 4, the results of motion measuring tests in calm water are shown. The model's conditions in the cases of Figures 3 and 4 are Condition A and Condition B shown in Table 1 respectively. And the model is accelerated at 5m/sec^2 up to 15m/sec in these cases. Figure 3 shows the results when Bow-Diving does not occur. Just after the start, the model downs its bow, however, it does not submerge and reaches steady running attitude, immediately. On the other hand, Figure 4 shows the results when Bow-Diving occurs. Just after the start, the model downs its bow and submerges through the running attitude which is shown in Figure 5.

Figure 6 shows the results when Bow-Diving occurs in head waves (wave height 40mm and wave period 0.8sec). The model's condition, Condition A, is shown in Table 1. In this case, the model is accelerated at 10m/sec^2 up to 6m/sec. Figure 7 shows an animation of the relative ship motion to the water surface obtained from the measured data shown in Figure 6. From this animation, it is looked clearly that the model downs its bow just after the start and submerges.

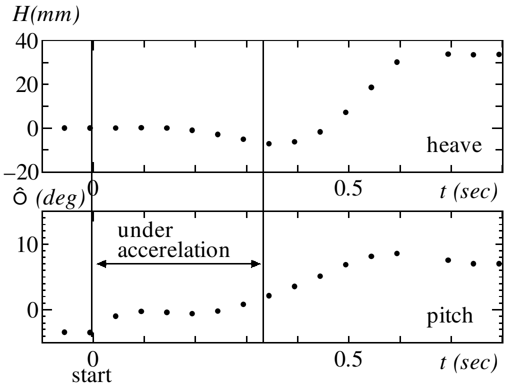


Figure 3: Time history of measured ship motions without Bow-Diving in Condition A.

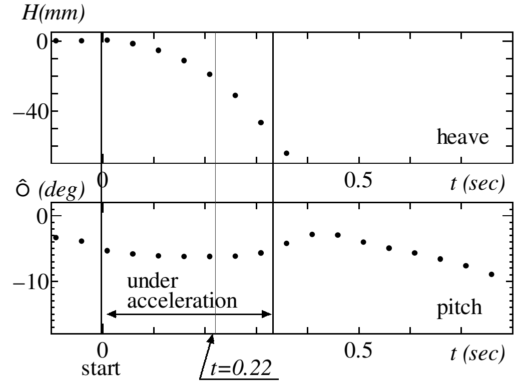


Figure 4: Time history of measured ship motions with Bow-Diving in Condition B.

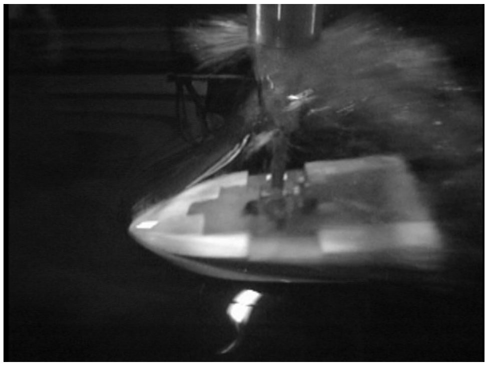


Figure 5: Photograph of flow around model during Bow-Diving in calm water (*t* = 0.22sec in Figure 4).

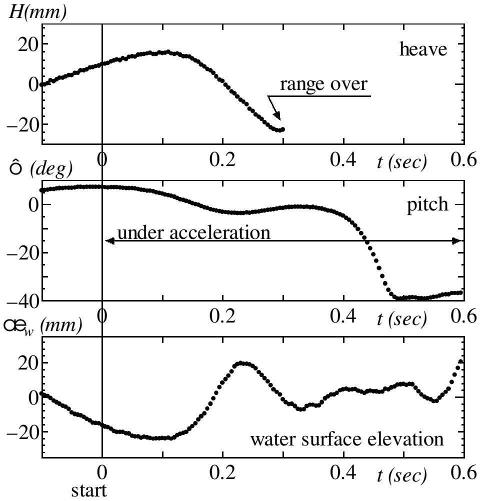


Figure 6: Time history of measured ship motions with Bow-Diving in Condition A and water surface elevation to still water surface in head wave (*Hw*=40mm, *Tw*=0.8sec).

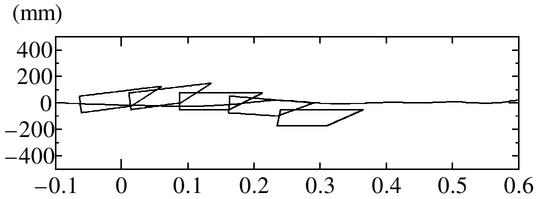


Figure 7: Animation of relative ship motion to the water surface obtained from the measured data shown in Figure 6.

