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Hydrodynamic Forces Acting on Porpoising Craft at High-Speed

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Abstract

An experimental investigation on hydrodynamic forces acting on a porpoising craft at high advanced speeds up to Froude numbers $Fn = 6.0(Fn = U\sqrt{(gL_{OA})}$: L_{OA} denote overall length of ship) in calm water is performed. Captive model tests and forced motion tests are carried out to measure the hydrodynamic forces. The results show that significant nonlinear effects for motion amplitudes appear in the restoring, the added mass and the damping coefficients. The experimental results are compared with the results of a prediction method of the hydrodynamic forces include the nonlinear effects, and show a good agreement with them. A simulation using the predicted hydrodynamic forces in a nonlinear motion equation is carried out to obtain the porpoising motion of a craft in calm water. The calculated results are in fairly good agreement with experimental ones.

1 Introduction

Pitch and heave coupling motion of a high speed craft in clam water is called 'porpoising'. Many investigations have been carried out to find the mechanism of porpoising, and the prediction methods for the criterion of its occurrence were proposed Day et al., Martin, Bessho et al. and Troesch[Day et al., 1952][Martin, 1978][Bessho et al., 1984][Troesch, 1992]. However, the predicted results were not always in good agreement with measured ones. These may be because the mathematical model and the hydrodynamic coefficients in the model are not suitable to express the porpoising. The authors measured the motion, hydrostatic forces and hydrodynamic forces acting on a craft to find that the coupling restoring coefficients between heave and pitch has different sign in the high speed region [Katayama et al., 1996][Katayama et al., 1997a]. This suggests that these coefficients may cause a kind of self-excited oscillation, which is porpoising. The predicted occurrence criteria of porpoising using the measured forces were confirmed to be in good agreement with experimental results [Katayama et al., 1997b].

Attention in this paper will be focused the nonlinearities of hydrostatic and hydrodynamic forces acting on a porpoising craft and the effects of them on porpoising. Measured forces by captive model tests and forced motion tests for a craft up to Froude nomber $Fn = 6.0$ are shown

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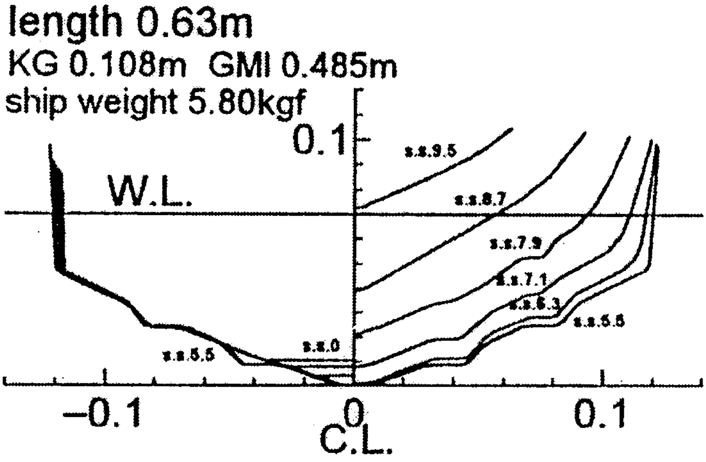

Figure 1. Body Plan of model ship.

for various amplitudes to clarify the nonlinear characteristics. A time-domain simulation using the predicted and measured coefficients is carried out to obtain porpoising motion.

2 Measurement of Hydrodynamic Forces

Used model is a 1/4 scale model of a personal water craft, the body plan of which is shown in Figure 1. To measure the restoring forces, captured model tests shown in Figure 2 are carried out. Drag, lift and trim moment acting on the craft are measured for various running attitudes and advanced speeds. Heave and pitch restoring forces are calculated to add 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 are carried out. The model is forced to heave or pitch motions sinusoidally by two moving cylinders for various motion frequencies and amplitudes, and forces are measured by two 1-component load cells.

