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Porpoising oscillations of very-high-speed marine craft

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Experimental and theoretical investigations on porpoising of a planing hull at high forward speed up to Froude numbers $Fr = 6.0$ ($Fr = U\sqrt{gL_{\mathrm{OA}}}$, where L_{OA} denotes the overall length of ship) in calm water are conducted. Captive model tests and forced motion tests are carried out to measure the hydrodynamic forces acting on the hull. The results reveal that without any exciting force, such a craft can porpoise as a self-excited oscillation originating from the existence of coupling restoring coefficients of different sign in a coupled system. The results also show that significant nonlinear effects for motion amplitudes appear in the restoring, the added mass and the damping coefficients. The measured hydrodynamic forces are compared with the results of an existing prediction method including nonlinear effects, and show a good agreement with them. Simulation of porpoising in calm water is carried out using the predicted hydrodynamic forces in a nonlinear equation of motion. The calculated results are in fairly good agreement with experimental ones.

Keywords: instability; porpoising; self-excited oscillation; coupled restoring forces; hydrodynamic forces; planing craft

1. Introduction

Stability problems of high-speed craft are very important even in calm water. For planing mono-hulls running with high speed it is well known that many types of dangerous motions can occur caused by transverse or longitudinal instability. Transverse instability can result in a sudden large heel, in loss of course-keeping ability due to the dynamically induced transverse-plane asymmetry, and in the condition known as 'chine-walking'. Longitudinal instability can cause self-induced heave and pitch oscillations ('porpoising') and submergence of the bow area ('bow-drop').

This paper focuses on porpoising of a high-speed planing monohull, which is a self-sustained coupled motion of pitching and heaving in calm water. Many investigations have been carried out to find the mechanism of porpoising, and the prediction methods for the criterion of its occurrence have been proposed (Day & Haag 1952; Martin 1978; Bessho & Komatsu 1984; Troesch 1992). However, the predicted results were not always in good agreement with measured ones. This may be because the mathematical model and the hydrodynamic coefficients in the prediction method are not appropriate for representing real porpoising phenomena.

In order to obtain an appropriate mathematical model, the authors have measured the motions' amplitudes as well as the hydrostatic and hydrodynamic forces acting on the hull. The experimental results suggest that the true cause of porpoising is the

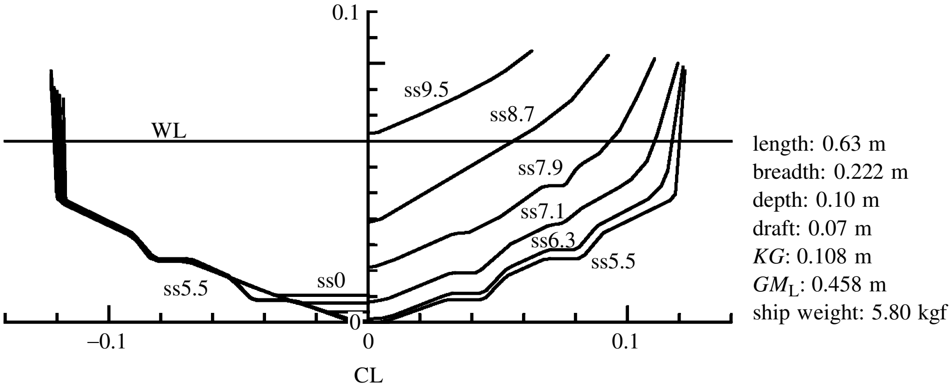

Figure 1. Body plan of model ship.

fact that the coupling restoring coefficients between heave and pitch obtain different sign in the high-speed region (Katayama & Ikeda 1996; Katayama *et al*. 1997). A time-domain simulation using the predicted and measure coefficients was carried out in order to reproduce the porpoising motion. Prediction porpoising, based on the measured forces, was found to be in good agreement with experimental results (Katayama *et al*. 1997).

The measured results also demonstrated that significant nonlinearity appears in hydrostatic and hydrodynamic forces acting on a moving craft at high forward speed, and its effects on porpoising are discussed.

2. Method of force measurement

The model used for the measurements is a 1:4 scale model of a personal water craft, the body plan of which is shown in figure 1. The model has relatively large 'spray rails' to whisk spray and to increase lift force. To measure the restoring forces, fully captive model tests (shown in figure 2) were carried out. Drag, lift and trim moment acting on the model were measured for various running attitudes and speeds. Heave and pitch restoring forces were obtained as sums of calculated static buoyancy forces and ship weight to these measured hydrodynamic forces. To measure the hydrodynamic added mass and damping forces, forced motion tests (shown in figure 3) were carried out. The model was forced to heave or pitch sinusoidally by two moving cylinders for various motion frequencies and amplitudes, and the forces acting on the model were measured by two one-component load cells.