3. CHARACTERISTICS OF RESTORING FORCES AT RUNNING

3.1 Measurement of hydrodynamic forces

In order to investigate the fundamental cause of Bow-Diving occurrence, the hydrodynamic forces acting on the model which is fully captive are measured for very large heave and pitch angle as is shown in Figure 8. In Figure 9 the schematic view of experiment is illustrated and the experimental conditions are given in Table 2.

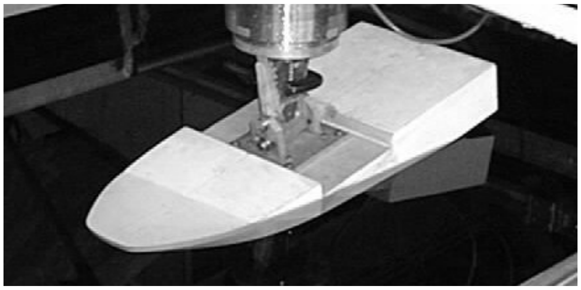


Figure 8: Photograph of experiment to measure hydrodynamic forces acting on model with various attitudes.

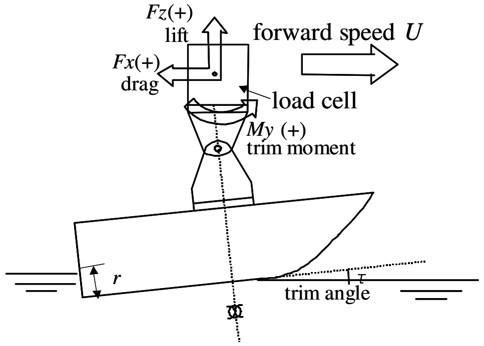


Figure 9: Schematic view of experiment.

Table 2: Experimental conditions.

aft-draft: r	-30, -10, 10, 30, 50 mm
trim angle: ô	-11, -9, -7, -5, -3, -1, 1, 3, 5 deg.
forward speed: Fn	1.0, 1.8, 2.3

Where $Fn = U\sqrt{gL_{OA}}$.

3.2. Restoring forces acting on hull

The hydrodynamic forces due to running attitude at a certain time in motion measuring tests are shown in Figure 10. Heave and pitch restoring forces (C_3 and C_5) are expressed with Eqs.(2) and (3) by using these hydrodynamic forces.

$$F_T = F_X(U,H,\tau) \quad (1)$$

$$C_3(U,H,\tau) = F_Z(U,H,\tau) + F_B(H,\tau) - W \quad (2)$$

$$C_5(U,H,\tau) = M_G(U,H,\tau) - F_T L_T + M_B(H,\tau) \quad (3)$$

where the drag F_X, the lift F_Z and the trim moment M_G around the centre of gravity do not include hydrostatic forces (buoyant forces). F_B and M_B are the buoyancy and hydrostatic trim moment around the centre of gravity. W is the displacement of the model, F_T is the towing force and L_T is the distance from the centre of gravity to the towing axis. H is vertical displacement of the centre of gravity of the model from the position at rest and τ is trim angle. And furthermore, in Eqs.(2) and (3), the attitudes (H and ô which satisfy C_3=C_5=0 are the steady running attitude for a forward speed as shown in Figure 11.

KG: height of the centre of gravity
LCG: longitudinal distance of the centre of gravity from transom
W: ship weight
KT: height of towing point from base line
LCT: longitudinal distance of towing point from transom

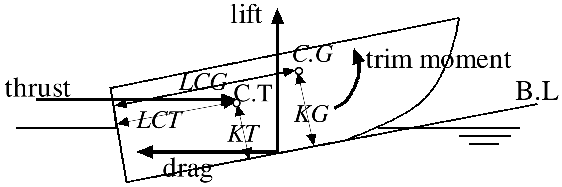


Figure 10: Forces acting on model in experiment.

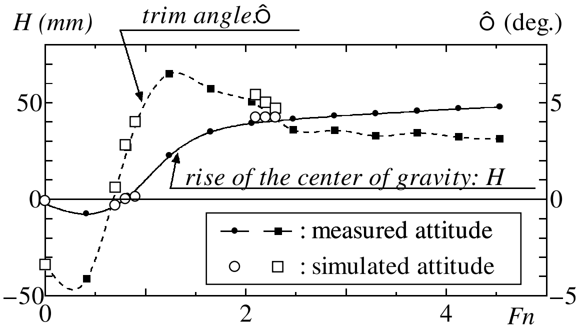


Figure 11: Comparison between with measured and simulated running attitudes of model at Condition A in calm water.