3 Measured Results and Discussions

In Figure 4, measured restoring coefficients are plotted versus heave or pitch displacements with calculated static buoyancy components at zero advanced speed. The results show that measured forces at high speed are generally different from the static ones, and that significant nonlinear effects for displacement can be seen in heave and pitch restoring coefficients, C_{33} and C_{55}. It should be noted that the nonlinearities in C_{33} and C_{55} significantly depend on advanced speed. On the contrary, the nonlinearies in the coupling coefficients, C_{35} and C_{53} are small. The results show that C_{35} and C_{53} at high speed are completely different from the static values at zero advanced speed and that have different signs each other. As mentioned in the introduction, this change of sign causes a self-excited heave and pitch combined motion.

In Figure 5, variations of C_{35} and C_{53} with Froude number are shown with calculated buoyancy components for each running attitude. The results show that the dynamic components are

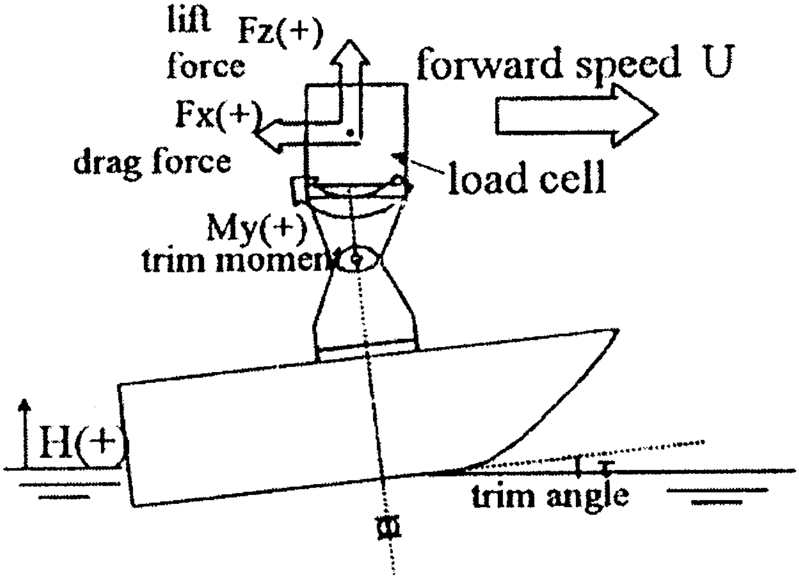

Figure 2. Schematic view of captive model test.

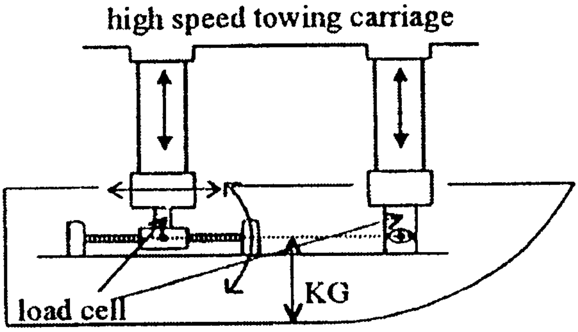

Figure 3. Schematic view of forced motion test.

