Effects of Roll Damping and Heave Motion on Heavy Parametric Rolling of a Large Passenger Ship in Beam Waves

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ABSTRACT

In this paper, effects of the roll damping and heave motion on the heavy parametric rolling in beam waves are experimentally investigated. Model experiments of a model of a large passenger ship with attached various bilge keels in beam waves demonstrate that roll damping affects occurrence and amplitude of the parametric rolling. To investigate the effect of heave motion, model experiments of the same model ship without bilge keel are carried out. The results demonstrate that the parametric rolling in beam waves may be caused by relative heave motion to wave surface due to heave resonance.

KEYWORDS

Parametric rolling; Beam sea; Large passenger ship; Dead ship; Damping; Bilge keel; Stability.

NOMENCLATURE

ϕ : roll angle

ϕ_0 : roll amplitude

ϕ_{max} : maximum roll amplitude at the peak of parametric rolling

H_w : wave height

$H_{w\ mim}$: minimum wave height for occurring parametric rolling

ζ_0 : wave amplitude ($=H_w/2$)

Z_0 : heave amplitude

T_{nr} : roll natural period

T_{nh} : heave natural period

T_r : roll period

T_h : heave period

T_e : encounter wave period ($=T_h$)

T_w : incident wave period

T_{rp} : encounter wave period at the peak of parametric rolling

INTRODUCTION

In the previous papers by the present authors (2005), it was experimentally found that heavy roll motion with much larger amplitude than that of the 1st harmonic resonance appears for a large passenger ship with twice wave period of encounter in heavy beam seas. Since the roll motion has twice period of encounter and almost similar period to half of the roll natural period of the ship, the authors pointed out that the roll motion must be a parametric rolling. Following the paper, Munif et. al. (2006) confirmed that when the ship has no bilge keels, parametric rolling occurs in wide range of heading angles including head and following seas as well as beam seas as shown in Fig. 1. It was also pointed out by them that the encounter periods at which the rolling phenomena have peaks are different in head and beam waves as shown in Fig. 2. They pointed out that large variation of *GZ* value in beam waves due to the flat and shallow stern-bottom and large flare of bow can induce the parametric rolling.

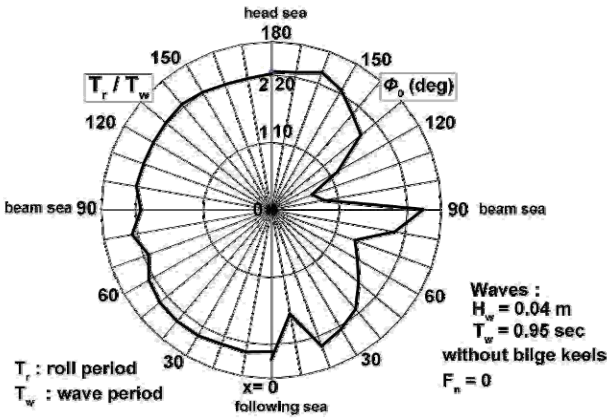

Fig. 1 Amplitude and period of parametric rolling in all heading angles of regular waves.

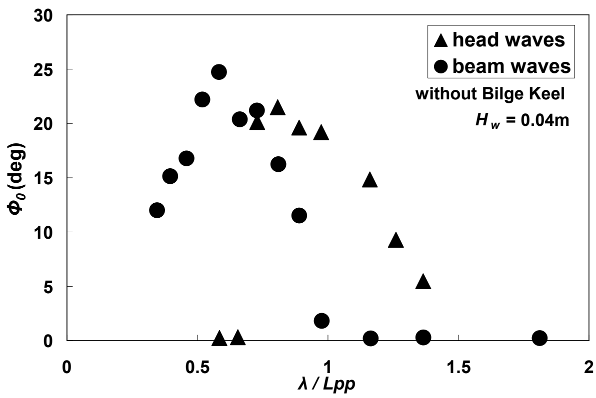

Fig. 2 Difference of wave periods at which parametric rolling appears in beam and head waves.

In the present paper, effects of the roll damping and heave motion on the heavy roll motion with a period of twice of the encounter wave period are experimentally investigated. First, by changing the roll damping systematically, the effect of the roll damping on the rolling is investigated. The results demonstrate that the roll damping significantly affect the region of the occurrence and the amplitude of the roll motion. Secondly, experiments for the same model ship are carried out to investigate the reason why such heavy rolling occurs in beam waves. The results suggest that the heavy rolling in beam waves may occur due to parametric resonance due to the variation of *GM* in time produced by time varying draft due to relative heave motions of a ship with respect to wave surface.

EXPERIMENTAL PROCEDURE

The ship used in the present study is a 110,000GT passenger ship designed by Fincantieri for an international cooperated research on damage stability of large passenger ships in IMO. The body plan and the principal particulars are shown in Fig. 3 and Table 1, respectively.

