Contemporary Ideas on Ship Stability
ELSEVIER Science Ltd., pp401-409 (2000)

STABILITY OF HIGH SPEED CRAFT

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ABSTRACT

The investigations on transverse and longitudinal instability of the motions of a high-speed craft in calm water carried out by the authors are reviewed.

It is experimentally confirmed that the transverse stability significantly decreases at high Froude number, and this causes large heel of a craft. The stability loss, which depends on trim angle, also generates roll motion when a craft has pitching motion.

It is found that porpoising of the craft is a self-exciting motion due to the different sign of the coupling restoring coefficients between pitch and heave motions. Finally prediction methods for the roll and heave damping including vertical lift force contribution are proposed.

KEYWORDS

High-Speed, Planing Craft, Stability, Damping, Unstable Phenomena, Porpoising, Pure Stability Loss

INTRODUCTION

A high-speed vessel has different motion characteristics from those of a conventional displacement-type vessel. For example it is well known that in following seas a high-speed vessel can capsize by broaching, parametric rolling or stability reduction by waves. Even in calm water a high-speed craft show unique motion characteristics, such a chine walking, sudden large heel and porpoising. In the present paper the investigations on the stability and unstable motions of a high-speed craft carried out by the authors for these five years are introduced.

STABILITY LOSS AT HIGH SPEED

It was pointed out that the transverse stability of a displacement-type ship running in calm water at relatively high speeds decreases over Froude number of 0.3 and that the decrease may be caused by the wave pattern on the side of the hull.

The same phenomena are observed for a high-speed ship of semi-displacement type and of planing type. Figure 1 shows the experimental results of roll motion of a planing craft, the body plan of which is shown in Figure 2, in calm water without any disturbance. The results demonstrate that large heel occurs at high Froude number. Measured restoring moment of the craft is shown in Figure 3. The results confirm that the large heel shown in Figure 1 is generated by the transverse stability loss due to high advanced speed. The stability loss depends on advanced speed, location of center of gravity and trim angle as well as hull shape. The effect of trim angle on the stability of a craft at high speed is shown in Figure 4.

UNSTABLE ROLLING INDUCED BY PITCHING MOTION

As pointed out in the previous chapter, the transverse restoring moment significantly varies with trim angle at high speed. This suggests that an unstable rolling motion induced by pitching motion and that the motion is a parametric oscillation system, because the restoring coefficient depends on trim. In Figure 5 simulation results of free roll motion test with an initial heel angle of the planing craft in calm water are shown. In each simulation a sinusoidal pitching motion with constant period and amplitude is given. The roll natural period is fixed to be 2.0sec., and the forced pitching periods are changed as 2.0, 1.0 and 0.667sec respectively. When the period of forced pitching motion is half of the roll natural period, roll motion increases with time as shown in Figure 5. These results suggest that pitching motion due to waves or porpoising may cause unstable roll motion when the pitch period is half of the roll natural period. The authors investigated the effects of moment of inertia, roll damping, restoring moment and pitch amplitude on the pitch induced roll motion. In Figure 6, the cases of occurrence of unstable roll motion are plotted by black circles. If the roll damping is larger than these black circles, no rolling occurs. The solid line in the figure shows the predicted roll damping of the craft. In the region where the solid line is larger than the circles, no roll motion occurs and the motion is stable.

UNSTABLE PITCH AND HEAVE COUPLING MOTION

Unstable pitch and heave coupling motion of a high-speed craft in calm water is called 'porpoising'. There are many investigations on the mechanism of porpoising, and several proposals of the prediction method to find the stability criterion. However it is not clear that which coefficients in the equation of motion have significant influence on occurrence of porpoising.

The authors measured restoring forces and moments acting on a craft, and obtained the coefficients in the motion equation for the heave-pitch coupling motion as shown in Figure 7.

The model used in the measurement is a hard chine planing craft similar to that shown in Figure 2. Note 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 terms have different sign in an oscillation system of two degree of freedom, a self-excited oscillation occurs. Therefore this experimental results suggest that porpoising is a self-exciting motion due to the different sign of the coupling restoring coefficients between pitch and heave motions.

