Experimental Techniques to Assess Dynamic Instability of High-Speed Planing Craft
- Non-zero Heel, Bow-Diving, Porpoising and Transverse Porpoising -

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SUMMARY

In this paper, several methods to assess the possibility of some dangerous motions of a planing craft due to dynamic instability are introduced. The methods are on the basis of the experimental data of hydrodynamic forces acting on a captured model for various attitudes, those means pitch, heave, roll and yaw, at high forward speed in steady state. The measurements are usually carried out to get the data bases of hydrodynamic forces for a running simulation in steady speed and manoeuvring for a planing craft. The same data, however, can be used to assess the possibility of occurrences of dynamic motions due to instability. The analysing procedures and some results for several kinds of such motions are explained.

NOMENCLATURE

a_{33}	Heaving added mass
a_{55}	Pitching added inertia moment
BL	Base line
C_3	Heave restoring force (kgf)
C_{33}	Heave restoring coefficient (kgf/m)
C_{35}	Heave coupling restoring coefficient from pitch (kgf/rad)
C_5	Pitch restoring force (kgfm)
C_{53}	Pitch coupling restoring coefficient from heave (kgfm/m)
C_{55}	Pitch restoring coefficient (kgfm/rad)
CG	Centre of gravity
CL	Centre line
Fn	Froude number ($Fn = \sqrt{U/gL_{OA}}$)
F_X	Drag (kgf)
F_Y	Side Force (kgf)
F_Z	Lift (kgf)
GZ	Roll moment lever (m)
H	Rise of CG
Hw	Wave height
I_{55}	Pitching inertia moment
KG	Height of CG from BL (m)
L_{OA}	Length of over all (m)
m	Hull mass (kg)
M_X	Roll moment (kgfm)
M_Y	Trim moment (kgfm)
M_Z	Yaw moment (kgfm)
PMM	Planer Motion Mechanism
PWC	Personal Water Craft
t	Time (second)
Tn	Roll natural period (second)
T_{por}	Period of porpoising (second)
Tw	Wave period (second)
U	Forward speed (m/sec.)
W	Hull weight (kgf)
z	Heave displacement
Z_{amp}	Heave amplitude
β	Drifting angle (degree)
λ	Wave length (m)
τ	Trim angle (degree)
θ	Pitch displacement (degree)
θ_{amp}	Pitch amplitude (degree)

1. INTRODUCTION

Planing craft are sometimes suffered by various unstable motions that are completely different from those for conventional displacement-type vessels. Some of them are known as non-zero heel, bow steering, bow diving, chine walking, corkscrew, porpoising and so on. Occurrence of these phenomena has close relation with high forward speed. Therefore, it can be safely said that these phenomena occur only when hydrodynamic forces are dominant compared with hydrostatic forces like buoyant forces. Then, these phenomena are generally referred to as dynamic instabilities (Blount & Codega, 1992).

Although the phenomena are dynamic, the occurrences of them are fundamentally governed by stability characteristics created by hydrodynamic forces at high forward speed. The author investigated these motions of a planing craft experimentally, revealed the mechanisms of the occurrences of some of the motions, and proposed several methods to assess the occurrences of them using measured hydrodynamic forces acting on a model towed steadily in high speed. These methods are introduced in this paper.

2. MEASUREMENT OF HYDRODYNAMIC FORCES

In order to measure hydrodynamic forces acting on a planing craft at high forward speed, a fully captive model tests are carried out. In this study, models that are scale model of PWC and about 0.6 m in L_{OA} are used.

This test system was developed by Ikeda et al (1988) to investigate the hydrodynamic drag, lift and trim moment acting on a scale model of a planing craft. Using the measured data, the steady running attitudes of it and the resistance acting on it can be simulated by solving the equilibrium equations of vertical force, horizontal force and trim moment. Using the hydrodynamic forces data obtained by the same test method, assessments of the occurrences of unstable motions due to dynamic instability can be done.