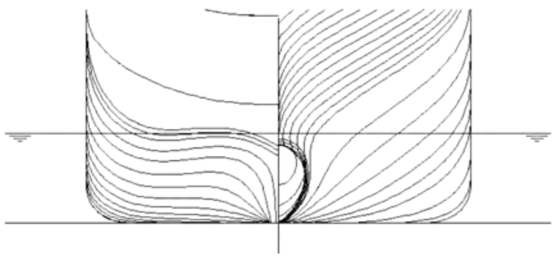

Fig. 3 Body plan of the ship.

Table 1 Principle particulars.

	Full Scale	Model
Scale	1/1	1/125.32
L_{OA}	290 m	2.200 m
L_{PP}	242.24 m	1.933 m
Breadth	36 m	0.287 m
Draft	8.4 m	0.067 m
Displacement	53,010 ton	26.98 kg
GM	1.579 m	0.0126 m
T_{nr}	23 sec	2.05 sec
BK width	1.1 m	0.0088 m
BK location	BK1: s.s.3.0 - 5.0 BK2: s.s.5.25 - 6.0	

In the experiments, the model ship was located in transverse direction in the towing tank of Osaka Prefecture University, and ship motions (roll, heave, pitch, sway and drift) are measured in regular beam waves with 0.04m height in model scale. Yaw and surge motions are fixed.

Size and location of Bilge Keel

The bilge keels designed for the ship are divided into two parts, a short forward (BK1) and a long aft ones (BK2). It was confirmed by Munif et. al.(2006) that the designed bilge keel (BK1+BK2) can completely suppress parametric rolling in any heading angles except for head and following waves. However, parametric rolling occurred in the case of the short bilge keel (BK1) in beam waves. Therefore, in the present experiments, areas of bilge keels are systematically changed from BK1 to the designed full one (BK1+BK2). The bilge keel length and attached position are shown in Table 2.

Table 2 Size and location of bilge keel in the experiments.

	BK location s.s. no.	BK Length	Area of Bilge Keel / Area of Designed Bilge Keel
BK1	5.25 - 6.00	150 mm	0.273
Mid 1	5.00 - 6.00	200 mm	0.364
Mid 2	4.75 - 6.00	250 mm	0.455
Mid 3	4.70 - 6.00	260 mm	0.473
Mid 4	4.60 - 6.00	280 mm	0.509
Mid 5	4.50 - 6.00	300 mm	0.545
Mid 6	4.25 - 6.00	350 mm	0.636
BK2	3.00 - 5.00	400 mm	0.727
BK1 + BK2	5.25 - 6.00 + 3.00 - 5.00	150 mm + 400 mm	1.000

Free Roll Test

Free decay tests of the model ship with attached various bilge keels are carried out, and the roll damping in terms of the extinction coefficient N at roll amplitude of 20° and the roll natural period are obtained.

In Fig. 4, the obtained results of the extinction coefficient N are shown. Since the ship has relatively small bilge radius, the extinction coefficient N is relatively large such as 0.018 even for naked hull. The N increases with increasing area of bilge keels, and reaches 0.03 for the designed full bilge keel.

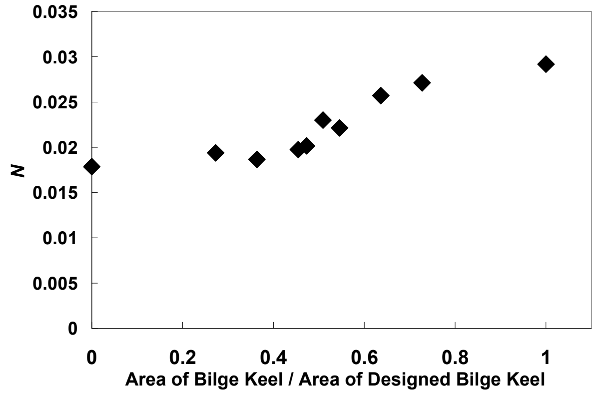

Fig. 4 Measured N coefficients at roll amplitude of 20 degrees for various bilge keel sizes.

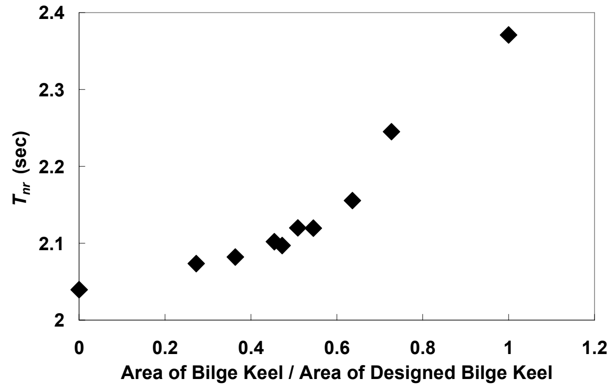

Fig. 5 Variation of roll natural period, T_{nr}, for various size of bilge keels.