3.3 Characteristics of restoring forces at high-speed

The restoring forces at *Fn*=2.3 are shown in Figures 12 and 13. In the same figures, the solid line on which the heave or pitch restoring force is zero and the circle (•) on which the both heave and pitch restoring forces are zero are shown. And the dotted line is the borderline where the model's bow is just submerged.

The heave restoring force in Figure 12 restores the model to a steady running attitude around the *H*>10mm and τ >0deg. However, such force does not necessarily act on the model at other attitudes except around the parameters given above.

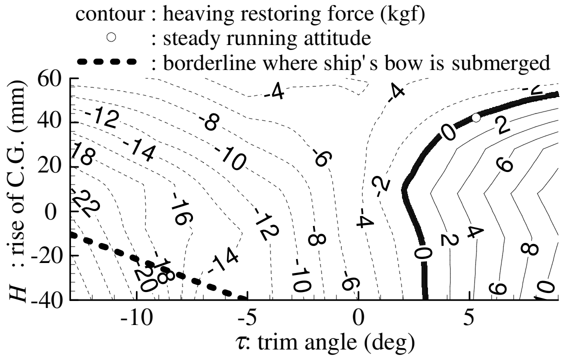


Figure 12: Contour of dynamic heave restoring force for Condition A at *Fn*=2.3.

On the pitch restoring moments shown in Figure 13, there is similar tendency with the heave restoring force. Moreover, two solid lines on which the pitch restoring moment is zero are in the same figure and the solid line 1 which does not include the steady running attitude (•), which are unsteady equilibrium attitudes where the pitch restoring moment is zero. That is, when running attitude of the model lowers its bow exceeding the solid line 1 by a certain cause, and model submerges immediately without force to restore the steady running attitude.

The fundamental cause of Bow-Diving occurrence is that heave and pitch pure stabilities are lost by the effects of high-speed at a running attitude where the bow of model is not necessarily submerging.

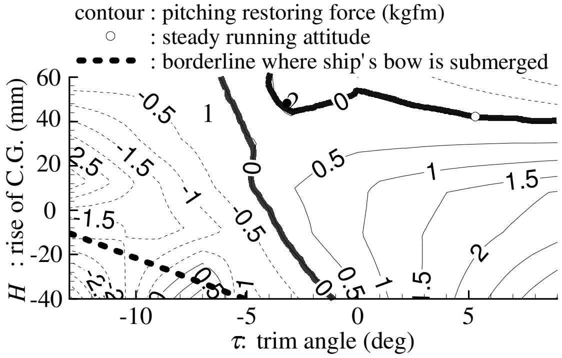


Figure 13: Contour of dynamic pitch restoring moment for Condition A at *Fn*=2.3.

4. ESTIMATION METHOD OF CRITERIA OF BOW-DIVING

4.1 Acceleration vector

For occurrence of Bow-Diving, the heave and pitch restoring forces play important role. In order to obtain them, fully captive model tests are carried out by systematically changing draft (rise) and trim angle. However, it is difficult to assess Bow-Diving occurrence using these two stability curves. Then, the authors propose an acceleration vector obtained from these stability curves. The acceleration vector is composed by heave and pitch accelerations, which are obtained as follows.

If the damping terms are assumed to be neglected, heave and pitch equations can be expressed using obtained heave and pitch restoring forces (C_3 and C_5) as follows.