3. Experimental results and discussion

(*a*) *Restoring coefficients*

The heave and pitch coupled motion of a high-speed craft without any excitation can be expressed by the following equation:

$$\begin{bmatrix} I_{33} & I_{35} \\ I_{53} & I_{55} \end{bmatrix} \begin{bmatrix} \ddot{z} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} B_{33} & B_{35} \\ B_{53} & B_{55} \end{bmatrix} \begin{bmatrix} \dot{z} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} C_{33} & C_{35} \\ C_{53} & C_{55} \end{bmatrix} \begin{bmatrix} z \\ \theta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix},$$

where z denotes the displacement of heave and θ denotes the angle of pitch. The coefficients I_{ij}, B_{ij} and C_{ij} are, respectively, the inertia coefficient (including added

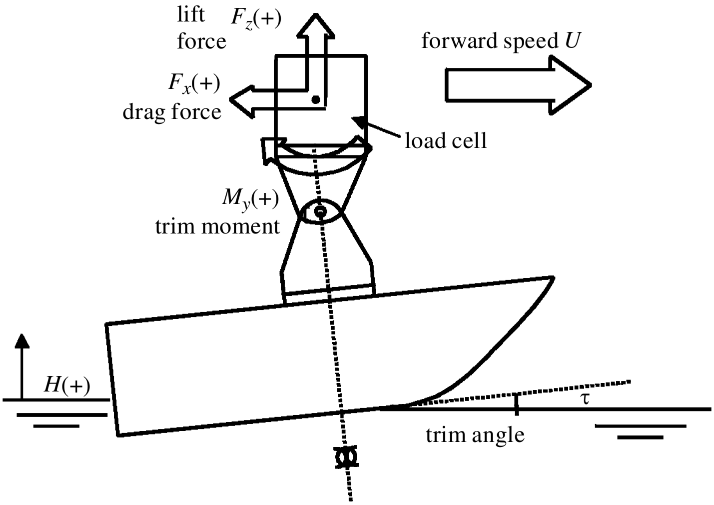

Figure 2. Schematic view of captive model test.

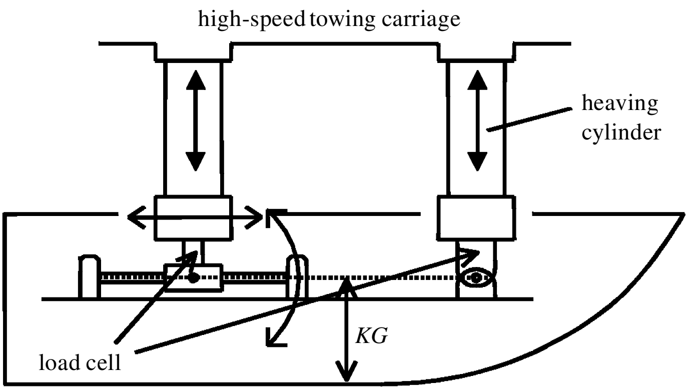

Figure 3. Schematic view of forced motion test.

mass A_{ij}), the damping coefficient and restoring force coefficient in direction i due to motion in the direction j (i, $j = 3, 5$, where 3 and 5 denote the direction of heave and pitch motions). Some coefficients are not always constant for high-speed craft, but depend on heave and pitch motions.

In figure 4, non-dimensional restoring coefficients $\hat{C}_{ij}$ (in the region where porpoising occurs, measured by fully captive model tests) are plotted versus heave or pitch displacements for various Froude numbers. The coefficients are non-dimensionalized in terms of porpoising frequency ω as follows:

$$\hat{C}_{33} = \frac{C_{33}}{\rho \nabla \omega^2}, \qquad \hat{C}_{35} = \frac{C_{35}}{\rho \nabla \omega^2 L_{\mathrm{OA}}},$$
$$\hat{C}_{53} = \frac{C_{53}}{\rho \nabla \omega^2 L_{\mathrm{OA}}}, \qquad \hat{C}_{55} = \frac{C_{55}}{\rho \nabla \omega^2 L_{\mathrm{OA}}^2},$$

where ρ denotes the density of water and ∇ denotes displacement.