In Fig. 5, roll natural periods are shown. The roll natural period increases with increasing area of bilge keels, and reaches a period 16% longer than that for naked hull.

Measurement of Parametric Rolling in Beam Sea

In Fig. 6, the maximum roll amplitudes of parametric rolling for each bilge keel in regular beam waves of 0.04m height are shown. The results demonstrate that the peaks of parametric rolling rapidly decrease with increasing area of bilge keels, or roll damping, and disappears at half area of the designed bilge keel. The roll periods shown in Fig. 7 clearly demonstrate that the period of roll motion changes from twice of encounter periods to the encounter ones at the point when the parametric rolling disappears in Fig. 6.

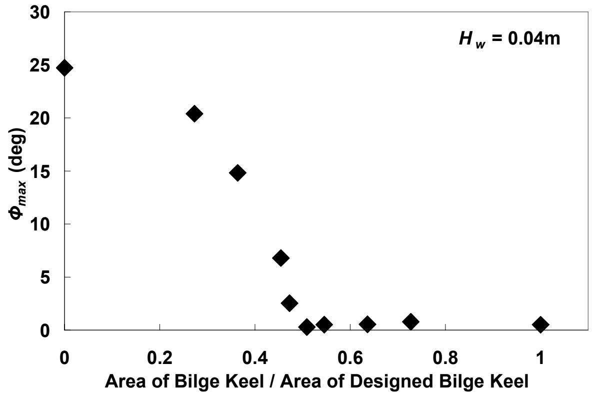

Fig. 6 Effect of area of bilge keels on maximum amplitude of parametric rolling in regular beam seas.

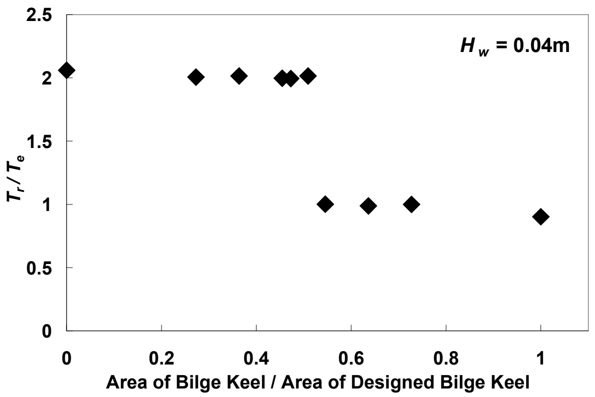

Fig. 7 Effect of the area of bilge keels on the ratio of the roll period to encounter wave period in regular beam seas.

The time histories of motions for the case where the model rolls with the period twice the encounter wave period are shown in Figs. 8 and 9. The time history of rolling motion shown in Fig. 8, which is a case when parametric roll amplitude is large, is substantially sinusoidal. On the contrary, the time history of the roll motion shown in Fig. 9, when parametric rolling amplitude is very small, is non-sinusoidal, and includes not only the component of twice period of the encounter wave period but also the component of the encounter wave period.

In order to clarify the effect of roll damping on parametric rolling in beam seas, measurements of ship motions of the model in the cases with BK1, Mid2-BK, Mid3-BK and without bilge keel are carried out in regular beam waves with various wave heights. The results of the experiments are shown in Fig. 10. These results demonstrate that the minimum wave height at which parametric rolling appears increases with increasing roll damping, and that the roll amplitudes saturate with increasing wave height, and the saturated roll amplitudes also depend on the roll damping.

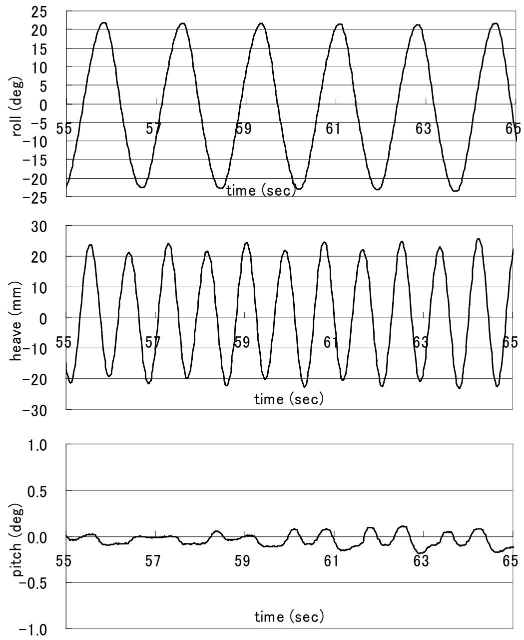

Fig.8 Time histories of ship motions without bilge keel.