$$\text{Heaving: } (m + a_{33})\ddot{H} = C_3(H,\tau) \quad (4)$$

$$\text{Pitching: } (I_{55} + a_{55})\ddot{\tau} = C_5(H,\tau) \quad (5)$$

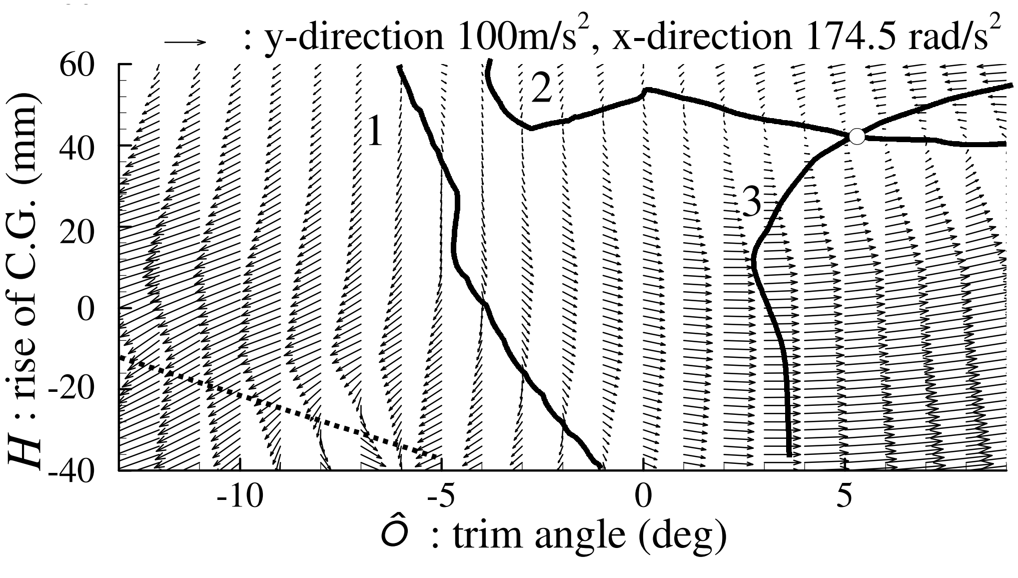
where *H* and *Ô* denote rise and trim angle respectively. The equations show that heave and pitch accelerations can be calculated by dividing C_3 and C_5 by corresponding inertia terms, $(m+a_{33})$ and $(I_{55}+a_{55})$ respectively. But, the coefficients of added mass and inertia are not taken into account in this study. Then the acceleration vector defined in Eq.(6) can be obtained as a function of *H* and *Ô*

Acceleration vector: $$\overset{\rho}{a} = (H\&\&, \tau\&\&) \qquad (6)$$

The vector indicates the direction and magnitude of excited motion due to the restoring forces at a certain attitude described by *H* and *Ô*

4.2 Criteria of bow-diving

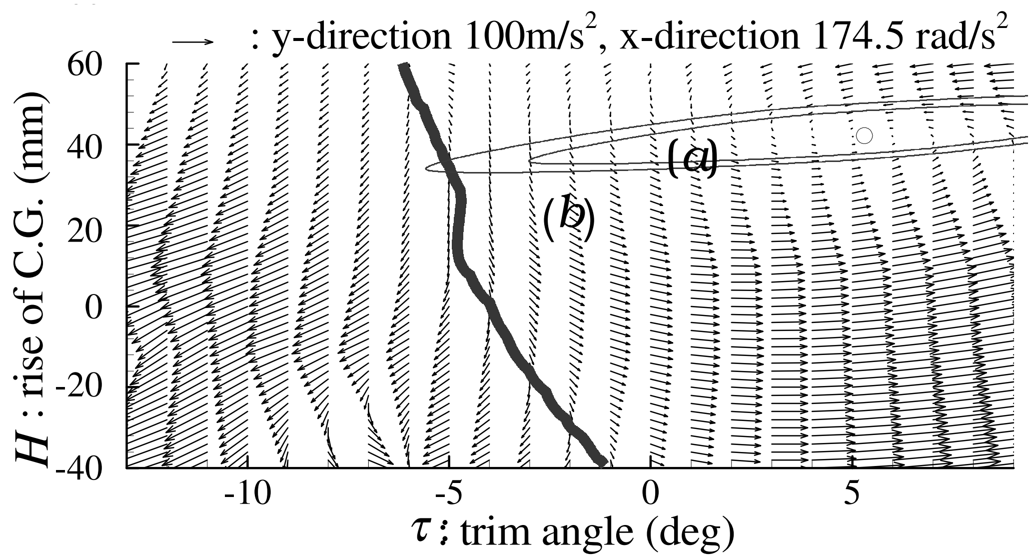
Figure.14 shows an obtained acceleration vector of a planing craft at Fn=2.3 in calm water. The solid lines 2 and 3 in the figure display the attitude in which the heave and pitch restoring forces are zero respectively, and the dotted line indicates the criteria where the model's bow submerges. The solid line 1 shows the criteria where acceleration vector heads in opposite directions. The small circle in the figure shows the steady running attitude. If some disturbance makes running attitude to be in the left side of Line 1, the craft is forced to go bow-down and sink. This means that Line 1 is the criteria of Bow-Diving.



