AN EXPERIMENTAL STUDY ON PARAMETRIC ROLLING OF A HIGH SPEED TRIMARAN IN HEAD SEA

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ABSTRACT

In this study, the occurrence of parametric rolling in head sea for a high-speed trimaran is experimentally investigated. At first, in order to check the conditions where parametric rolling occurs, a towing tank test is carried out. A model of trimaran is stabilized slender mono-hull type high-speed craft. In the test, the longitudinal position of side-hulls is changed. Next, in order to make clear the dominant reasons of the variation of roll restoring moment as a cause of occurrence of parametric rolling, a captive model test with heave and pitch free conditions is carried out. And the results indicate that the variation is mainly caused by side-hulls. Moreover, using the measured roll restoring moment and the predicted roll damping by the prediction method proposed in previous our study (Katayama et al., 2008), the occurrence of parametric rolling is estimated. And it is confirmed that the estimated results can be agreement with the measured results.

Keywords: *trimaran, stabilized slender mono-hull, parametric rolling, roll damping*

1. INTRODUCTION

Recently, a stabilized slender mono-hull concept trimaran has been applied to fast passenger ferry. However, such a vessel has a possibility that large variation of roll restoring moment caused by a drastic change of side-hull's underwater volume in longitudinal sea. As the results, parametric rolling may be induced (e.g. Giles et al., 2008, Umeda et al., 2003).

In this paper, the occurrence of parametric rolling in head sea for a high speed trimaran is experimentally investigated. And in order to investigate the variation of roll restoring moment, a partly captive model test with heaving and pitching is carried out. Moreover, using the measured roll restoring moment and the predicted roll damping by the prediction method proposed in the previous study (Katayama et al., 2008), the occurrence of parametric rolling is estimated.

2. MODEL

The body plan of a trimaran model is shown in Fig.1, and its principle particulars are shown in Table 1. The hull type of the model is called Stabilized Mono-hull type trimaran. Its principle particulars are decided by refering to a real high speed vehicle-passenger trimaran ferry (Armstrong et al., 2003), and the roll natural period and *GM* value are decided by referring to the paper by Bulian, et al., (2008).

Table 1. Principal particulars of the model.

	main-hull	side-hull
	L/B=14.6	L/B=25
L_{OA} [m]	1.46	0.89
L_{WL} [m]	1.41	0.71
breadth [m]	0.0914	0.0407
over all breadth [m]	0.36	
depth [m]	0.087	0.0797
draft [m]	0.045	0.035
displacement: W[kgf]	3.03	0.084×2
KG [m]	0.086	
T_n [sec.]	1.26	
GM [m]	0.075	

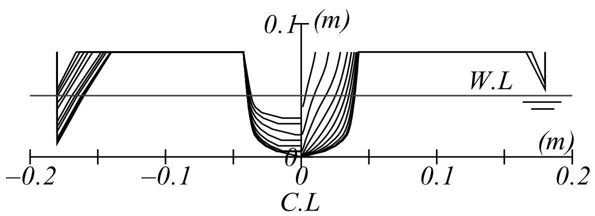


Figure 1. Body plan of the model.

3. PARAMETRIC ROLLING IN HEAD SEA

3.1 Outline of Model Experiment

In order to investigate the occurrence of parametric rolling, a towing test in regular head waves is carried out at the towing tank of Osaka Prefecture University (length 70 m, breadth 3 m, depth 1.5 m). Schematic view of the experiment is shown in Fig.2. The model is attached to a towing carriage with two elastic rope (Hashimoto et al., 2007). At zero forward speed in calm water, the model is heeled by a small weight. After the carriage reaches to a steady speed, the small weight is removed and roll motion is measured using a video tracer system (Video Tracker G260 by OKK Inc.) The experimental conditions are shown in Table 2. In the tests, when the model is towed in head waves at Fn=0.254 and the ratio of wavelength to ship length λ/L_{WL}=1.1, the encounter period is half of the roll natural period. (Fn=0.254 is 18knots in the actual scale.)