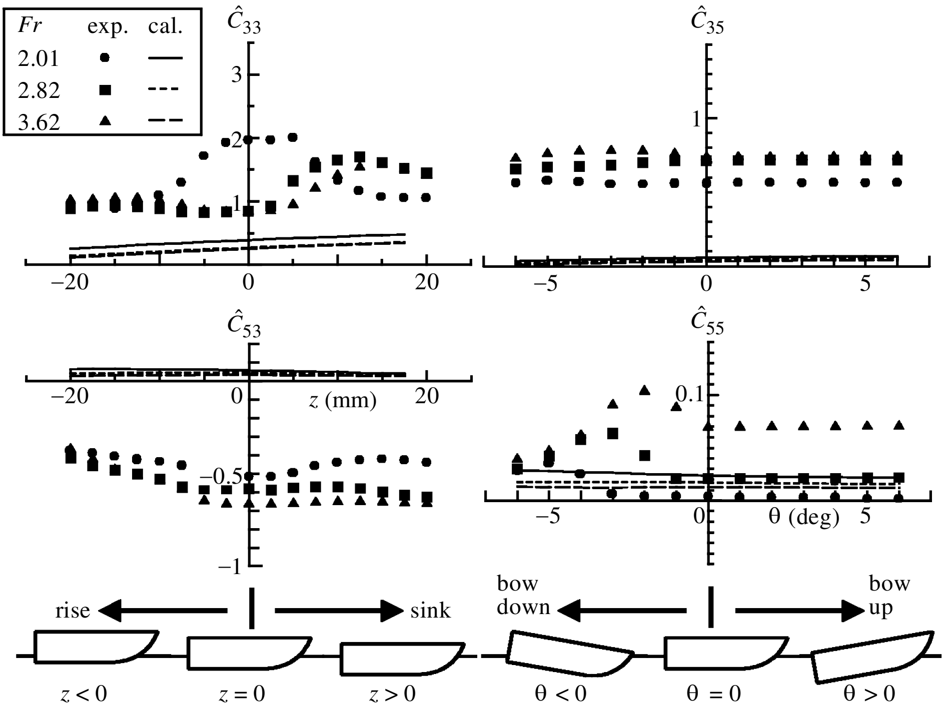

Figure 4. Restoring coefficient of heave–pitch coupling motion versus motion displacements at $Fr = 2.01$, 2.82 and 3.62 for each corresponding running attitude (exp., measured by fully captive test; cal., calculated buoyancy components). Here, z is the heave displacement (mm) and θ is the pitch (trim) angle (deg).

Calculated static buoyancy components at zero forward speed are also shown by solid and broken lines in the figure. The results show that measured coefficients at high speed are different from the static ones at zero forward speed, and that significant nonlinear effects for heave and pitch displacements can be seen in the heave and pitch restoring coefficients C_{33} and C_{55}. It should be noted that the nonlinearity in C_{33} and C_{55} significantly depends on forward speed. On the contrary, the nonlinearity in the coupling coefficients C_{35} and C_{53} is relatively small.

The experimental results show that, at high speed, the coefficients C_{35} and C_{53} are completely different from the static values at zero forward speed, and that those have different signs from each other. As explained in many textbooks on vibration (Rao 1990; Nakagawa *et al*. 1986; Bolotin 1963), this difference in sign of the coefficients causes a diverging self-excited combined motion in two degrees of freedom, since the energy of motions is fed into the system through self-exciting forces which are the coupled restoring forces. Bending-torsion flatter of a wing of an aeroplane is a typical example of this self-excited motion.

Variations of C_{35} and C_{53} with Froude number were measured by a fully captive model test, as shown in figure 5. In the measurements, the attitude at each speed was adjusted to that in free-attitude condition. Calculated static buoyancy components for each running attitude are also shown in the figure. Since the dynamic component in C_{35} rapidly increases and that in C_{53} decreases with forward speed, C_{35} and C_{53}