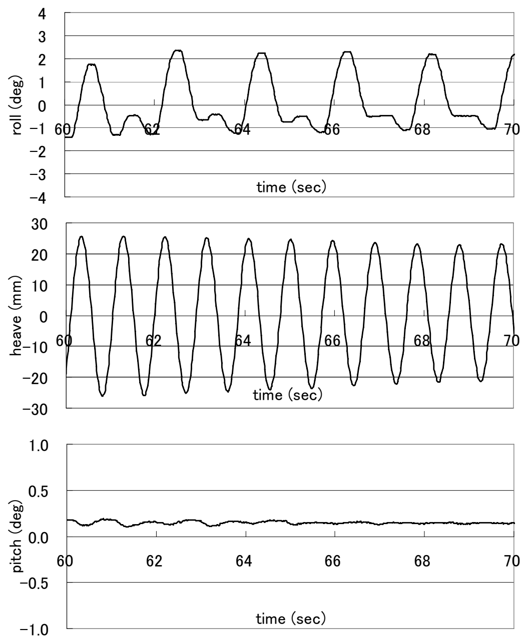

Fig.9 Time histories of ship motions with Mid3 bilge keel.

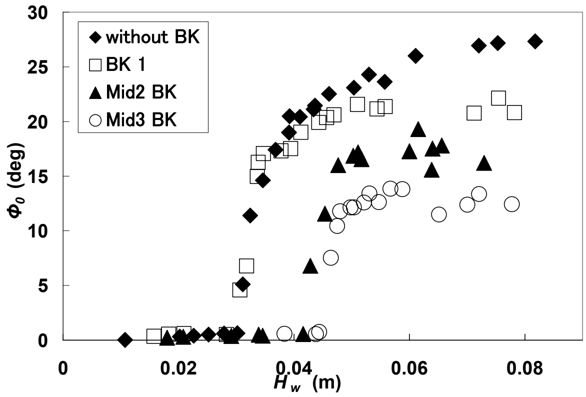

Fig. 10 Roll amplitude as a function of the wave height for the cases with parametric rolling of the ship in regular beam seas.

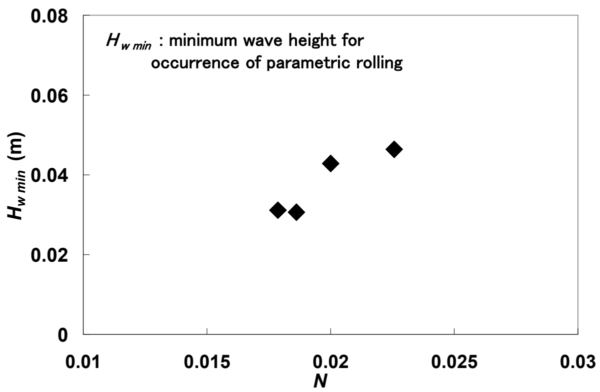

Fig.11 Effect of roll damping on critical wave height for occurrence of parametric rolling of the large passenger ship in beam seas.

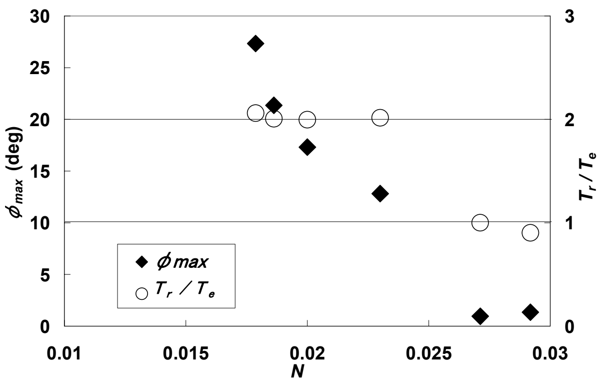

Fig.12 Effect of roll damping on maximum parametric roll angle $\phi_{\max}$ and ratio of roll period to wave period in 0.04m wave height.

The relation between the roll damping and the critical wave height for the occurrence of parametric rolling, which is deduced from the experimental results shown in Fig. 10, is shown in Fig. 11. Using the figure, we can determine the roll damping required to eliminate parametric rolling in beam seas for the large passenger ship. The relation between the roll damping and the maximum parametric rolling amplitude at 0.04m waves is shown in Fig. 12. Using the figure, we can determine the required roll damping limiting parametric rolling to a prescribed amplitude in beam seas. For example, N should be larger than 0.024 to maintain the roll amplitude to less than 10 degrees in 0.04m beam waves.

CAUSE OF PARAMETRIC ROLLING IN BEAM WAVES

The cause of the parametric rolling in beam waves has not been clarified yet. In this section, the authors will investigate the cause of the large rolling.