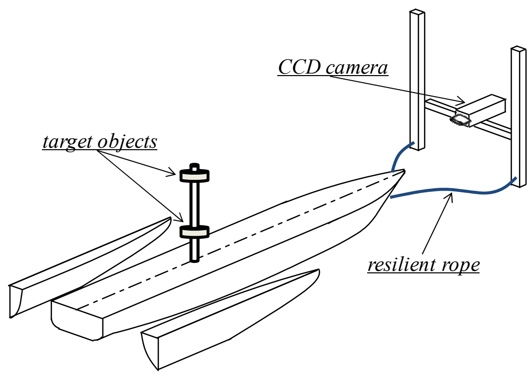


Figure 2. Schematic view of the motion measurement test.

Table 2. Conditions of the test in longitudinal waves.

Fn	0.19	0.254	0.325
wave period: T_w[sec]	1.0	0.837, 0.95, 1.0, 1.05, 1.14	1.0
λ/L_{WL}	1.1	0.77, 0.99, 1.1, 1.22, 1.44	1.1
encounter period: T_e[sec.]	0.68	0.63,0.66	0.56
wave height: H_w[mm]	20, 35		

3.2 Parametric Rolling in head sea

In the experiment, it is confirmed that a parametric rolling occurs. In Fig.3, three typical time histories of measured roll motions are shown. In these figures, the period of roll motion are twice of the encounter period. The upper figure shows a roll motion with constant roll amplitude, which is parametric rolling. The middle figure shows a decaying roll oscillation. The lower figure shows the middle state of above-mentioned two roll motions, which is slightly damped during measuring and may be a transition to steady state of a small amplitude parametric rolling. The measured roll motions are examined and classified according to above-mentioned three states. The results are shown in Table 3.

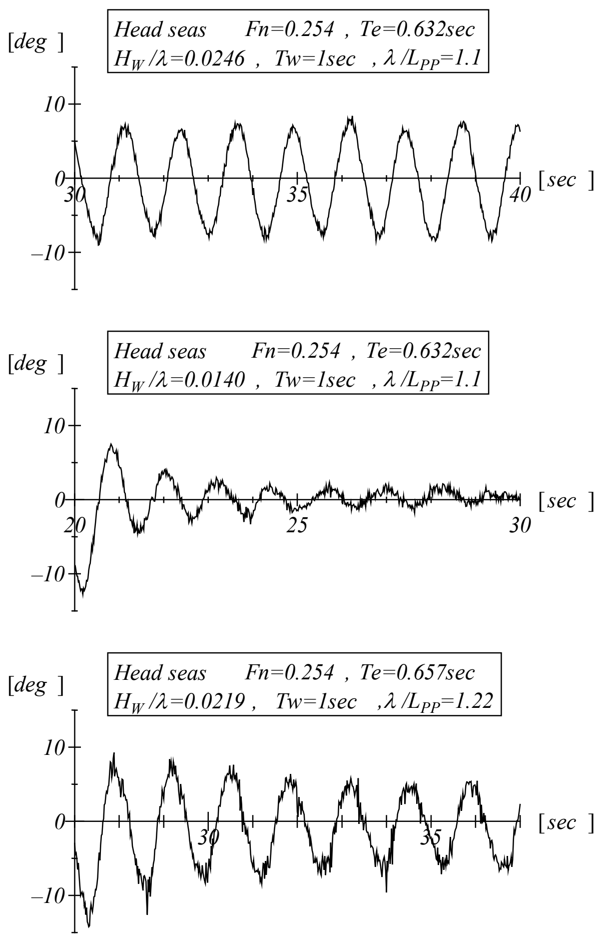


Figure 3. Time histories of measured rolling in regular head waves.

Table3. The results of the motion measurement test in head waves.