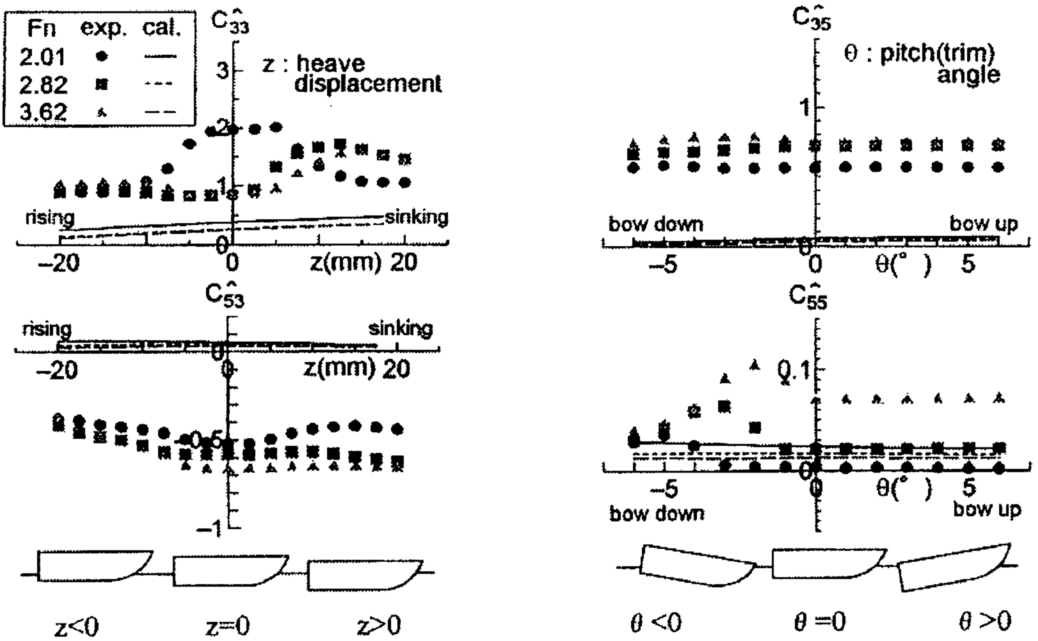

Figure 4. Restoring coefficients of heave-pitch coupling motion versus motion amplitudes(exp.: measured by forced motion test, cal: calculated buoyancy components).

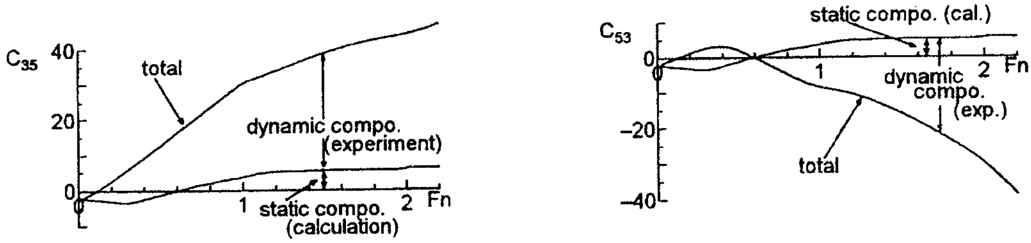

Figure 5. Measured heave and pitch coupling restoring coefficients C_{35} and C_{53} versus advanced speed with calculated buoyancy components.

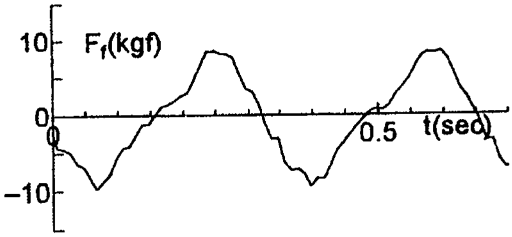

Figure 6. Time history of measured heave force, when by forced to oscillate pure heave.

rapidly increase with advanced speed, and that these coefficients have different sign over Froude number $Fn = 0.6$.

In Figure 6, an example of time history of measured heave forces acting on the model by forced heaving test is shown. Although the given ship motion is sinusoidal, the measured force show triangular, or saw's teeth shape. Moreover, the time history shows significant non-symmetry that means different forces act on the model in upward and downward motions.

Added mass and damping components are calculated from the measured values at the moments when the acceleration and the velocity of motion are maximum respectively. In Figure 7 and 8, measured added mass and damping coefficients are plotted versus heave and pitch amplitudes with estimated ones by a strip method based on potential theory, 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} and B_{55} significantly depend on the direction of acceleration and velocity, and that some measured coefficients are different from the estimated ones. These suggest that a prediction taking into account the nonlinear effects is needed for accurate calculations of porpoising motion.