5. ESTIMATION METHOD OF BOW-DIVING OCCURRENCE

5.1 Simplified estimation method

A simplified estimation method of Bow-Diving occurrence of a planing craft in regular head waves using the afore-mentioned acceleration vector is shown. The ship moves around the steady running attitude shown by the circle in Figure 15. The ship motion is calculated by a strip method (called OSM in Japan), and the relative attitude to incident wave surface at the midship is obtained as illustrated by Curves (*a*) and (*b*) in the same figure. Curves (*a*) and (*b*) show the results for different wave height. Since Curve (*a*) (ë/L_{OA} =5.16, *Hw/d*=0.3 and heading sea) in the figure does not go into the area on the left side of Solid Line, it is considered that Bow-Diving does not occur in this wave. Curve (*b*) is for slightly larger wave height (*Hw/d*=0.4), however, it goes into the area on the left side of Solid Line, and this means that there is a possibility of Bow-Diving occurrence in the wave. Thus, using the acceleration vector diagram obtained by heave and pitch restoring forces, Bow-Diving occurrence can be judged simply. It should be noted that if a more accurate method is used for calculation of ship motion, the accuracy could be improved.



(*a*): ë/L_{OA}=5.16, *Hw/d*=0.30, head sea (*b*): ë/L_{OA}=5.16, *Hw/d*=0.40, head sea

Figure 15: Criteria of Bow-Diving occurrence in regular head wave using acceleration vector. Ship motion calculated by a strip method and the relative attitude to incident wave surface at the midship is obtained as illustrated by Curves (*a*) and (*b*). Solid Line is limiting line of Bow-Diving occurrence.

5.2 Computer simulation

A motion simulation method [3] in time domain for Bow-Diving of planing craft is developed. For the simulation, measured hydrodynamic forces for the wide range of running attitude including bow-submerged attitude are used. Some simulated results of a planing craft under forward acceleration in calm water are shown in Figure 16. In this figure, the results with and without Bow-Diving occurrences are shown with corresponding experimental results. The simulated results are in fairly good agreement with experimental ones, and it can be safely said that Bow-Diving occurrence can be assessed by the simulation method, too.

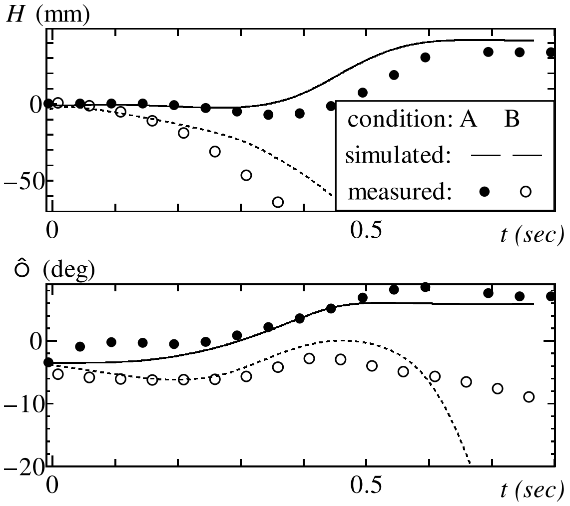


Figure 16: Time histories of simulated ship motions with and without Bow-Diving under forward acceleration in calm water.

6. CONCLUSIONS

The cause of the occurrence of Bow-Diving is experimentally and theoretically investigated and these following conclusions are obtained.

1. By model experiment, it is confirmed that Bow-Diving, which the model downs its bow just after the start and submerges immediately, occur when the model rapidly accelerates.

2. The criteria of Bow-Diving where heaving and pitching stabilities are lost are estimated by using the acceleration vector obtained from the measured restoring forces.

3. A simplified estimation method of Bow-Diving occurrence in regular head waves using the acceleration vector is investigated.

4. A motion simulation method in time domain for Bow-Diving of planing craft under rapidly acceleration is developed and it is confirmed that the simulated results are in fairly good agreement with experimental results in calm water.

7. REFERENCE

[1] Cohen, S. H. and Blount, D. L., Research Plan for the Investigation of dynamic Instability of Small High-Speed Craft, *SNAME Transactions*, Vol.94, pp.197-214, 1986.

[2] Y. Ikeda, T. Katayama, Y. Yamashita, K. Otsuka and T. Maeda, Development of an Experimental Method to Assess the Performance of High Speed Craft (1st Report) -Development of High Speed Towing System-, *Journal of Kansai Society of Naval Architects, Japan*, No.223, pp.43-48, 1995.

[3] Katayama, T. and Ikeda, Y., Acceleration Performance of high-Speed Planing Craft from Rest, *Journal of Society of Naval Architecture of Japan*, Vol.185, pp.81-89, 1999.