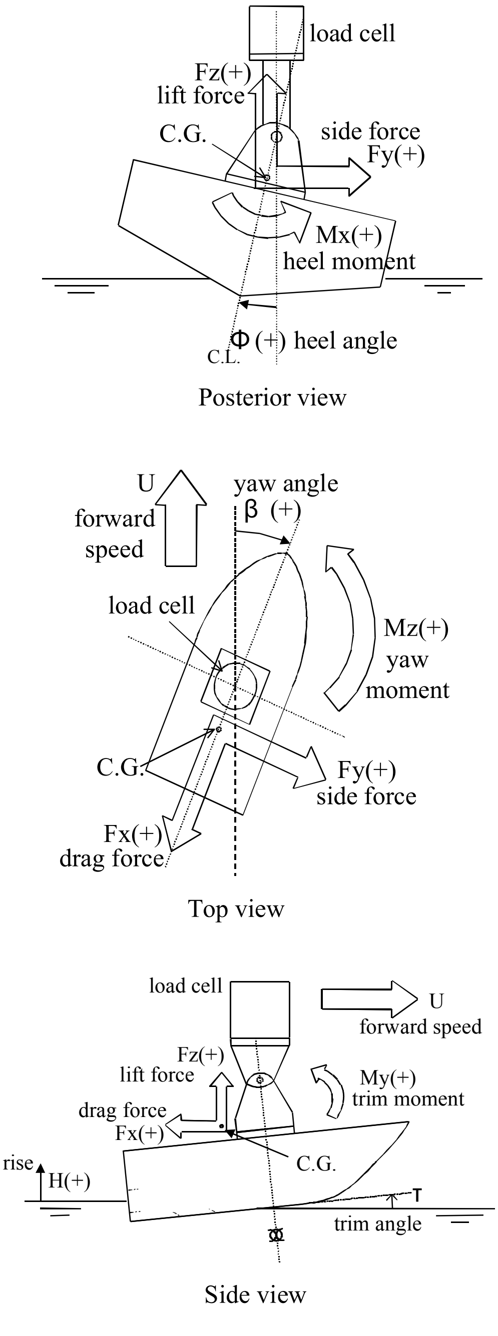


Fig.1 Schematic drawing of experimental set-up of fully captive model test.

2.1 EXPERIMENTAL PROCEDURE

The experimental set-up is shown in Fig.1. A model is captured by a 6-component load cell, and they are towed by the high speed towing carriage, the maximum speed of which is 15m/s, developed by Ikeda et al (1995). This experiment is carried out by systematically changing the draft, heel angle, trim angle and drifting angle (yaw angle) according to the purpose. The zero levels of all measured forces are set at rest just before starting of each measurement. The measured roll, pitch and yaw moments about the load cell are converted into the values about the standard location of the centre of gravity of the model.

2.2 CALCULATION PROCEDURE FOR RESTORING FORCES AT HIGH FORWARD SPEED

In order to assess the unstable motions, the measured hydrodynamic forces should be converted into restoring forces around the equilibrium condition at each forward speed. This means that restoring forces depends on real running attitudes of a craft at each speed. The restoring forces are obtained as follows.

At first, calculated hydrostatic forces at rest are added to the measured hydrodynamic forces at forward speed. In the following analysis, a coordinate system that *x-y* plane is horizontal, *x*-axis agrees in the direction of bow direction and the centre of coordinate system agrees the centre of gravity is used. The running attitudes, where the forces at forward speed are balanced with ship weight and towing force (thrust), are calculated at forward speed in consideration. Around the calculated attitudes in an equilibrium condition at the forward speed, the restoring forces depending deviation from the equilibrium attitudes can be calculated. Coupling forces in other directions can be also obtained. The coefficients of restoring forces including coupling forces are obtained by dividing these forces by the deviation.

3. TRANSVERSE MOTIONS

In this chapter, two examples of unstable transverse motions of a planing craft, which can be predicted using transverse stability obtained by the experimental method, will be described.

3.1 NON-ZERO HEEL

The roll restoring force curves, or *GZ* curves obtained by Katayama et al (1995) from measured hydrodynamic forces of a planing craft are shown in Fig. 2. In this case, the model tests were carried out by systematically changing the draft, heel angle and trim angle. The *GZ* curves at high forward speeds, *Fn*=1.4, 1.6 and 1.8, are shown in the figure as well as that at zero forward speed. The *GZ* curves for *Fn*=0 and 1.4 crosses the horizontal line only at φ=0. On the other hand, the *GZ* curve for *Fn*=1.6 touches the line at φ=10, and that for *Fn*=1.8 crosses the line at φ=15. The results suggest that the large heel is generated by the transverse stability loss at high forward speed. The facts were confirmed by measured roll motion at same initial condition of the model as shown in Fig.3. It was pointed out by Katayama et al. (1995) that the stability loss of a planing craft depends running trim the height of centre of gravity.