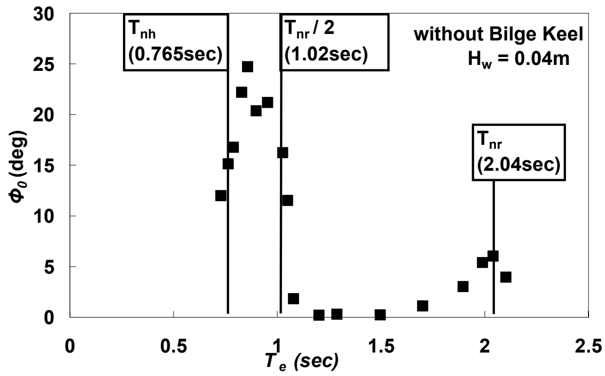

Fig. 13 Measured roll amplitude without bilge keel in regular beam waves

In Fig. 13, the measured roll motion amplitudes in beam waves are shown with indicated roll natural period T_{nr}, its half T_{nr} / 2 and the heave natural period T_{nh}. It can be seen that large parametric rolling appears at the period between half of roll natural period and heave natural period. The results may suggest that heave resonance causes parametric rolling in beam waves. In order to investigate this hypothesis, measurements of roll motions of the model ship are carried out for various roll natural periods. Roll natural periods of the ship are systematically changed by changing moment of inertia, as shown in Table 2. This means that the centre of gravity of the ship keeps at original location.

Table 2 Conditions of model experiments

T_{nr} (sec)	T_{nh}		T_w (sec)	H_w (m)
	Exp. (sec)	Cal. (sec)		
1.18	0.750		0.40 ~ 1.18	
1.40	0.760		0.45 ~ 1.40	
1.66	0.727		0.50 ~ 1.65	
2.04	0.765	0.740	0.60 ~ 2.30	0.04
2.39	0.733		0.70 ~ 2.40	
2.92	0.760		1.00 ~ 2.92	
3.33	0.740		1.40 ~ 1.70	

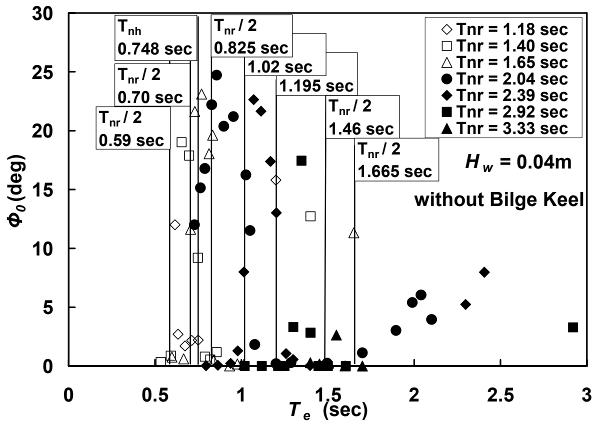

Fig. 14 Parametric rolling in beam waves for various roll natural periods.

The experimental results shown in Fig. 14 demonstrate that with changing roll natural period roll amplitude in parametric rolling also changes. From the experimental results shown in Fig.14, the dependency of roll natural period on encounter wave period at the peaks of parametric rolling in beam waves is obtained as shown in Fig. 15. The horizontal bar at each mark shows the region where the parametric rolling occurs. The results demonstrate that the peak period of the parametric rolling approximately coincides with half of roll natural period. However, when roll natural period T_{nr} is smaller than 1.65sec, the peak periods are close to half of T_{nr}, while for larger T_{nr}, the peak periods are smaller than half of T_{nr}.

Effects of the ratio of roll natural period to heave natural period, T_{nr} / T_{nh} on the peak of roll amplitude of the parametric rolling are shown in Fig. 16. Intuitively, maximum parametric rolling should appear when T_{nr} / T_{nh} is equal to 2, if heave resonance causes parametric rolling in beam waves. The results shown in Fig. 16, however, demonstrate that maximum parametric rolling occurs at T_{nr} / T_{nh} of 2.67.

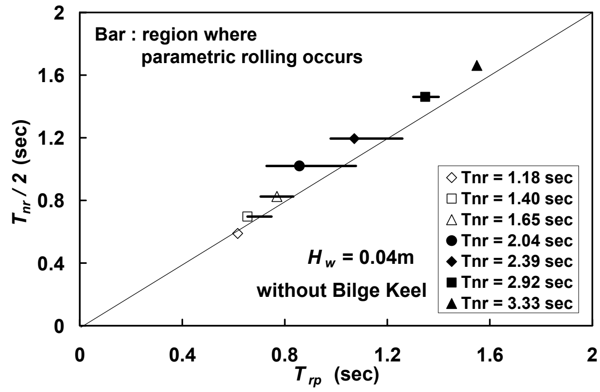

Fig. 15 Relationship between half of roll natural period and peak period of parametric rolling in beam waves.