Forced heave and pitch tests of the craft model were also carried out in order to find the effects of hydrodynamic inertia and damping forces on porpoising. The results show that significant nonlinear effects can be seen in these hydrodynamic forces. This fact suggests that a linear prediction theory to find porpoising limit may not be sufficient and that a nonlinear theory should be used to obtain accurate prediction of porpoising.

A simulation using a nonlinear equation with nonlinear hydrodynamic and hydrostatic coefficients is carried out to obtain porpoising of the craft. The Runge-Kutta method of the fourth order is used in the simulation. The results of the simulation are shown in Figure 8 with experimental results. The heaving and pitching amplitudes, Z_{amp} and θ_{amp}, are overestimated near Froude number of 3.0. This is because of lack of data of hydrodynamic forces. Over Froude number of 4.0, the agreement between simulated and measured results is in fairly good.

The heave and pitch coupling restoring coefficients, C_{35} and C_{53}, of the craft are shown in Figure 9. We can see that the dynamic components generated by advanced speed are significant, and that these coefficients have different sign over 0.6 of Froude number. Over this Froude number, porpoising can occur if there is no damping. As increasing the damping, Froude number where porpoising begins increases.

Figure 10 shows the resistance increase of the craft running in calm water due to porpoising. The solid line in the figure denotes the simulation result of steady running condition without any motions, and the circles denote the measured resistance.

At low advanced speed where no porpoising occurs, the agreement between them is in fairly good, but after occurrence of porpoising, or in unstable region, the measured resistance with porpoising is larger than the resistance at steady condition without motions. These results may suggest that the energy for porpoising is given by the thrust of the craft and that if porpoising occurs, the resistance increase would reduce the advanced speed of a running craft.

ROLL AND HEAVE DAMPING CREATED BY VERTICAL LIFT FORCE

As described in previous chapters, unstable motions due to the instability of the motion equation can be avoided by increasing damping of the motions as shown in Figure 6. However the characteristics of the damping of semi-planing and planing craft have not been clarified yet, and there is no practical prediction method for such a planing craft. In this chapter, the roll damping and the heave damping will be discussed.

As shown by Ikeda et al., the lift component of the roll damping is dominant at high advanced speed. The horizontal lift force created by the horizontal pressure acting on a hull generates the lift component, and prediction methods for a displacement-type ship and a semi-displacement-type ship have been proposed by Ikeda et al..

For a planing craft, however, the projected area of the side hull is usually very small particularly when it runs at very high speed. Therefore instead of the transverse lift force, the vertical lift force acting on the bottom of the craft may play an important role in the damping. On the basis of quasi-steady assumption, the roll and heave damping can be obtained as follows,

$$\text{Roll damping :} \quad B_{44L} = \frac{1}{24}\rho B_{w.l}{}^{4} U k_L(\tau_1) \ ,$$

$$\text{Heave damping :} \quad B_{33L} = \frac{1}{2}\rho B^2 U^2 k_L \alpha = \frac{1}{2}\rho B^2 U k_L \, ,$$

where B denotes the breadth of water plane, k_L the differential coefficient of vertical lift coefficient with respect to trim angle, β deadrise angle in degree. In Figures 11 and 12 the predicted results of the heave and roll damping coefficients by the previous prediction method and the present one are shown.

Although the previous method including only transverse lift contribution underestimates the damping, the present method including the vertical lift contribution gives fairly good prediction results.

CONCLUSIONS

Stability loss due to high advanced speed, unstable roll motion induced by pitching motion and longitudinal instability called 'porpoising' of a high speed planing craft are investigated experimentally and theoretically, and following conclusions are obtained.

1. The transverse stability of a craft decreases at high advanced speed.
2. The stability loss causes a large heel at high advanced speed.
3. The dependency of the stability loss on trim angle generates unstable rolling motion induced by pitching motion.
4. Porpoising of a craft is a self-exciting motion due to the different sign of the coupling restoring coefficients between pitch and heave motions.
5. The damping plays an important role to avoid the occurrence of unstable motions.
6. A prediction method of the roll and heave damping including the vertical lift contribution is proposed, and it is confirmed that the agreement between predicted and measured is fairly good.