○: parametric rolling occurring
×: no parametric rolling

△: slightly damped parametric rolling

Fn		0.19	0.326
λ/L_{WL}		1.1	1.1
H_w[mm]	20	×	×
	35	△	△

Fn		0.254				
λ/L_{WL}		0.77	0.99	1.1	1.22	1.44
H_w[mm]	20		×	×	×	
	35	×	△	○	△	×

4. VARIATION OF ROLL RESTORING MORMENT IN LONGITUDINAL WAVES

It is well known that a parametric rolling in longitudinal waves caused by the time variation of GZ-curve with about half period of the roll natural period of ship. In order to make clear the dominant cause of the variation, a captive model test with heave and pitch free conditions and fixed small heeling ϕ is carried out in longitudinal regular waves (Hamamoto, M., Umeda, N., et al. 1982). The schematic view of the test is shown in Fig.4. Sway force, roll moment, heave motion and wave profile are measured. In the test, two models have different longitudinal position of side-hulls shown in Fig.5 is used.

In the analysis, the roll moment around the center of gravity is obtained by the following equation,

$$M_{XG} = M_X + F_Y \times l(t) \tag{1}$$

where M_{XG}, M_X, F_Y and $l(t)$ are roll moment around the center of gravity, roll moment around the center of the load-cell, sway force and the distance between the center of the load-cell and the center of gravity. In addition, they are noted that $l(t)$ is changed according to heave motion. Then, in the analysis, they are considered.

Using roll moment around the center of gravity, false or shifting metacentric (see

APPENDIX) height with forward speed in waves $GM_{\phi}(t)$ is obtained as follow,

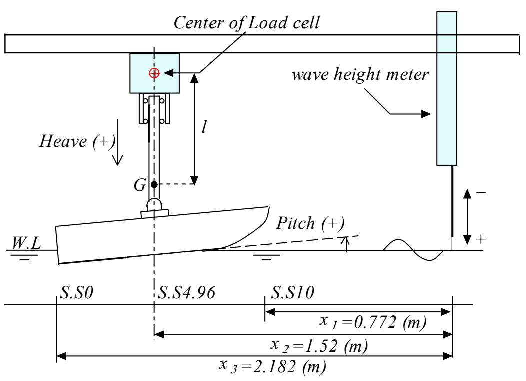
$$\frac{M_{XG}+WGZ_{\phi}}{W\cdot\phi}=GM_{\phi}(t) \qquad (2)$$
$$=\Delta GM_{\phi}(t)+GM_{U\phi}+GM_{S\phi}$$

$GM_{\phi}(t)$ consists of three components. $GM_{S\phi}$ and $GM_{U\phi}$ are the constant components at zero forward speed and with forward speed in calm water. $\Delta GM_{\phi}(t)$ is the time variation component caused by waves.

The time histories of false metacentric height with forward speed $GM_{\phi}(t)$ obtained by Eq.(2) using the roll moment M_{XG} is represented with Fourier-series and its amplitude, phase difference to waves and average are obtained. The conditions in the experiment are shown in Table 4.

Table 4. Conditions of the captive model test.

Wave direction	head waves	following waves	head waves
Side-hull position	Rea	Rea	Mid
Fn	0.254	0.326	0.254
λ/L_{WL}	1.1	1.1	1.1
H_w [mm]	0, 20, 40	0, 20, 35	20, 40
ϕ [deg]	-10, -5, 0, 5, 10	-5, 10	-10, -5, 0, 5, 10



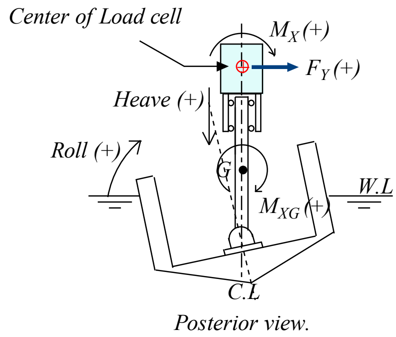


Figure 4. Schematic view of the restoring moment measurement test.

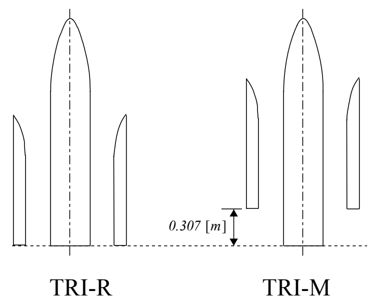


Figure 5. Positions of side-hull.