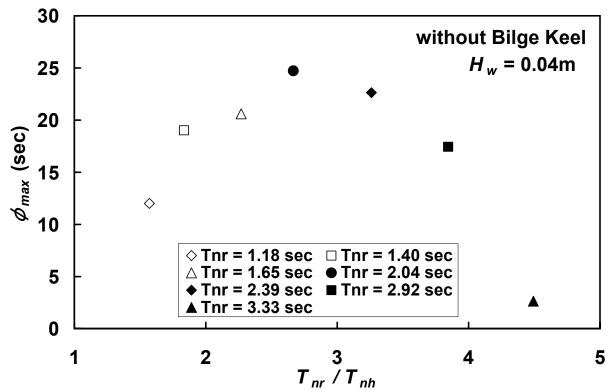

Fig. 16 Effect of ratio of roll natural period to heave natural period on maximum roll amplitudes at peaks of parametric rolling in beam waves.

Fig. 17 shows roll amplitude at each peak of the parametric rolling for various roll natural period in beam waves. We can see large skew in the figure. The skew may be caused by the nonlinearity of GZ at large roll amplitude as can be seen in Fig. 18. The GZ-curve shows that GZ at 25 degrees of roll angle is larger by 16.2% than the linear value, $GM\phi$.

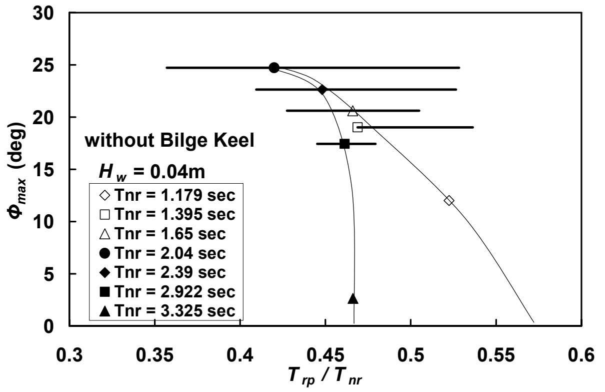

Fig. 17 Maximum roll amplitude at peaks of parametric rolling in beam waves for various roll natural period.

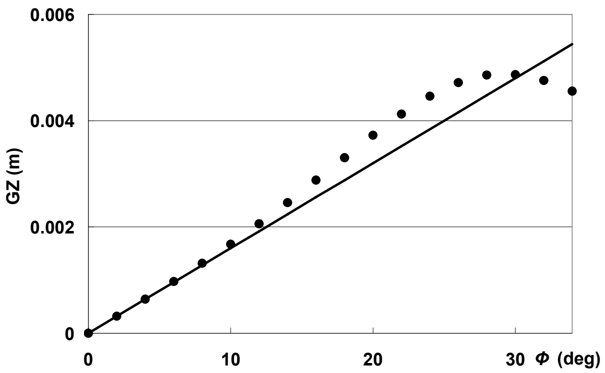

Fig.18 Non-linearity of *GZ*-curve of the model in calm water.

Response of heave motion

Measured amplitudes and phase angles from incident waves of heave motions are shown with calculated results by a strip method (OSM) in Figs. 19, 20 and 21. In Fig. 19 the heave amplitudes for the cases where parametric rolling occurs are plotted, and in Fig. 20 those when no parametric rolling occurs are plotted. We can see that both response functions are similar, and cannot find any significant differences. In Fig. 21, the measured phase angles of heave motion with respect to encounter waves are shown. The results show the phase angle rapidly changes near the heave natural period as well known. It should be noted that the phase angles in heave resonant condition may change the relative heave motion with respect to the water surface, and that it may cause time variation of the *GZ* value in beam waves.

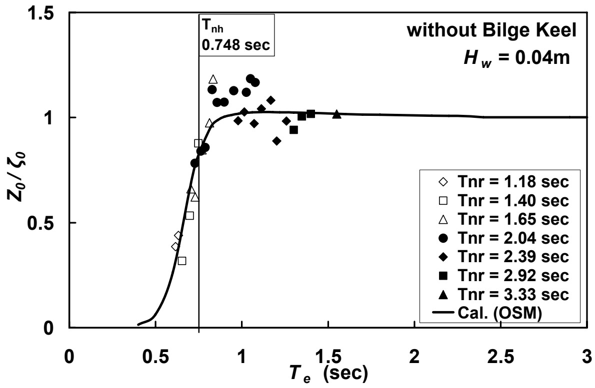

Fig. 19 Heave response curve when parametric rolling occurs.