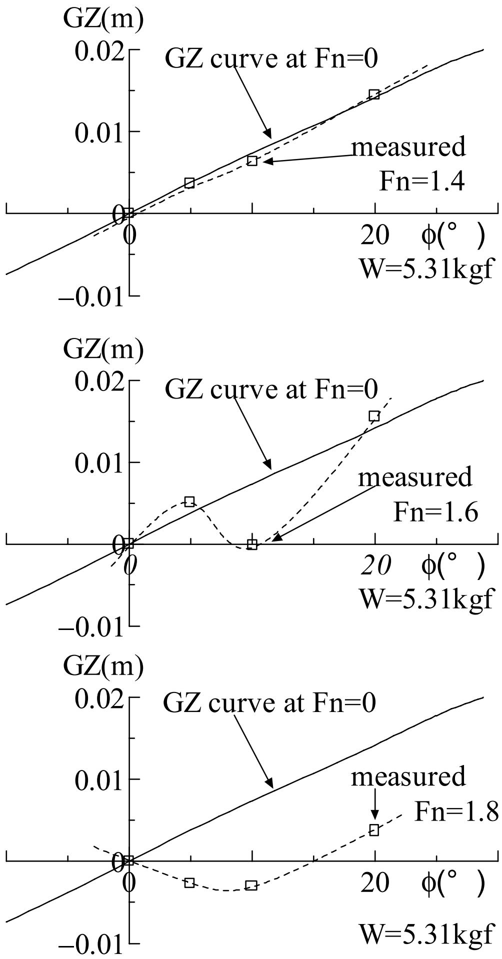


Fig.2 *GZ* curve of a planing craft at trim angle of 2 degrees for several advance speeds.

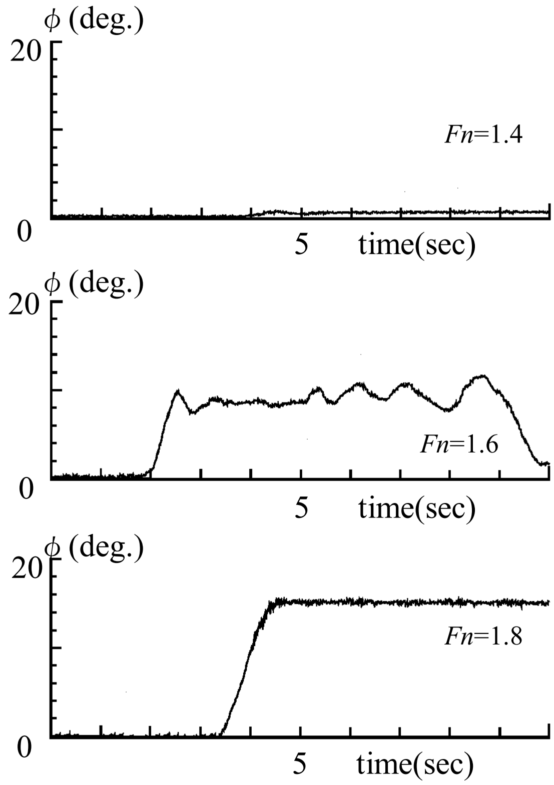


Fig.3 Time histories of roll motion of the planing craft shown in Fig.2 at trim angle of 2 degrees measured by free rolling test, without initial heel angle.

3.2 ROLL INDUCED BY PITCH

As pointed out in previous section, the roll restoring force significantly varies with trim angle at high forward speed as shown in Fig.4. This figure suggests that an unstable roll motion due to parametric oscillation may be induced by any pitch motion, because the roll restoring coefficient varies with time by changing pitch angle. The simulation program was developed by Katayama et al (1996), and the simulation results of free roll motion of a planing craft with an initial heel angle in calm water are shown. in Fig.5. In each simulation a sinusoidal pitch motion with constant period and amplitude is given. The roll natural period is fixed to be 2.0 seconds, and the forced pitch periods are changed as 2.0, 1.0 and 0.667 seconds respectively. When the period of forced pitch motion is half of the roll natural period, roll motion grows up with time as shown in Fig.5. These results suggest that pitch motion due to waves or porpoising in calm water may cause unstable large roll motion when the period of pitch motion is half of the roll natural period.

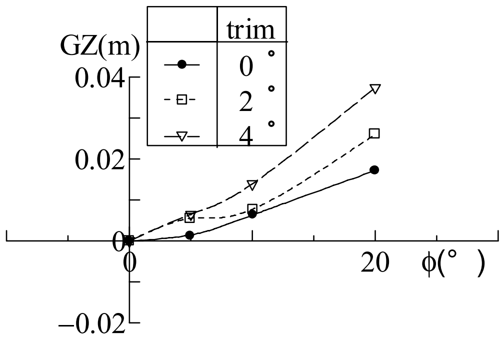


Fig.4 GZ curve of a planing craft at Fn=1.6.