Measured Variation of False Metacentric Height

In Figs.6-8, the results of the captive model tests are shown. In these figures, $GM_{\phi}(t)$, relative aft-draft of side-hulls, pitching and change of relative position of the model to water surface are shown.

From the results in head waves shown in Figs.6 and 7, the amplitude of $\Delta GM_{\phi}(t)$ becomes larger according to increase of wave height for both TRI-R and TRI-M. $GM_{\phi}(t)$ becomes the smallest before the relative aft-draft becomes the smallest. And the moment is when the underwater volume of side-hulls becomes the smallest. It is supposed that the variation of false metacentric height of trimaran is mainly caused by the time change of the underwater volume of side-hulls.

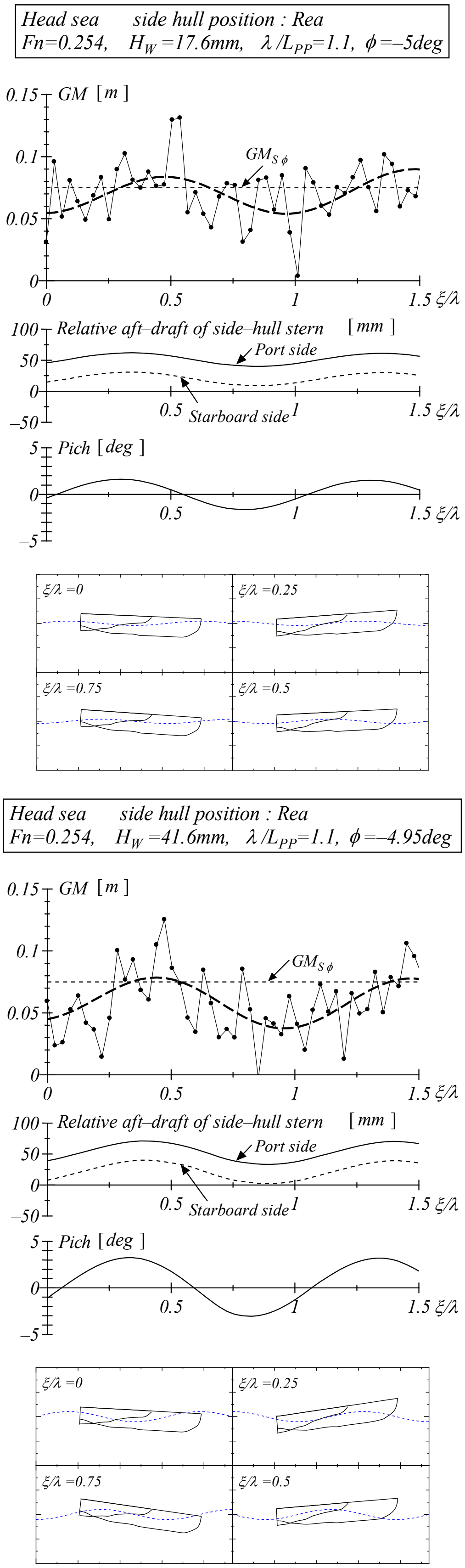


Figure 6. Measured $GM_{\phi}(t)$, relative aft-draft of side hulls and ship motion of TRI-R in head waves .