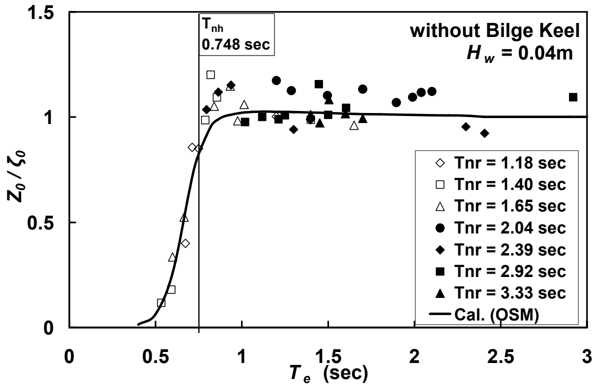

Fig. 20 Heave response curve when parametric rolling does not occur.

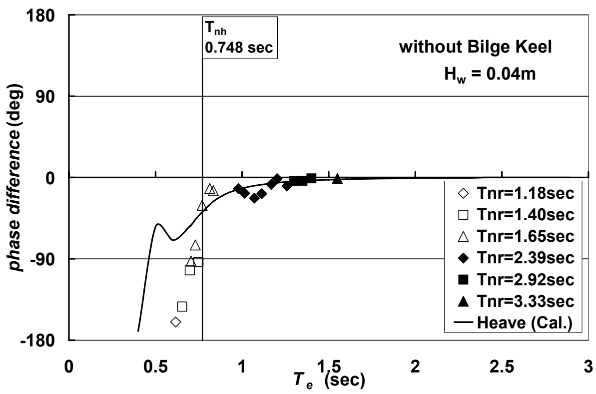

Fig. 21 Phase angle of heave motion vs. incident wave encounter period for the cases where parametric rolling occurs.

Calculation of relative heave motion

Using measured data of heave motions and encounter waves, relative heave motions with respect to wave surface can be calculated. The calculated results are shown in Figs. 22-27. The results demonstrate that relative heave motions are large in the region where large parametric rolling occurs. In these figures the heave natural period and the half of roll natural period are also shown. We can see the peaks of the parametric rolling are located between these two periods in almost all cases. The parametric rolling becomes large when the two periods are close to each other. As shown in Fig. 25, however, large parametric rolling and large relative heave motion can be seen even if the two periods are different from each other by about 50%. It should be noted that the peak periods of the parametric rolling are near half of roll natural period when the heave natural period and the half of roll natural period are relatively separate.

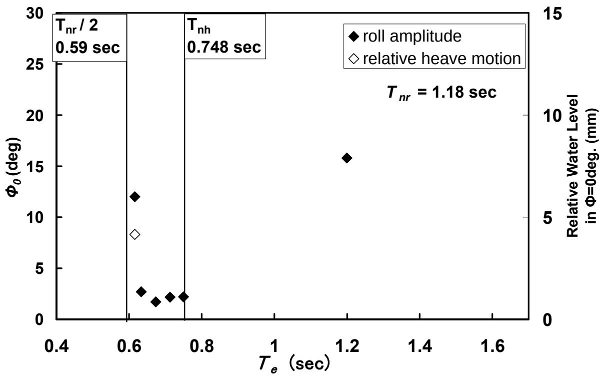

Fig. 22 Parametric rolling in beam waves and relative heave motion. Calculated at T_{nr} =1.18sec.

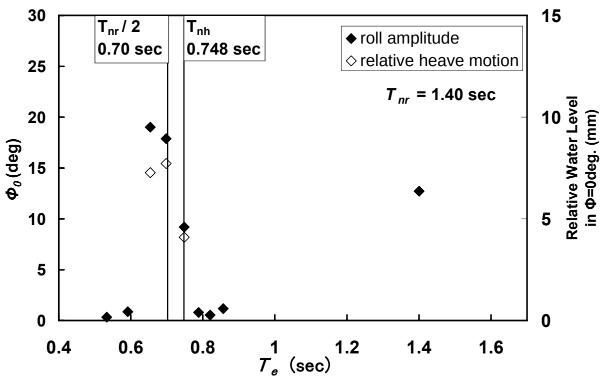

Fig. 23 Parametric rolling in beam waves and relative heave motion. Calculated at T_{nr} =1.40sec.

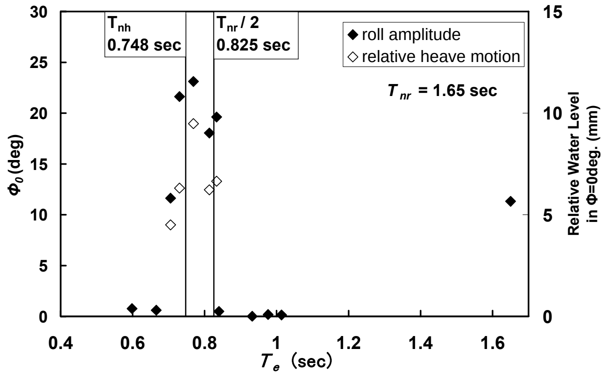

Fig. 24 Parametric rolling in beam waves and relative heave motion. Calculated at T_{nr} =1.65sec.