4 Prediction Method of Hydrodynamic Forces

In this section, results by a prediction method of hydrodynamic forces including some nonlinear effect and linear 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 NSM and nonlinear calculation methods proposed [Yamamoto et al., 1978][Takaki et al., 1996]. Furthermore, hydrodynamic damping effects due to vertical lift force on the heave damping B_{33} and the coupling damping B_{53} are taking account by the simple prediction methods proposed [Ikeda et al., 1998].

The comparisons of the predicted results and measured ones are shown in Figure 9. It can be said that the agreements between predicted and measured results are roughly good.

5 Simulation of Porpoising

Time domain simulations using linear coupling equations and nonlinear coupling equations are carried out. In the nonlinear calculation, hydrodynamic coefficients obtained by the method mentioned in previous section are used. In the linear calculation, measured coefficients for very small amplitude are used.

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 by the nonlinear simulation are in fairly good agreement with experimental ones.

Using the nonlinear simulation, effects of damping and coupling terms in restoring forces on porpoising are investigated. The results are shown in Figure 11. If the coupling terms in restoring forces are ignored, no porpoising occurs as shown in this figure. It 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 result when the

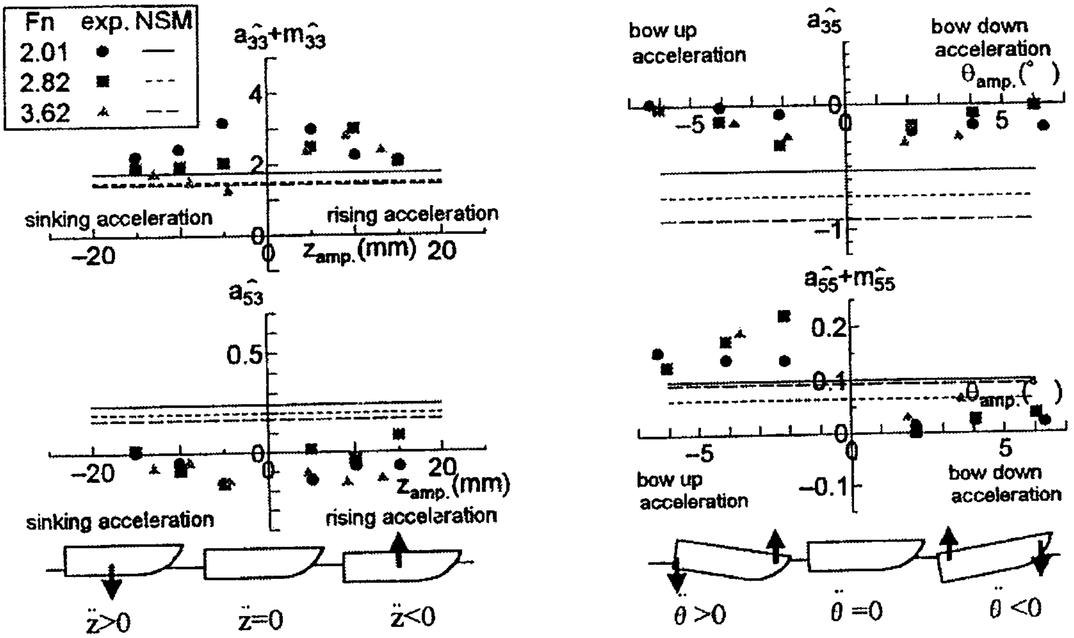

Figure 7. Added mass coefficients of heave-pitch coupling motion versus motion accelerations (exp.: measured by forced motion test, NSM: calculated by strip method based on potential theory).