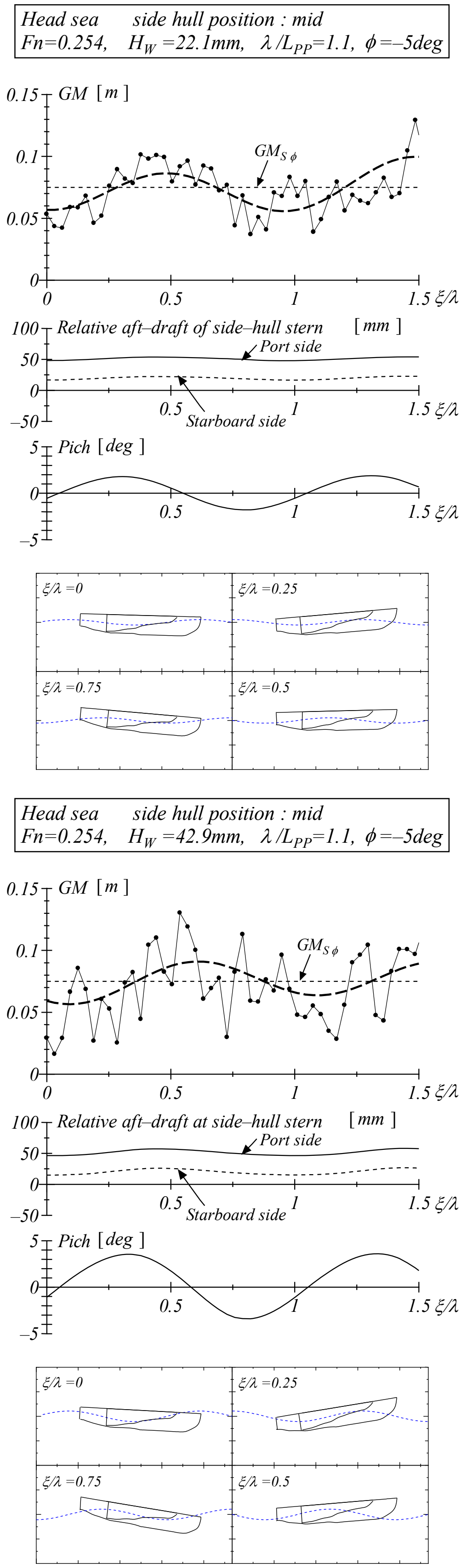


Figure 7. Measured $GM_{\phi}(t)$, relative aft-draft of side-hulls and ship motion of TRI-M in head waves.

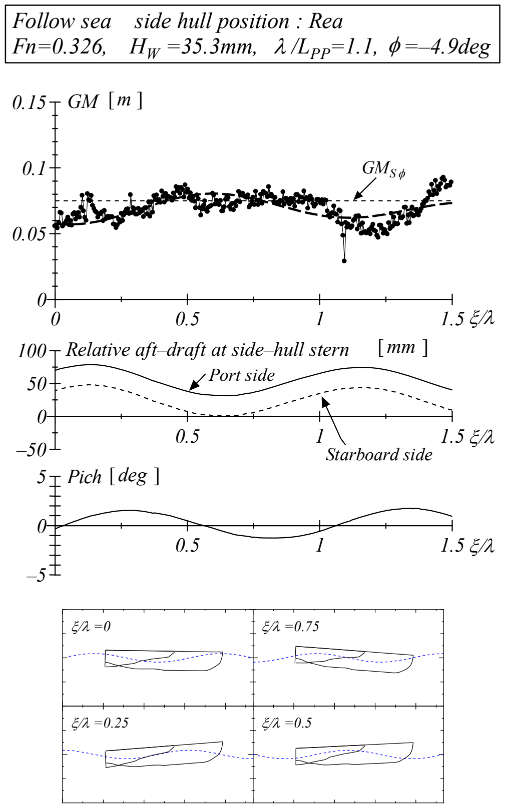


Figure 8. Measured $GM_\phi(t)$, relative aft-draft of side-hulls and ship motion of TRI-R in following waves.

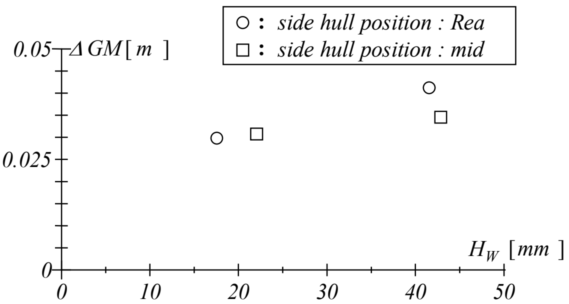


Figure 9. Effects of longitudinal side-hull position on the amplitude of $\Delta GM_\phi(t)$ at Fn=0.245 and ϕ=-5[deg].