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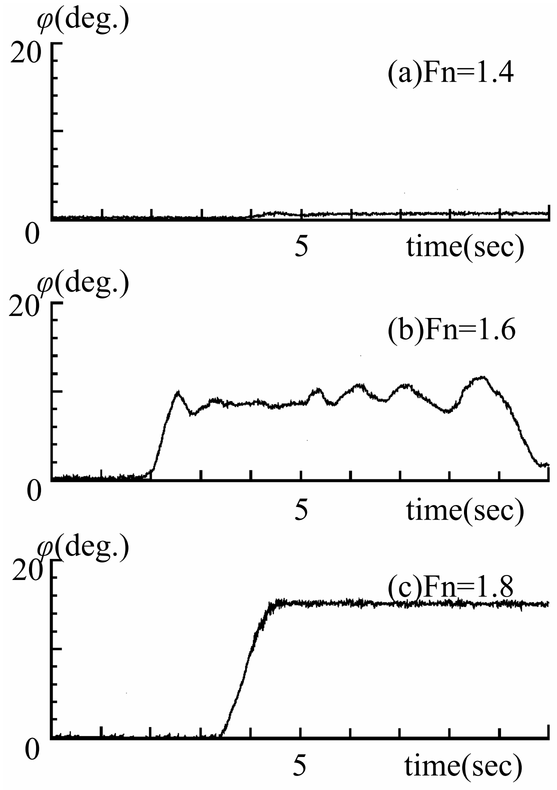

Figure 1: Time histories of roll motion of ShipB-45 at trim angle of 2deg. measured by free rolling test, without initial heel

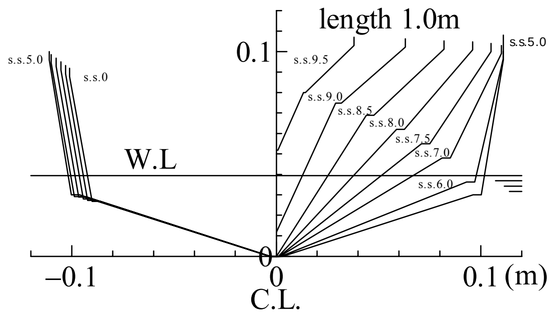

Figure 2: Body Plan of ShipB-45

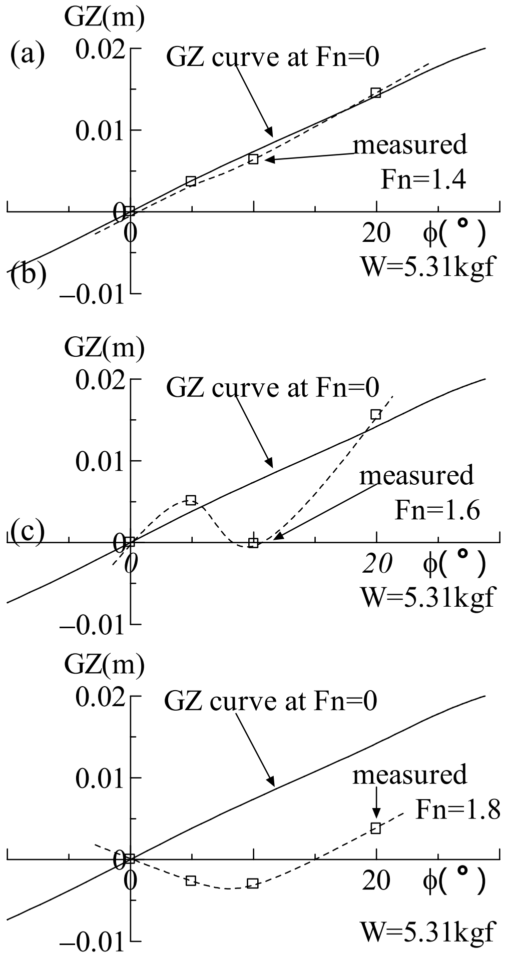

Figure 3: GZ curve of ShipB-45 at trim angle of 2deg., center of gravity 0.074m, ship weight 5.31kgf for several advance speeds :(a)Fn=1.4 (b)Fn=1.6 (c)Fn=1.8

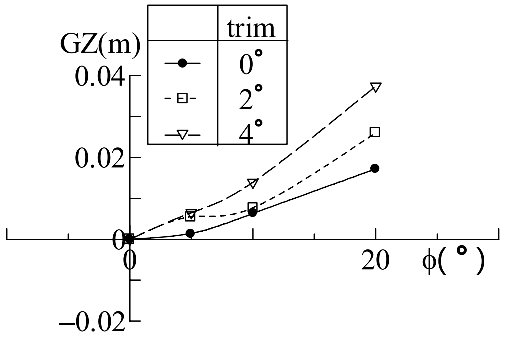

Figure 4: GZ curve of ShipB-45 at center of gravity 0.04m, ship weight 5.31kgf and Fn=1.6