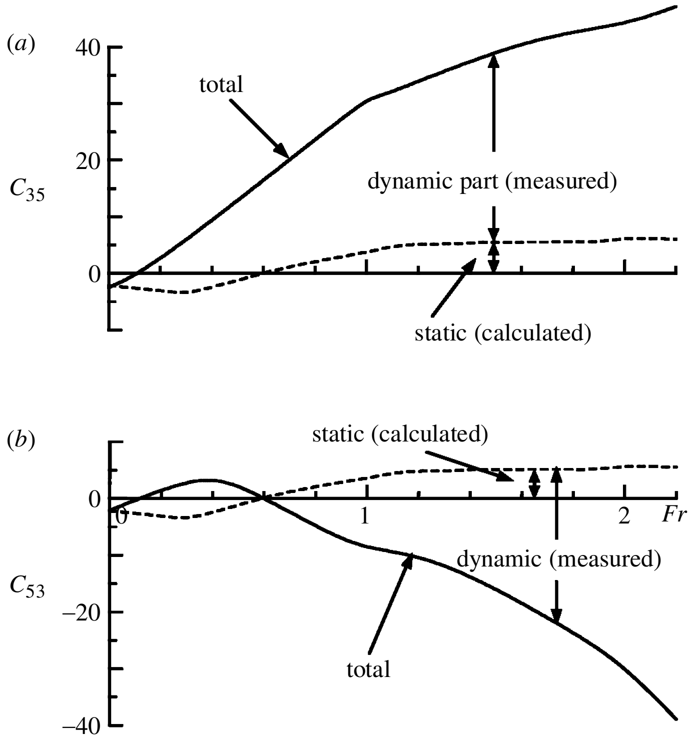

Figure 5. Variation of heave and pitch coupling restoring coefficients C_{35} and C_{53} with forward speed.

each have a different sign over a Froude number of 0.6. This means that porpoising can occur over $Fr = 0.6$ if no damping for each motion is assumed to act on the hull.

(b) *Oscillating components*

In figure 6, an example of the time history of measured heave forces acting on the model by a forced heaving test is shown. Although the given ship motion is sinusoidal, the measured force shows a triangular, or saw's teeth, shape. Moreover, the time history shows significant non-symmetry, and this means different forces act on the model in upward and downward motions. Added mass and damping components can be obtained from the measured force data at the moments when the acceleration and the velocity of motion are maximum in each direction, respectively.

4. Prediction method of hydrodynamic forces

(a) *Linear strip method*

In figures 7 and 8, measured added mass and damping coefficients are plotted versus heave and pitch amplitudes with estimated mass and damping coefficients by a strip method based on potential theory (new strip method, NSM). The sign of the amplitude in these figures indicates the direction of acceleration and velocity, respectively. The results show that added mass and damping coefficients in pitch a_{55}

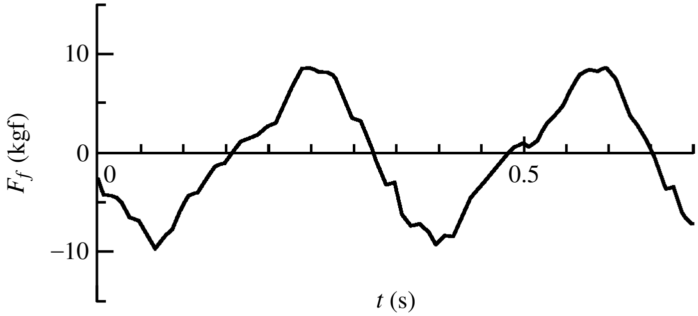

Figure 6. Time history of measured heave force by forced sinusoidal heaving test.