The effects of longitudinal position of side-hull on $GM_\phi(t)$ is shown in Fig.9. From this figure, the measured $\Delta GM_\phi(t)$ of TRI-R is larger than that of TRI-M. From the results in following waves shown in Fig.8, the measured $GM_\phi(t)$ becomes smaller than that in head waves. It is supposed that the main reason is the relative ship motion in following sea, which is small because of long encounter period.

5. ESTIMATION OF ONSET OF PARAMETRIC ROLLING

5.1 Estimation Method of Onset of Parametric Rolling

In this study, the following equation is applied to express roll motion including parametric rolling in longitudinal waves,

$$\phi = \phi_a \cos(\omega_e t)$$

$$\begin{aligned}&(I_{44} + a_{44})\ddot{\phi} + B_{44\phi_a}\dot{\phi} \\ &+ W\left(GM_{\phi_a} - \Delta GM_{\phi_a}\cos(\omega_e t - \varepsilon)\right)\phi = 0\end{aligned} \quad (3)$$

where ϕ_a is roll amplitude, (I_{44} + a_{44}) are the inertia coefficient, $B_{44\phi a}$ is the equivalent linear damping coefficient, $WGM_{\phi a}$ is the constant component of restoring coefficient, ω_e is the encounter frequency, ε is the phase difference, $W\Delta GM_{\phi a}$ is the time variation of restoring coefficient.

When parametric rolling occurs, an encounter frequency assumed to be twice of the roll natural frequency and Eq.(3) is re-written as following equation,

$$\begin{aligned}&(I_{44} + a_{44})\ddot{\phi} + B_{44\phi_a}\dot{\phi} \\ &+ W\left(GM_{\phi_a} - \Delta GM_{\phi_a}\cos(2\omega_n t - \varepsilon)\right)\phi = 0\end{aligned} \quad (4)$$

where ω_n is roll natural frequency. The energy integral (or first integral) for one cycle of motion is applied to Eq.(4). The energy dissipation term with $B_{44\phi a}$ become as follow,

$$\int_0^{Tn}\left(B_{44\phi_a}\dot{\phi}\right)\dot{\phi}dt = \pi B_{44\phi_a}\phi_a{}^2\omega_n \quad (5)$$

And the term expressing change potential energy with $W\Delta GM_{\phi a}$ are obtained as follow,

$$\int_0^{T_n}\left\{W\left(GM_{\phi_a}-\Delta GM_{\phi_a}\cos(2\omega_n t-\varepsilon)\right)\phi\right\}\dot{\phi}dt$$
$$=\int_0^{T_n}\begin{bmatrix} W\left\{GM_{\phi_a}-\Delta GM_{\phi_a}\cos(2\omega_n t-\varepsilon)\right\} \\ \times\phi_a\cos(\omega_n t)\{-\phi_a\omega_n\sin(\omega_n t)\}\end{bmatrix}dt$$
$$=\frac{W\Delta GM_{\phi_a}\phi_a{}^2\omega_n}{2}\sin\varepsilon\int_0^{T_n}\sin^2(2\omega_n t)dt \tag{6}$$
$$=\frac{W\Delta GM_{\phi_a}\phi_a{}^2\pi}{2}\sin\varepsilon$$

The potential energy term has the phase difference ε. Here, the phase difference is $\pi/2$ according to the assumption of the maximum efficiency of energy absorption in the conditions of synchronous resonances. And it means that most of energy caused by the time variation of *GM* is used for rolling.

If the following inequality is satisfied at ϕ_a=0[deg], it means that a parametric rolling occurs, that is, left-hand side of inequality is the threshold value for parametric rolling. Moreover, in the case of parametric rolling occurring, the roll amplitude, which makes both side of Eq.(7) equal, is the amplitude of parametric rolling.