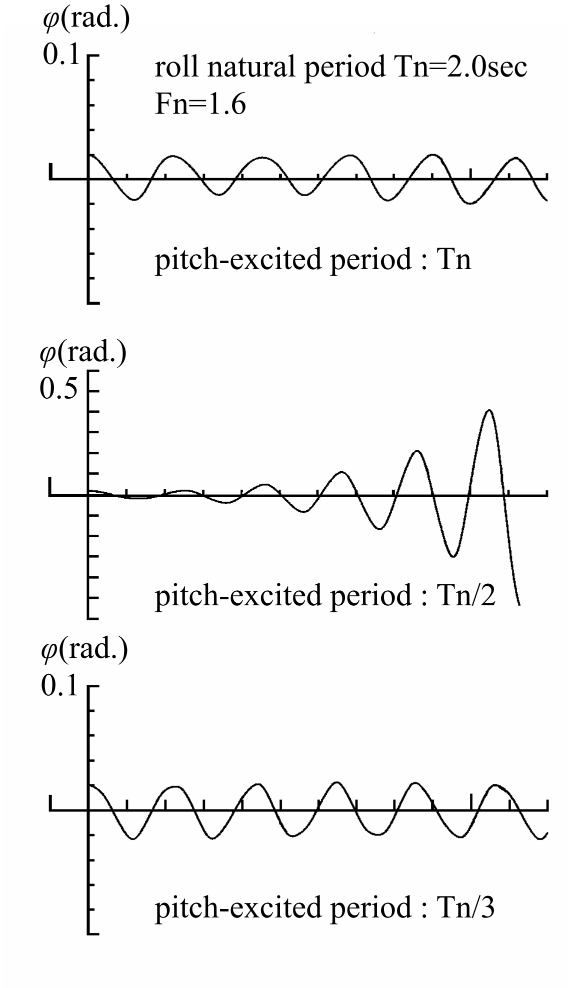

Figure 5: Time histories of roll motion induced by forced pitching motion

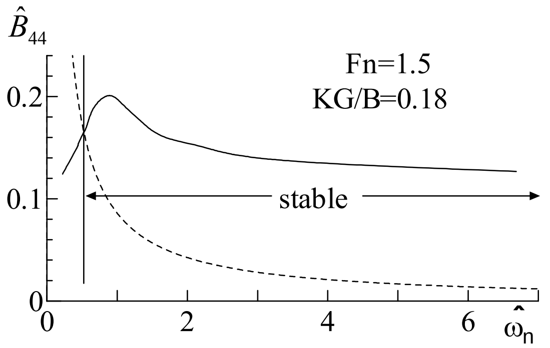

Figure 6: Judgement of whether ShipB-45 is stable or not

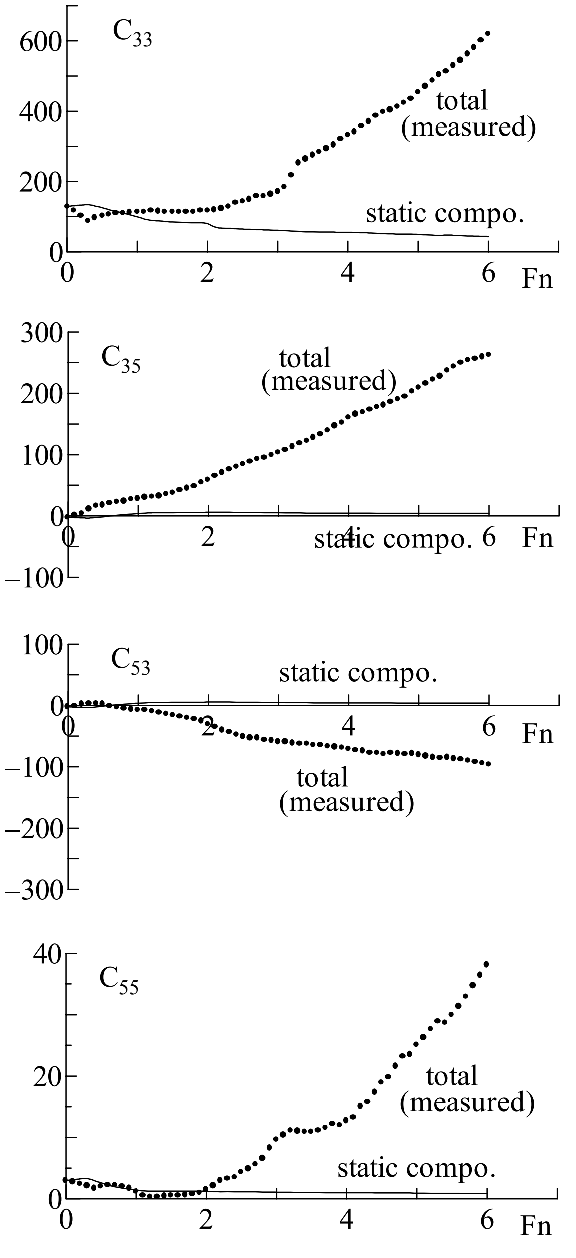

Figure 7: Coefficients of restoring forces and moments of motion equations for heave and pitch; heave restoring force C_{33}, coupled restoring force from pitch to heave C_{35}, coupled restoring moment from heave to pitch C_{53} and pitch restoring moment C_{55}