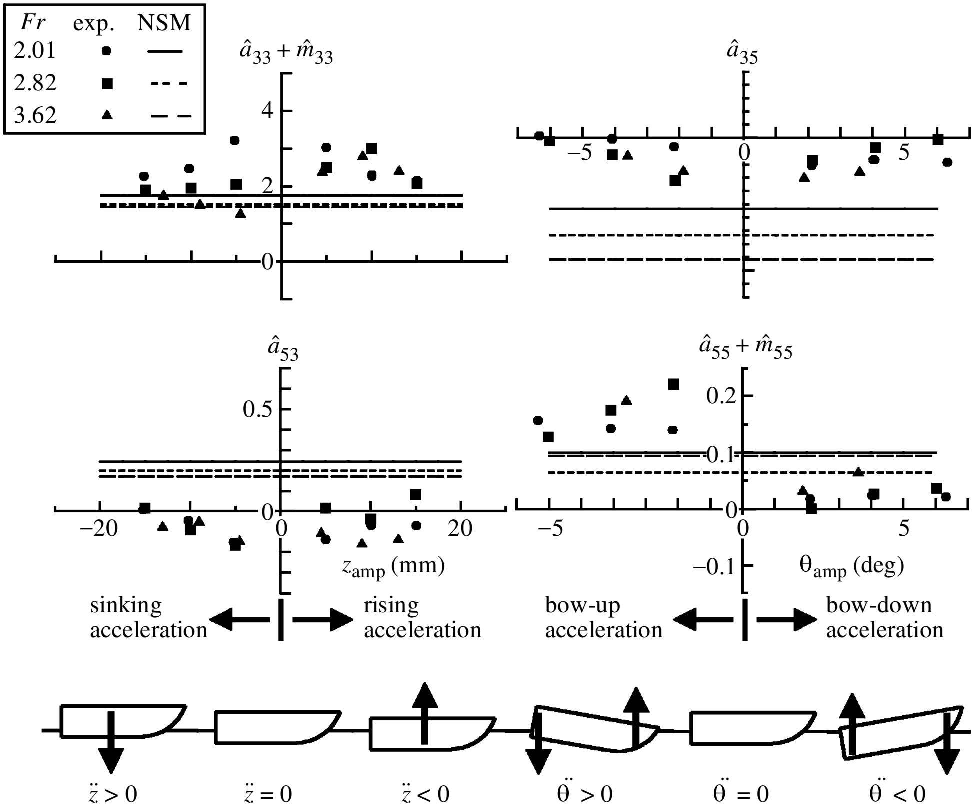

Figure 7. Added mass coefficients of heave–pitch coupling motion versus motion accelerations (exp., measured by forced motion test; NSM, calculated by a strip method based on linear potential theory called 'new-strip method').

and B_{55} significantly depend on the direction of acceleration and velocity, and that some measured coefficients are different from the estimated ones. This suggests that a prediction with the nonlinear effects taken into account is necessary for accurate calculations of porpoising motion.

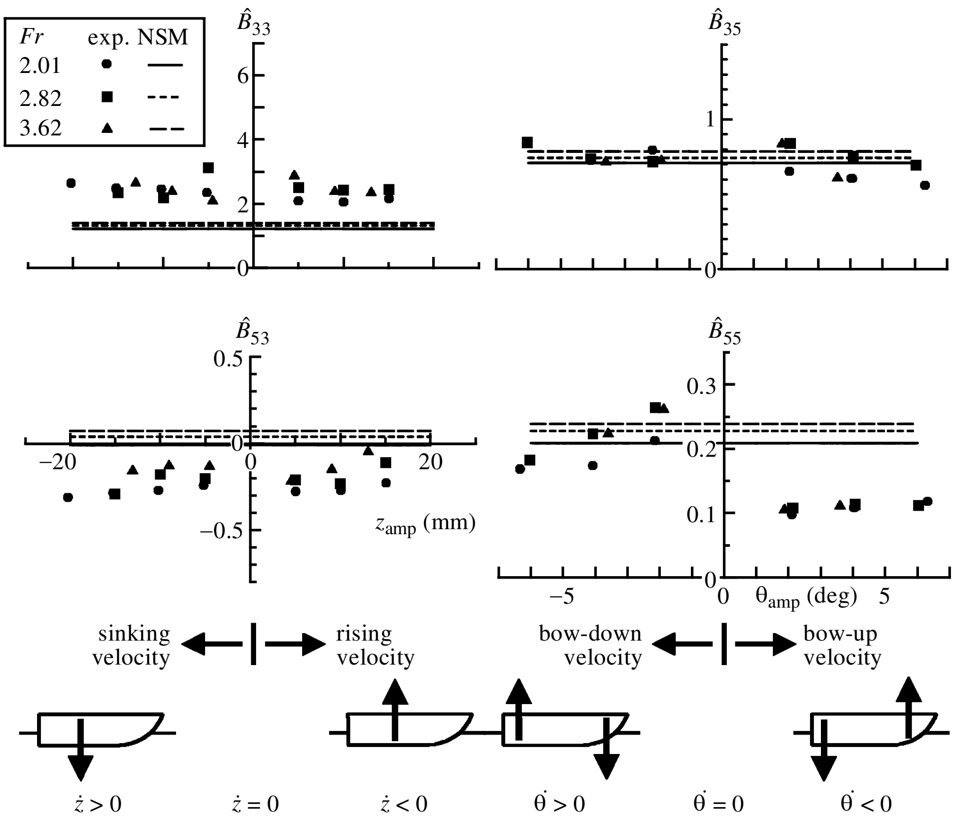

Figure 8. Damping coefficients of heave–pitch coupling motion versus motion velocity (exp., measured by forced motion test; NSM, calculated by a strip method based on linear potential theory called 'new-strip method').