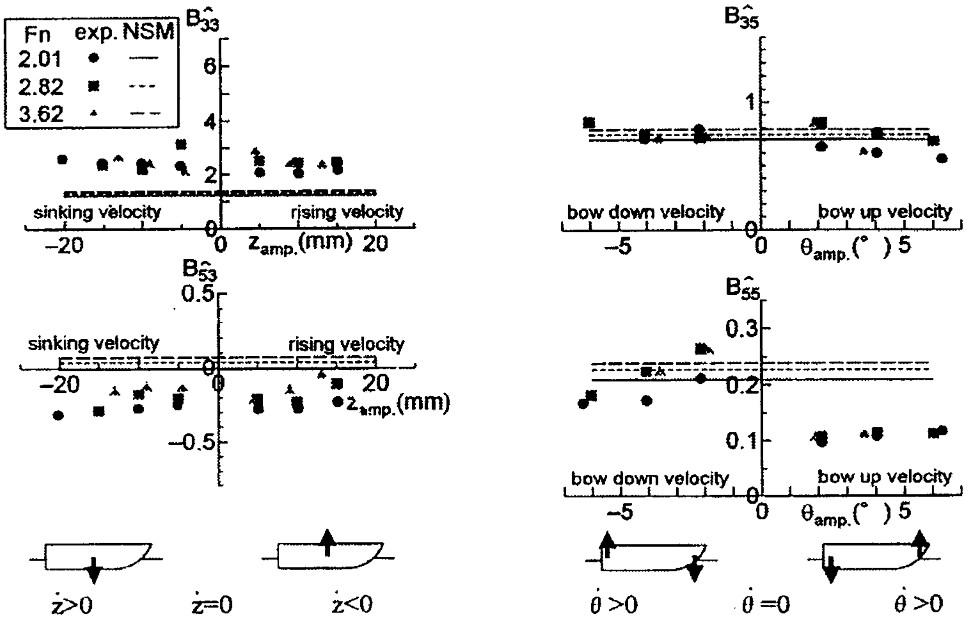

Figure 8. Damping coefficients of heave-pitch coupling motion versus motion accelerations (exp.: measured by forced motion test, NSM: calculated by strip method based on potential theory).