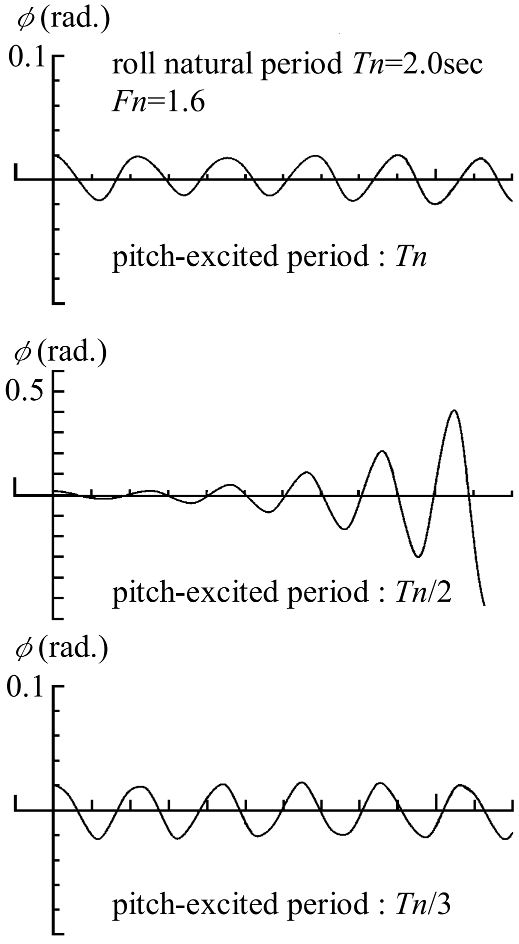


Fig.5 The simulated result of time histories of rolling motion induced by forced pitching motion.

4. LONGITUDINAL MOTIONS

In this chapter, bow-diving and longitudinal motion induced by roll will be treated.

4.1 BOW-DIVING

For occurrence of bow-diving, the heave and pitch restoring forces must play important role. 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 using these two stability curves. Then, the author proposed an acceleration vector obtained from these stability curves (Katayama et al. 2002b). 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.

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

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

where H and τ 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. Then the acceleration vector defined as Eq. (6) can be obtained as a function of H and τ.

Acceleration vector: $$\vec{a} = (\ddot{z}, \ddot{\theta}) \quad (6)$$

The vector shows the direction and magnitude of excited motion due to the restoring forces at a certain attitude described by H and τ.

Fig.6 shows an obtained acceleration vector of a planing craft at Fn=2.3. The solid lines 2 and 3 in the figure show the attitude in which the heave and pitch restoring forces are zero respectively, and the dotted line shows 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 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.

As an example of a simplified diagnosis of bow-diving occurrence using the above-mentioned acceleration vector, bow-diving of a planing craft in regular head waves is shown. The ship moves around the steady running attitude shown by the circle in Fig.6. The ship motion is calculated by a strip method, and the relative attitude to incident wave surface is obtained as shown by

Curves *a* and *b* in Fig.7. Curves *a* and *b* show the results for different wave height. Since Curve *a* (λ/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 Line 1, it is considered that bow-diving does not occur in this wave. Curve *b* for slightly larger wave height (Hw/d=0.4), however, goes into the area on the left side of Line 1, 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, occurrence of bow-diving 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.

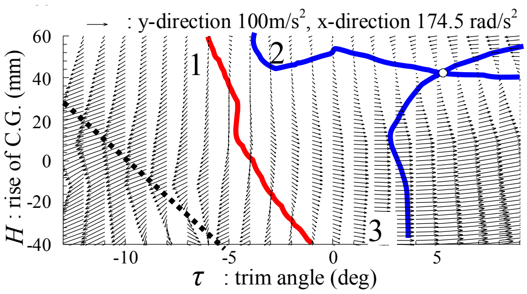
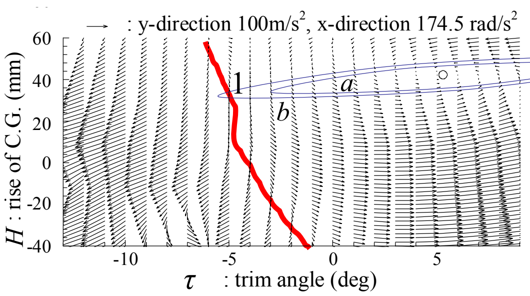


Fig.6 Acceleration vector obtained from measured restoring forces at Fn=2.3. Solid Lines 1, 2 and 3are attitudes which restoring forces are zero and ○ shows steady running attitude. The dot line is the borderline where a ship's bow is submerged in water.