$$B_{44\phi_a}<\frac{W\Delta GM_{\phi_a}}{2\omega_n} \tag{7}$$

5.2 Prediction of Roll Damping for High Speed Trimaran

The prediction method of roll damping of trimaran is a component discrete type estimating method based on Ikeda's prediction method (Ikeda, Y., 1984). Roll damping consists of the main-hull component B_{44m}, the side-hull wave making component B_W, the side-hull eddy making component $B_{E\text{-}S}$ and the side-hull lift component $B_{L\text{-}S}$ as following equation,

$$B_{44}=B_{44m}+B_{W-S}+B_{F-S}+B_{E-S}+B_{L-S} \tag{8}$$

Based on the principle of the minimum energy in the condition of parametric rolling occurring, when $GM_\phi(t)$ becomes the smallest, the roll angular velocity is the maximum and the roll angle is zero. It indicates that the underwater volume of side-hulls is the minimum in the moment when the roll angular velocity is the maximum. And the relative draft of side hull must be significant for the roll damping. In order to take the effects into account the roll damping prediction, the measured relative drafts of side-hulls are used for estimation of the side-hull roll damping components.

In Fig.10, the predicted results of roll damping coefficient at the conditions where parametric rolling occurs are shown. In this figure, the value of roll damping coefficient, which is calculated by Eq.(7) using the measured $GM_\phi(t)$, are also shown. From the result, the predicted roll damping coefficient increase according to increase of roll amplitude. On the other hand, the value of roll damping coefficient calculated by Eq.(7) decrease according to increase of roll amplitude. The cross point of both values must be between 5[deg] and 10[deg]. The measured roll amplitude of parametric rolling is almost 7[deg] shown in the upper figure of Fig.3. Therefore, the estimated results are good arrangement with measured results.

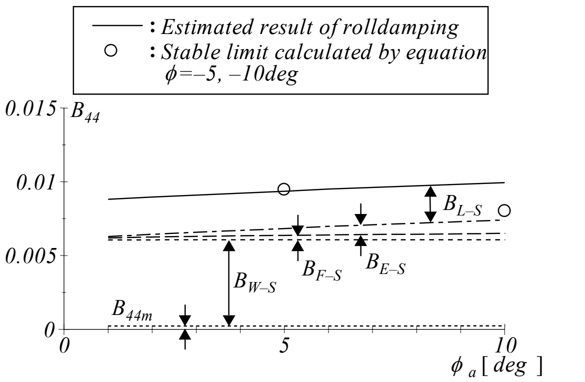


Figure 10. Estimated result of B_{44} at *Fn*=0.245, $T\phi$=1.26[sec] and sable limit of B_{44} calculated by measured ΔGM.

6. CONCLUSIONS

The occurrence of parametric rolling for a high-speed trimaran and the variation of roll restoring moment in head waves are experimentally investigated. Moreover, using the measured roll restoring moment and the predicting roll damping, the occurrence of parametric rolling is estimated. And the following conclusions are obtained.

- For the trimaran model used in this study, the possibility of parametric rolling occurring can be confirmed experimentally.
- The time variation of roll restoring moment in head waves mainly depends on the time variation of underwater volume of side-hulls.
- In order to take account of these effects, relative draft of side hull in head waves must be significant. And it is also important for prediction of roll damping.
- For the trimaran model, the measured $\Delta GM_{\phi}(t)$ of TRI-R is larger than that of TRI-M.
- In order to estimate the occurrence of parametric rolling, the method to apply the roll damping prediction method (Katayama et al., 2008) is proposed. And it is confirmed that the estimated result of the occurrence of parametric rolling using the predicted roll damping and the measured variation of false metacentre is good agreement with the measured results.

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8. APPEENDIX

At the condition of large angle of heel, the force of buoyancy can no longer be considered to act vertically upward through the initial metacenter. The schematic view of the initial metacenter and the false or shifting metacenter is shown in Fig.11. For the trimaran model, because of transverse position of side-hulls, small heeling induces large shifting of the centre of buoyancy. And the metacenter is shifting upward (false or shifting metacenter).

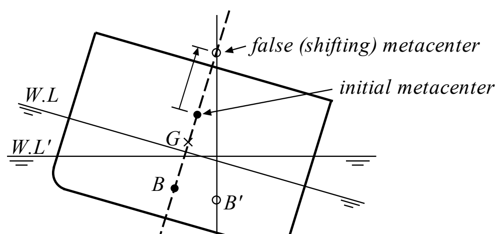

Figure 11. Schematic view of initial metacenter and false or shifting metacenter.