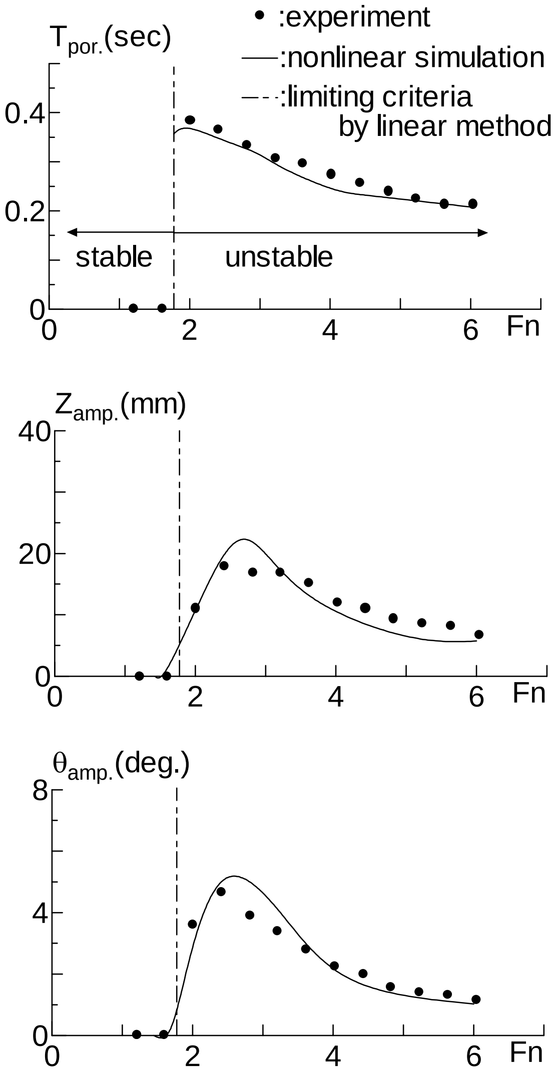

Figure 8: Result of nonlinear motion calculations

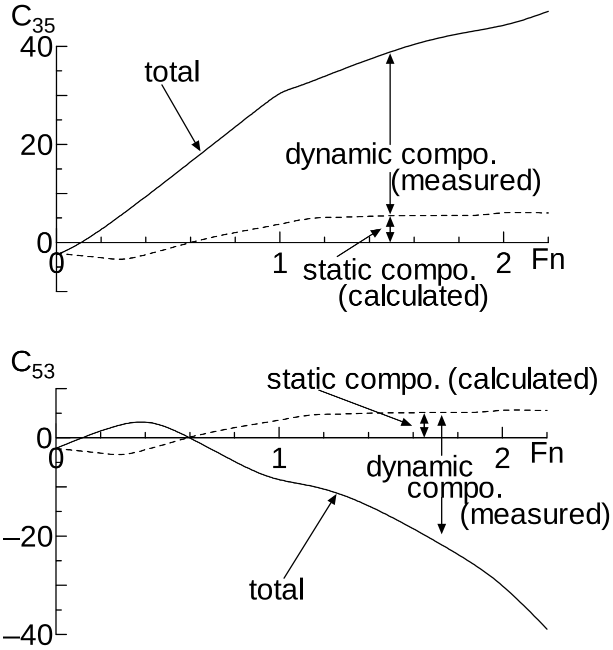

Figure 9: Heave and pitch coupling restoring coefficients, C_{35} and C_{53}

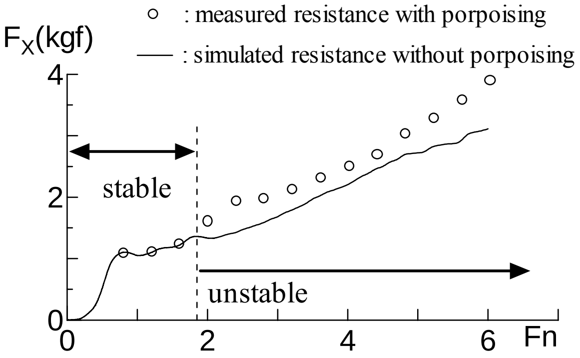

Figure 10: Resistance increases during porpoising

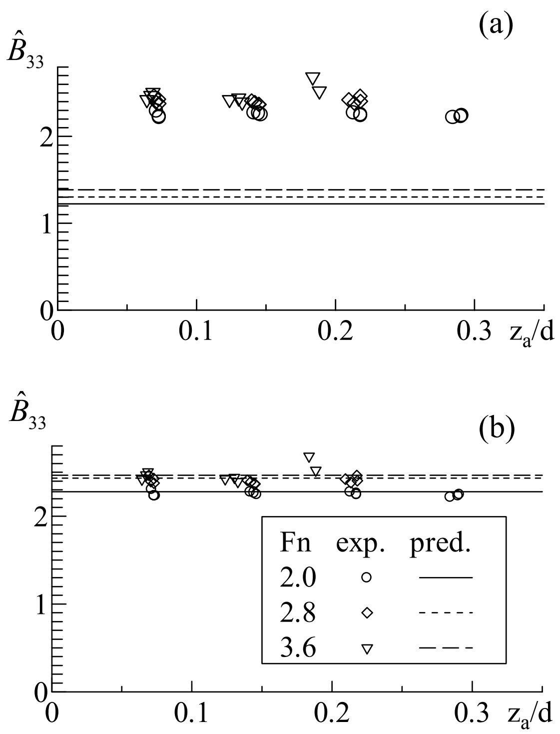