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

Fig.7 Criteria of Bow-diving in regular head wave using acceleration vector and ship motion calculated by a strip method. Solid Line 1 is limiting line of bow-diving occurrence.

A motion simulation method in time domain for bow-diving motion of planing craft was developed by Katayama et al (1999). For the simulation a database of measured hydrodynamic forces in the wide range of running attitude including bow-submerged attitude are used. Some simulated results for a planing craft under forward acceleration are shown in Fig.8. 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 results, and it can be safely said that occurrence of bow-diving can be assessed by the simulation method, too.

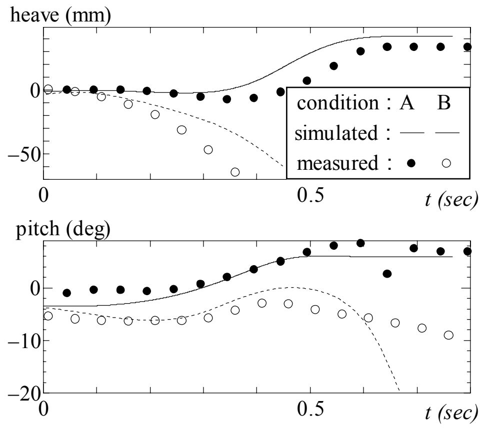


Fig.8 Time histories of simulated ship motions with and without bow-diving.

4.2 LONGITUDINAL MOTIONS INDUCED BY ROLL

The experimental results of heave forces and pitch moment by fully captive model tests for various attitudes including heel angle can demonstrate another unstable motion. An example of measured results is shown in Fig.9. It is shown that the lift decreases and the trim moment increases with increasing heel angles. The results suggest that if large amplitude of rolling occurs, the heave and pitch motions of the half period of roll period may be induced. The simplified simulation program is developed by Katayama et al (2000), and the simulated results are compared with experimental one. In Fig.10, a time histories of measured and simulated heave and pitch motions induced by roll motion is shown. A simulated result is in good agreement with the experimental result and the heave and pitch periods are half of the roll period.

Above-mentioned results suggest that roll motion due to waves or manoeuvring motion like a slalom may cause such heave and pitch motions. In Fig.11, an experimental result by carried out partly captured PMM tests, in which heave, pitch and roll of a model are free and periodic manoeuvring motions are given, are shown. This result shows that large heave, pitch and roll coupling motion are induced by manoeuvring motion and such a violent motions like a corkscrew can be occurred when manoeuvring period agrees in twice of the heave and pitch period.

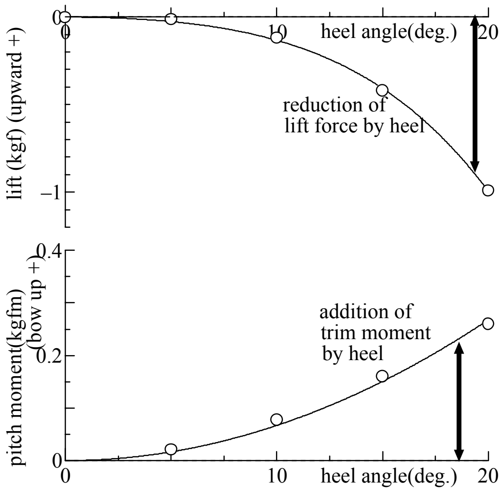


Fig.9 Effects of heel angle on lift force and pitch moment at *Fn*=2.0.

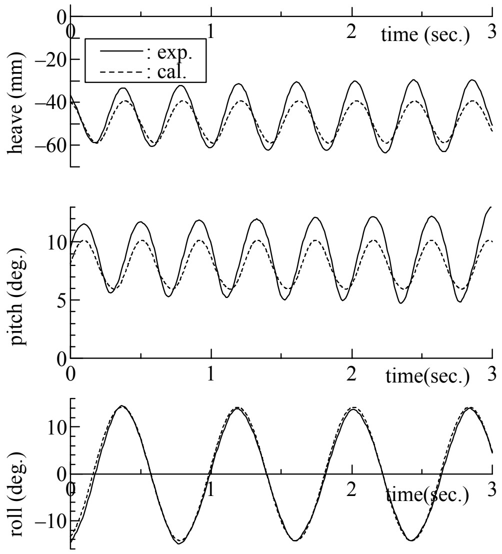


Fig.10 Comparison of time histories between measured and calculated motions at *Fn*=2.0.