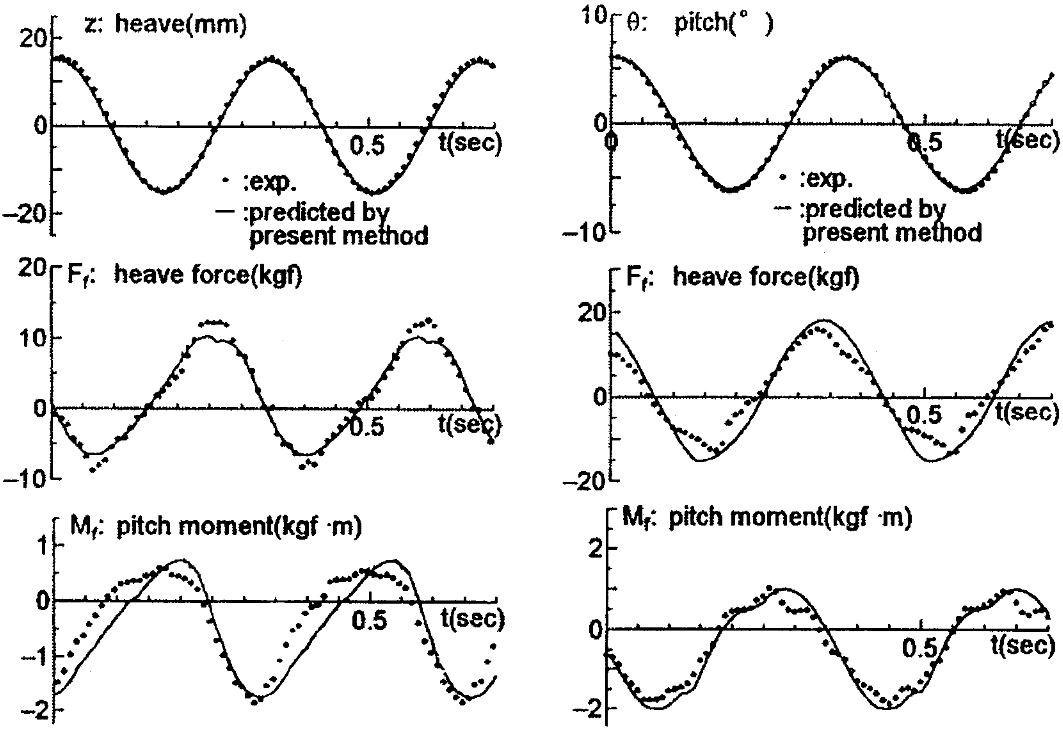

Figure 9. Time histories of nonlinear heave force and pitch moment calculated by present method.

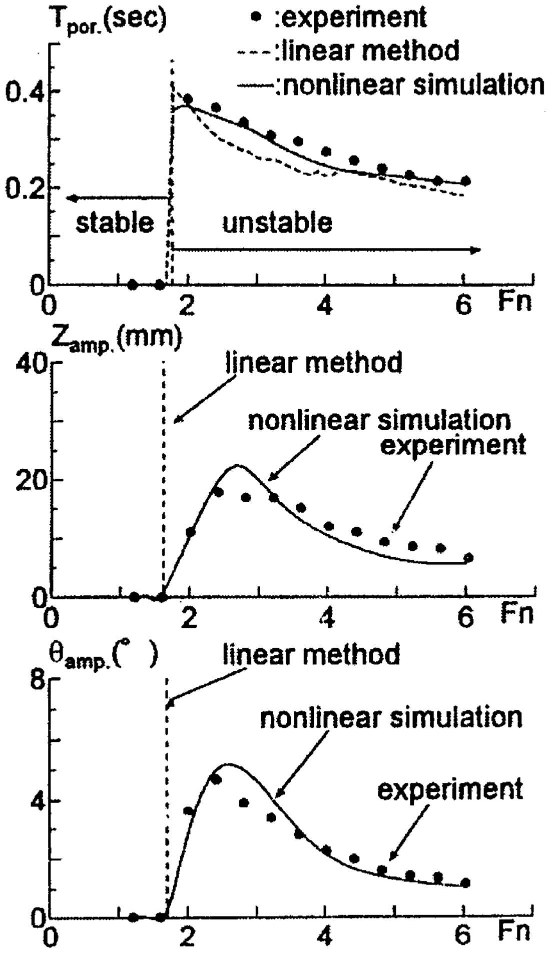

Figure 10. Results of estimated porpoising by nonlinear simulation and linear method.

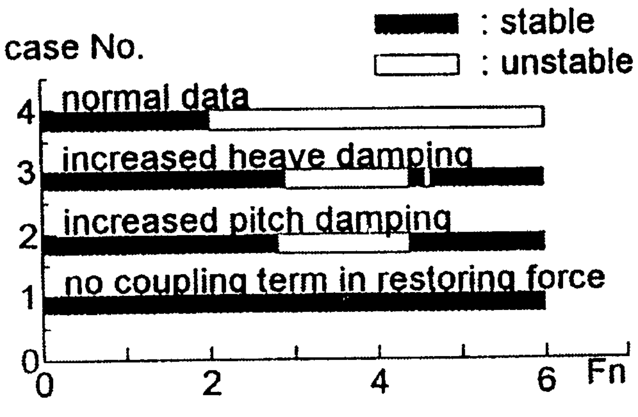

Figure 11. Advanced speed ranges of porpoising occurring.

heave or pitch damping is twice in the simulation is also shown in the same figure. The results show the unstable region where porpoising occurs becomes narrow due to the damping effects.

6 Conclusions

In this paper, the nonlinearity of hydrodynamic forces acting on a porpoising craft and its effects on porpoising are discussed. Following conclusions are obtained.

1) The nonlinearities of the hydrodynamic forces acting on a planing craft moving in heave and pitch are significant.

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

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

4) Without accurate coupling restoring coefficients between heave and pitch, no porpoising occurs in the present cases.

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

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