Figure 11: Predicted heave damping coefficient due to heave motion; $\hat{B}_{33}$: (a) potential theory (b) potential theory included lift component due to heave motion

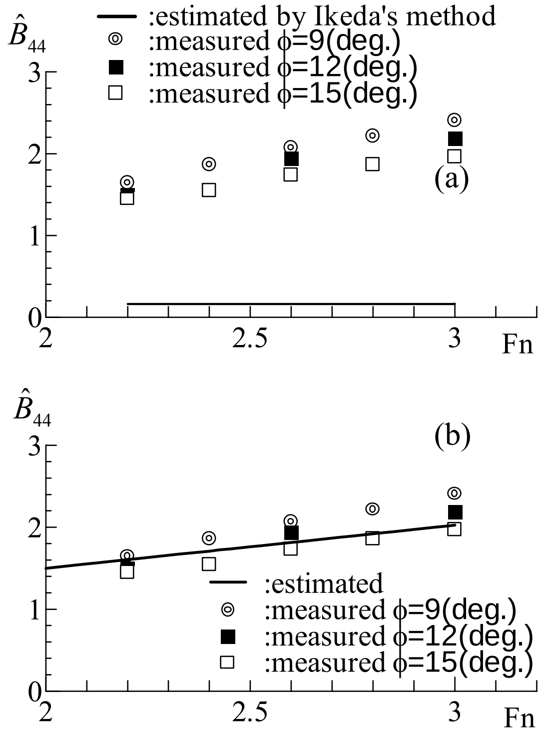

Figure 12: Comparison of roll damping coefficient between measured and estimated by Ikeda's formula; (a) and by present method; (b)