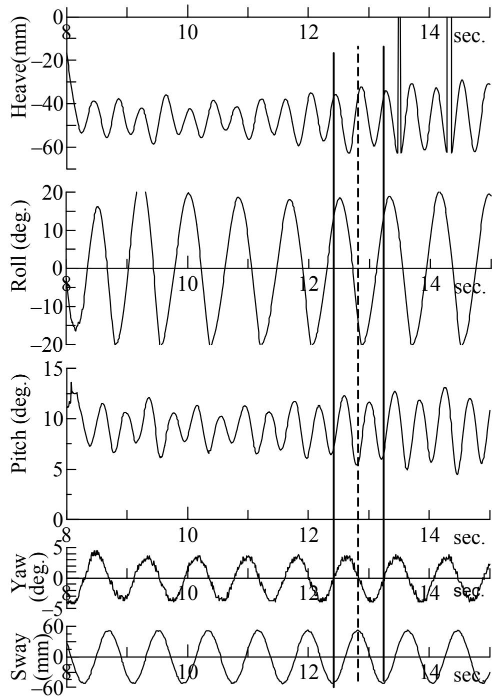


Fig.11 Time histories of measured motions obtained by partly captured PMM test with pure yaw motion when the period of forced manoeuvring motion is twice of heave and pitch natural periods.

5. LONGITUDINAL AND TRANSVERSE PORPOISINGS

5.1 PORPOISING

Unstable pitch and heave coupling motion of a high-speed craft in calm water is called porpoising. There were many investigations on the mechanism of porpoising, and several proposals of the prediction method to find the stability criterion. However, it has not be clarified that what mechanism in the equation of motion cause porpoising.

The heave and pitch restoring forces acting on a planing craft model in the attitudes where porpoising occurs are measured by Katayama et al (1997). The measured coefficients of restoring forces in the heave and pitch coupling motion equation are shown in Fig.12. The results show that the coupling restoring coefficients between heave and pitch motions, C_{35} and C_{53}, have different signs each other. As well known, when the coupling restoring coefficients have different sign in an oscillation system of two degree of freedom, a self-excitation oscillation can occur. Therefore, this result suggests that porpoising must be a self-excitation motion due to the different sign of the coupling restoring coefficients between heave and pitch motions. In Fig.13, the heave and pitch coupling restoring coefficients, C_{35} and C_{53}, of the craft are divided into dynamic and static components. This results demonstrates that the dynamic component created by forward speeds rapidly increases with forward speed and that these coefficients becomes different sign over Fn=0.6. Over this Fn, porpoising can occur if there is no damping. As increasing the damping, Fn where porpoising begins increases.

A simulation using a non-linear equation with non-linear hydrodynamic and hydrostatic coefficients is carried out to obtain porpoising of the craft. The 4th order Runge-Kutta method is used in the simulation. The results of the simulation are shown in Fig.14 with experimental results. The agreement between simulated and measured results of the heave and pitch amplitudes are fairly good.

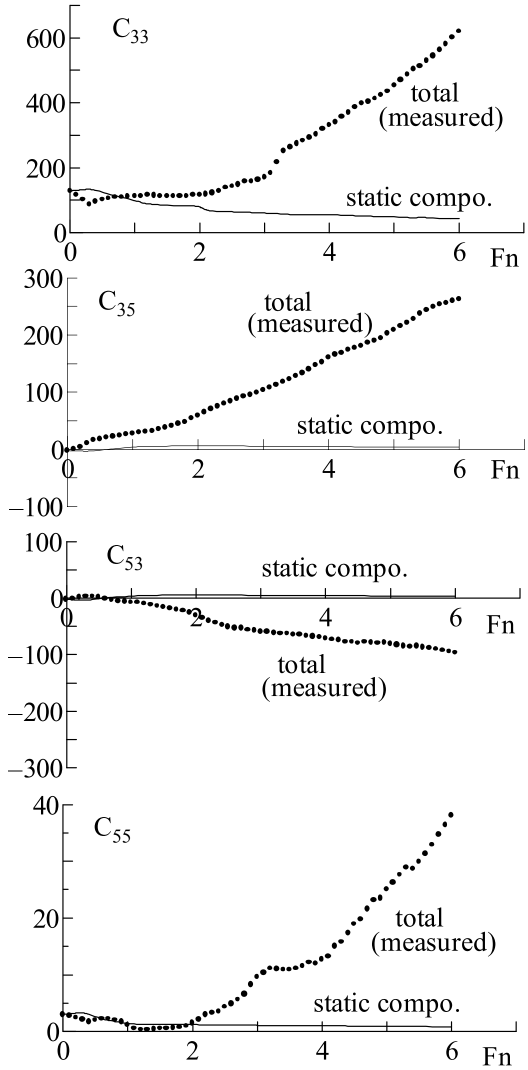


Fig.12 Coefficients of restoring forces and moments of motion equations for heave and pitch; heave restoring force C_{33}, coupled restoring force from pitch to heave C_{35}, coupled restoring moment from heave to pitch C_{53} and pitch restoring moment C_{55}.