(*b*) *Nonlinear strip method*

In this section, results by a prediction method combining hydrodynamic forces, including some nonlinear effect, and a vertical lift component are compared with experimental results. In the method, restoring forces are calculated by interpolation of systematic data files of measured forces by captive model tests, and added mass and damping forces are estimated by the nonlinear calculation methods based on potential theory proposed by Yamamoto *et al.* (1978) and Takaki *et al.* (1996). Furthermore, hydrodynamic damping effects due to the vertical lift force on the heave damping B_{33} and the coupling damping B_{53} are taken into account by the simple prediction methods proposed by Ikeda *et al.* (1998). The comparisons between the predicted results and the measured ones are shown in figure 9. It can be concluded that the agreements between predicted and measured results are good.

5. Simulation of porpoising

Time-domain simulations using linear coupling equations and nonlinear coupling equations were carried out. In the nonlinear calculation, hydrodynamic coefficients

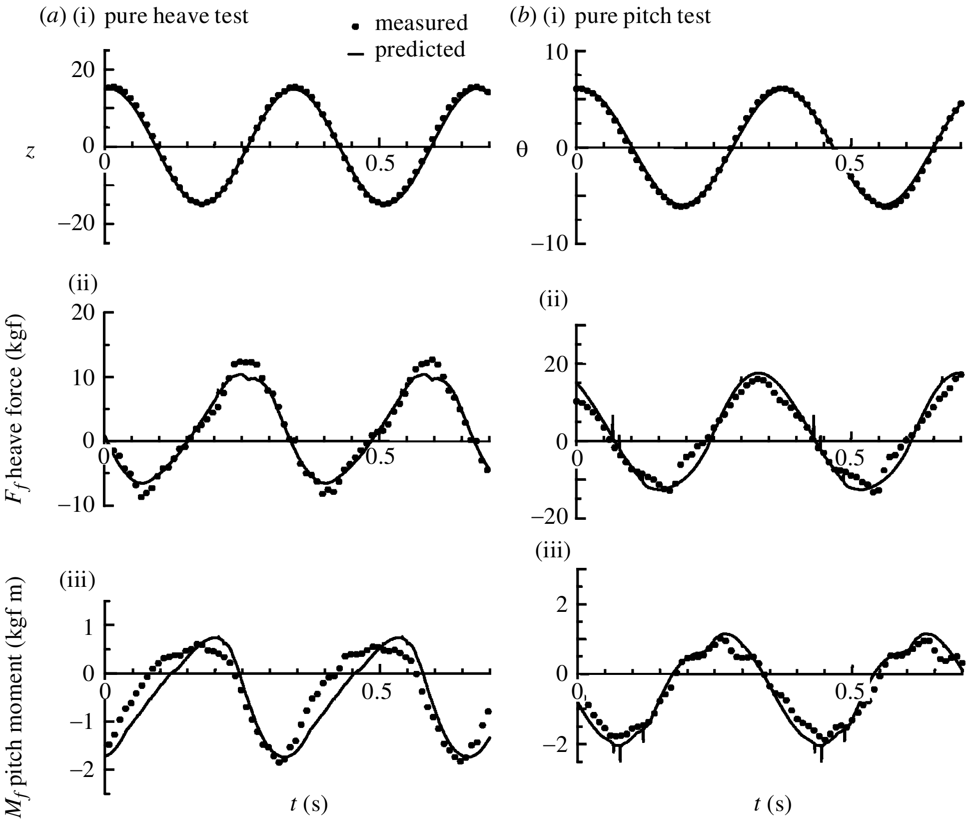

Figure 9. Comparison of time histories of measured and predicted heave force and pitch moment. Here, z is the heave (mm) and θ is the pitch (deg).

obtained by the method mentioned in the previous section were used. In the linear calculation, linearized coefficients of forces at very small amplitude were used on the basis of measured coefficients. By the linear calculation, we can obtain the limiting criteria of unstable motion.

The results of the simulations are shown in figure 10. Even by the linear method, the limiting speed of occurrence of porpoising can be predicted accurately, as shown in figure 10. However, it is impossible to obtain the amplitudes of heave and pitch motions by a linear method because the amplitudes diverge. The results from the nonlinear simulation are in fairly good agreement with those from the experiments.