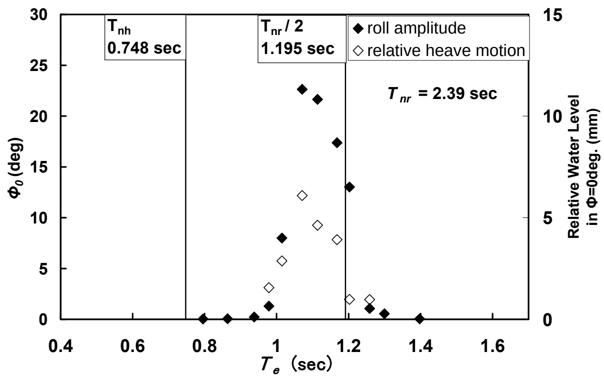

Fig. 25 Parametric rolling in beam waves and relative heave motion. Calculated at T_{nr} =2.39sec.

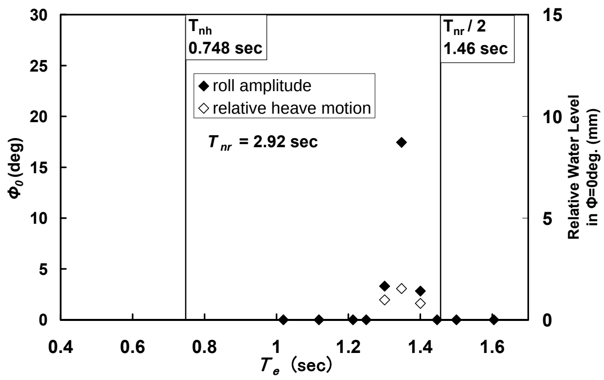

Fig. 26 Parametric rolling in beam waves and relative heave motion. Calculated at T_{nr} =2.92sec.

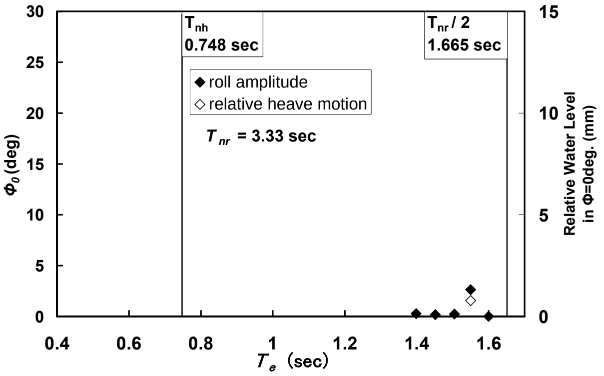

Fig. 27 Parametric rolling in beam waves and relative heave motion. Calculated at T_{nr} =3.33sec.

The relative heave motions can generate time variation of the draft of the ship, and the *GZ* curves for different drafts can be calculated by a hydrostatic calculation. An example of the calculated *GZ* is shown in Fig. 28. From this result, large variation of *GZ* values of the ship in beam waves can be confirmed. Kuroda et. al. (2002) also pointed out that variation of relative water level could change GZ value drastically in the 1st harmonic resonance of heave motion.

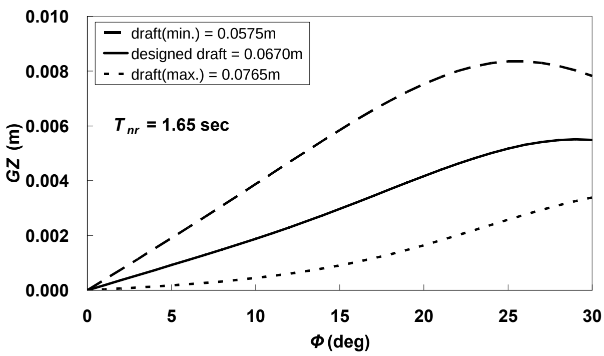

Fig. 28 Calculated *GZ* curve when draft is assumed to be changed due to relative heave motion in beam waves.

CONCLUSIONS

In the present study, effects of roll damping and heave motion on parametric rolling of a large passenger ship in beam waves are experimentally investigated and the following conclusions are obtained:

1) When the ship has the designed bilge keel, parametric rolling does not occur in beam waves. However, parametric rolling occurs when size of the bilge keel is smaller than half of the area of the designed bilge keels.

2) Roll damping significantly affects the critical wave height for occurring of parametric rolling in beam waves. The critical wave height increases with increasing roll damping. The amplitude of the parametric rolling rapidly increases with wave height above the critical one, and saturates to a maximum one which also depends on the roll damping.

3) Parametric rolling of a ship in beam waves may be caused by relative heave motion due to heave resonance. The vicinity of heave natural period and half of roll natural period may be the key factor for the occurrence of the phenomenon.

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