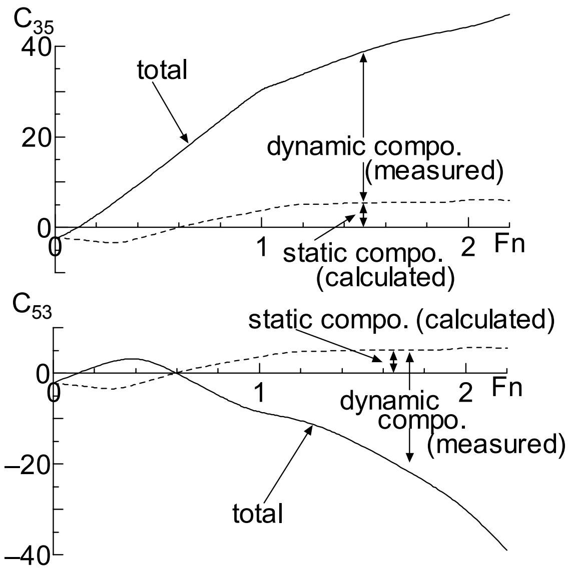


Fig.13 Heave and pitch coupling restoring coefficients, C_{35} and C_{53}

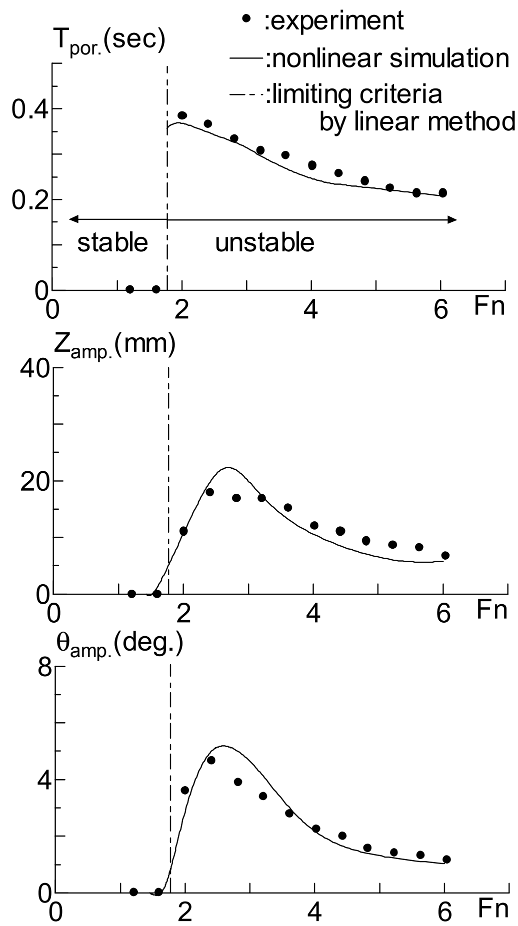


Fig.14 The simulated result of porpoising by non-linear simulation.