Energy of porpoising motion must be transformed from the energy of other modes of motion, such as forward motion of the craft. Figure 11 shows the comparison of the resistance acting on the hull between porpoising and non-porpoising conditions. The value in the non-porpoising condition is obtained by solving an equilibrium equation of steady forces acting on the hull in steady running condition. The resistance in the porpoising condition is larger than that in the steady running condition without porpoising. This may demonstrate that the energy to make porpoising comes from the increase in resistance, i.e. the thrust force by the engine of the craft.

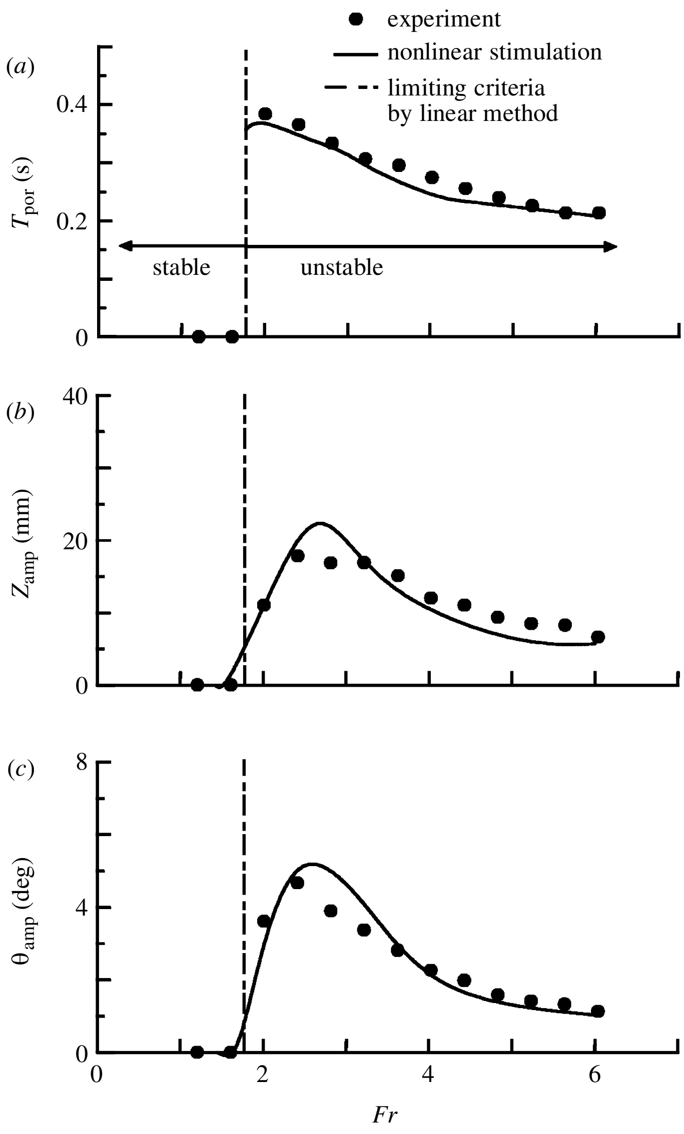

Figure 10. Results of porpoising obtained by nonlinear simulation and the linear method.

With the nonlinear simulation method, effects of damping and coupling terms in restoring forces on porpoising are investigated. The results are shown in figure 12. If the coupling terms in restoring forces are ignored, no porpoising occurs, as shown in case 1 of this figure. This may demonstrate that the porpoising measured in the present study is a self-excited motion in the oscillation system of two degrees of freedom with coupling restoring coefficients of different sign. The results when the heave and pitch damping are twice those in the simulation are shown as case 2 and 3, respectively. The results show that the unstable region where porpoising occurs becomes narrower because of the damping effects.

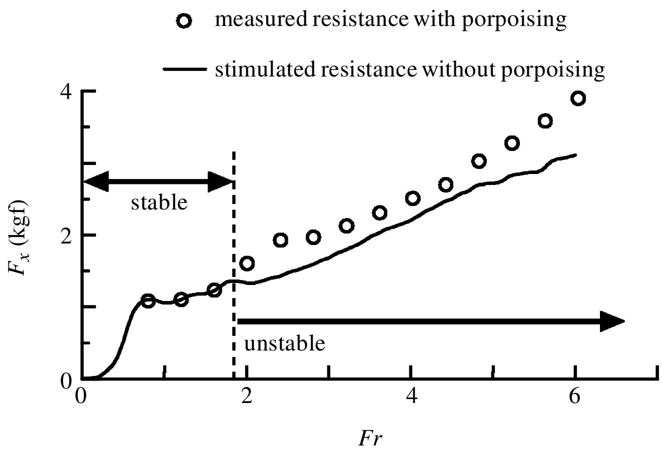

Figure 11. Comparison of resistances with and without porpoising.