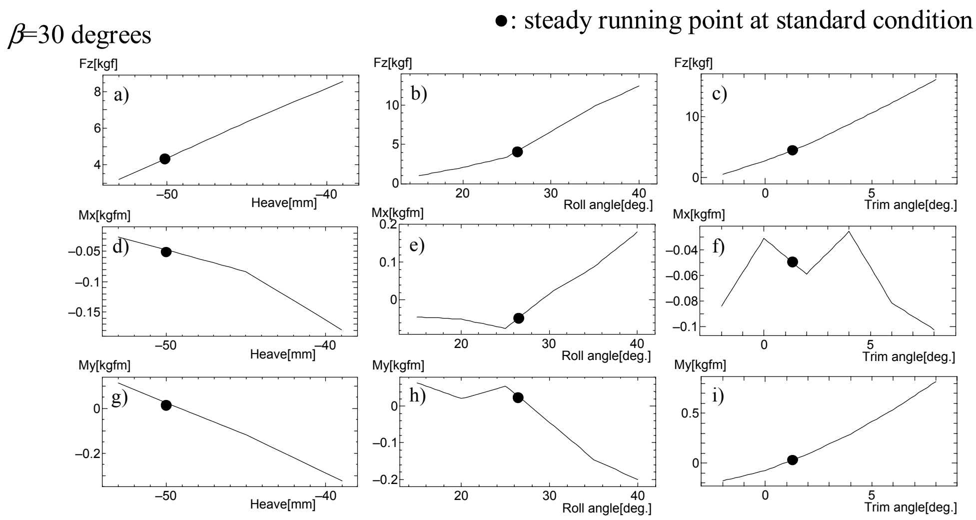


Fig.15 Restoring forces of acting on hull obtained by fully captive model test at forward speed *Fn*=2.0 and drift angle *β*=30 degrees.

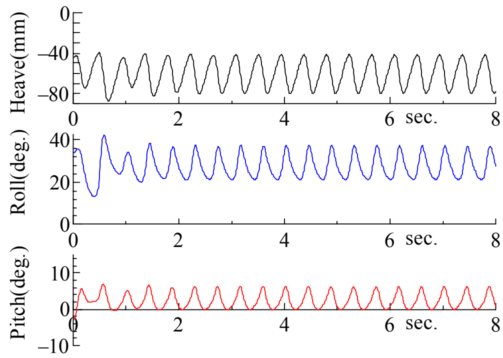


Fig.16 Simulated time histories of motions (*Fn*=2.0, *β*=30 degrees).

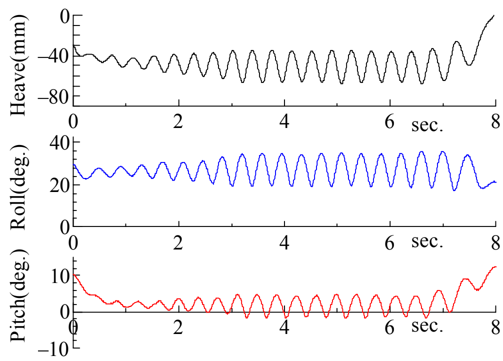


Fig.17 Measured time histories of motions (*Fn*=2.0, *β*=30 degrees).

5.2 TRANSVERSE PORPOISING

When a small planing craft turns at high speed, it drifts with large drifting angle in the direction to put its bow inside to a turning trajectory. Under such drifting motion, a craft sometimes make large heaving, pitching and rolling coupling motion like a porpoising and the motion is usually called transverse porpoising.

It was pointed out by Katayama et al (2001) (2002a) that occurrence of the transverse porpoising can be assessed by coupling restoring coefficients of heave, pitch and roll motions. To obtain the coefficients, fully captive model test to measure the three restoring forces should be carried out by systematically changing the draft, trim angle, heel angle and drifting angle. In Fig.15, the measured results for a planing craft at drift angle of *β*=30 degrees are shown. The results show that the coupling restoring coefficients between heave and pitch motions have the different sign each other ($\partial Fz/\partial\theta > 0$, $\partial My/\partial z < 0$) and the coupling restoring coefficients between heave and roll motions also have the different sign each other ($\partial Fz/\partial\phi > 0$, $\partial Mx/\partial z < 0$). The results suggest that the transverse porpoising that is self-excitation motions in heave, pitch and roll coupling motion may occur for the planing craft at the forward speed and the drift angle.

The simulation program of heave, pitch and roll coupling motion equation using the measured hydrodynamic forces were developed by Katayama et al (2001) (2002a), and motions in a time domain are calculated using the 4th order Runge-Kutta method. The calculation result and measurement result of motion are shown in Figs.16 and 17. It is confirmed that the simulated results are in fairly good agreement with experimental ones.

7. CONCLUSIONS

In this paper, techniques to assess occurrences of unstable motions for a planing craft using measured restoring forces at high forward speed are explained. The experimental method used here is a fully captive model test.

- By investigating the characteristic of transverse stability force, the possibility of occurrences of non-zero heel and roll induced by pitch can be assessed.
- By investigating the characteristic of longitudinal stability, the possibility of occurrence bow-diving and longitudinal motion induced by roll can be known.
- By investigating the sign of the coupling term of restoring forces, the possibility of occurrence of self-excitation motion, such as porpoising and transverse porpoising, can be assessed.
- In order to understand about dynamic instability, it is important to investigate the characteristic of the restoring force at high forward speed.

8. ACKNOWLEDGEMENTS

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