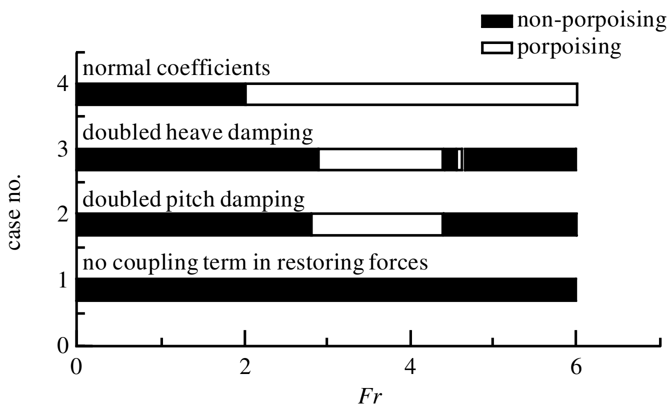

Figure 12. Effects of heave and pitch damping and coupling restoring coefficients on porpoising occurrence.

6. Conclusions

In this paper, the mechanism of porpoising of a planing monohull and the effect of nonlinearity of hydrodynamic forces acting on the hull on porpoising were investigated. The following conclusions were obtained.

(1) Porpoising is a kind of self-excited oscillation in a coupled system between heaving and pitching with coupling restoring coefficients with different signs from each other.

(2) The nonlinearity of the hydrodynamic forces acting on a planing craft moving in heave and pitch is significant.

(3) The nonlinear added mass and damping forces can be approximately predicted by the existing prediction methods.

(4) The simulation results of porpoising using the predicted hydrodynamic forces and measured restoring forces are in fairly good agreement with experimental ones.

(5) The nonlinear simulation predicts both the region and amplitude of porpoising reasonably well, while the linear method predicts only its region.

(6) Accurate coupling restoring coefficients between heave and pitch are essential to predict porpoising.

(7) The damping force plays an important role in occurrence of porpoising.

References

Bessho, M. & Komatsu, M. 1984 Two-dimensional unsteady planing surface. *J. Ship Res.* **28**, 18–28.

Bolotin, N. V. V. 1963 *Nonconservation problems of theory of elastic stability*. Oxford: Pergamon.

Day, J. P. & Haag, R. J. 1952 Planing boat porpoising—a study of the critical boundaries for a series of prismatic hulls. Thesis, Webb Institute of Naval Architecture.

Ikeda, Y., Katayama, T. & Tajima, S. 1998 A prediction method of vertical lift component of the roll and heave damping. *J. Kansai Soc. Naval Architects, Japan* **229**, 105–110.

Katayama, T. & Ikeda, Y. 1996 A study on coupled pitch and heave porpoising instability of planing craft (1st report). *J. Kansai Soc. Naval Architects, Japan* **226**, 127–134.

Katayama, T. & Ikeda, Y. 1997 a study on coupled pitch and heave porpoising instability of planing craft (3rd report). *J. Kansai Soc. Naval Architects, Japan* **228**, 149–156.

Katayama, T., Ikeda, Y. & Otsuka, K. 1997 a study on coupled pitch and heave porpoising instability of planing craft (2nd report). *J. Kansai Soc. Naval Architects, Japan* **227**, 71–78.

Martin, M. 1978 Theoretical determination of porpoising instability of high-speed planing boats. *J. Ship Res.* **22**, 32–53.

Nakagawa, K., Murotsu, Y. & Iwatsubo, T. 1986 *Mechanical vibration*, pp. 153–169. Tokyo: Morikita.

Rao, S. S. 1990 *Mechanical vibrations*. Addison-Wesley.

Takaki, M., Lin, X. & Ideguchi, M. 1996 A practical prediction method of ship motion with large amplitude. In *Proc. of Third Korea–Japan Workshop on Ship and Marine Hydrodynamics*, pp. 141–148.

Troesch, A. W. 1992 On the hydrodynamics of vertically oscillating planing hulls. *J. Ship Res.* **36**, 317–331.

Yamamoto, Y., Fujino, M. & Fukasawa, T. 1978 Motion and longitudinal strength of a ship in head sea and the effects of non-linearities. *J. Soc. Naval Architects, Japan* **143**, 179–187.