Prediction of Parametric Rolling in Irregular Head Waves

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ABSTRACT

For providing a benchmark data for numerical codes of parametric rolling prediction, a model experiment of a post-Panamax C11 class containership whose hull form is slightly modified from its original but opened for public was conducted and significant parametric rolling in irregular head waves was recorded. The existing numerical model developed by the authors for parametric rolling in regular longitudinal waves was extended to be applied to irregular longitudinal waves. Comparisons between the model experiment and the numerical result show reasonably good agreement under consideration of dispersion due to practical non-ergodicity. By utilizing the developed numerical model, it was demonstrated that small height of the bilge keel is a main reason why significant parametric rolling could happen for the C11 class post-Panamax containership.

KEYWORDS

Parametric Rolling; Irregular Head Waves; Post-Panamax C11 Class Containership; Benchmark Data; Bilge Keel.

INTRODUCTION

Since parametric rolling is well known as one of the most dangerous phenomena particularly for modern containerships, there was an urgent need for developing physics-based criteria for the restoring variation problem including parametric rolling in the current revision of intact stability criteria at IMO (International Maritime Organization). Comparison results of parametric rolling in irregular waves show significant scatters among existing numerical codes as reported by SAFEDOR [Spanos and Papanikolaou, 2009]. Each organization has developed a numerical code and claims that its code is validated with their own model experiments. However, it is difficult to make a comparison between different organizations because of the used hull forms are generally not available for different organizations mainly because of commercial reasons.

To overcome this situation, a model experiment of a post-Panamax C11 class containership was conducted to provide a benchmark data. The hull form is slightly modified by MARIN [Levadou and van't Veer, 2006] from its original which had suffered severe head-sea parametric rolling at the North Pacific in 1998 [France et al., 2003]. Roll motions in long-crested irregular head waves were recorded for several significant wave heights, Froude numbers and realisations at Osaka University. As a result, significant parametric rolling was successfully recorded in irregular head waves.

To predict parametric rolling in irregular waves, the existing 3DoF (degrees of freedom) numerical model for parametric rolling in regular waves [Hashimoto and Umeda, 2010] was extended to be applied to irregular waves. Then, numerical results were compared with the experimental results for validation of the numerical code. The extended numerical model shows a reasonably good agreement with measured parametric rolling in irregular head waves for the C11 class post-Panamx containership.

By utilizing the developed numerical model, we have examined the reason why such significant parametric rolling could happen for the C11 class post-Panamax containership by comparing its roll restoring variation and roll damping with other post-Panamax containership. As the result, a main reason is presumed that the height of bilge keel of the C11 post-Panamax containership is much smaller than that of other post-Panamax containership.

MODEL EXPERIMENTS

For providing a benchmark data for numerical codes of parametric rolling prediction, a model experiment of the Post-Panamax C11 class container ship, whose hull form is slightly modified by MARIN from its original but opened for public, was conducted to measure parametric rolling in irregular head waves at the towing tank of Osaka University. Roll decay tests with and without forward velocities were also done to estimate the roll damping. The ship model was towed by a towing carriage through soft elastic ropes. The body plan and the principal particulars of the C11 class post-Panamax containership are shown in Fig.1 and Table 1.

Model experiments were conducted for constant wave mean period, T_{01}, of 9.99 seconds, and several significant wave heights, $H_{1/3}$, of 5.22, 7.82, 10.43m. Parametric rolling without forward velocity was recorded for all significant wave heights. Model runs with forward velocity (Fn=0.05, 0.1) were also done for the case of $H_{1/3}$ of 7.82m. The measuring time duration of the experiments were 4200, 2400, 1200 seconds in full scale for Fn of 0.0, 0.05, 0.1, respectively. Here, the measuring time duration for Fn of 0.0 was determined by the experimental guidance utilizing the running standard deviation [Umeda et al., 2011].

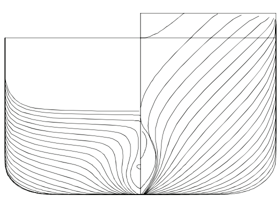

Fig.1 Body plan of the C11 class post-Panamax containership

Table 1 Principal particulars of the C11 class post-Panamax containership

item	value
length between perpendiculars : L	262.0 m
breadth : B	40.0 m
depth : D	24.45 m
mean draught : T	11.5 m
displacement : W	69441 ton
block coefficient : C_b	0.56
metacentric height : GM	1.965 m
natural roll period : T_ϕ	25.1 s

MATHEMATICAL MODEL

The 3DoF coupled model of the heave-roll-pitch motions based on the nonlinear strip theory had been developed by the authors for the prediction of parametric rolling in regular head and following waves. This model can almost quantitatively predict parametric rolling in regular head waves (Hashimoto and Umeda, 2010). In this research, we have extended this model to be applied to head and following irregular waves. This newly-extended time domain simulation program is named as OU-PR (Osaka University - simulation program for Parametric Rolling). In the simulation, a ship motion is determined by time integration of the differential equations of a ship motion with the Runge-Kutta method. Nonlinear Froude-Krylov forces are directly calculated by integrating wave pressure up to an irregular wave surface profile. The 2D hydrodynamic forces used for the radiation and diffraction forces are calculated for the submerged hull by the integral equation method with taking an instantaneous roll angle into account. The wave pressure used for the Froude-Krylov calculation and the diffraction forces are calculated with the linear superposition principle. In default, the number of sine wave is 200. The diffraction forces are calculated by the STF method [Salvesen et al., 1970], and transfer functions with respect to a frequency and a heel angle are prepared in advance. The radiation forces in roll are calculated for the natural roll frequency and those in vertical motion (heave and pitch) are done for the peak of mean wave frequency. Linear and quadratic roll damping coefficients are used in the mathematical model, which are determined from an experimental result of roll decay tests if it is available. Otherwise, they are determined by the Ikeda's semi-empirical method [Ikeda, 2004]. The equations of a ship motion used in the numerical model are expressed as Eqs.(1)-(3).

$$\begin{aligned}&(m + A_{33}(\phi))\ddot{\zeta} + B_{33}(\phi)\dot{\zeta} + A_{34}(\phi)\ddot{\phi} + B_{34}(\phi)\dot{\phi}\\&+A_{35}(\phi)\ddot{\theta} + B_{35}(\phi)\dot{\theta} = F_3^{FK}(t,\zeta,\phi,\theta) + F_3^{DF}(t,\phi)\end{aligned} \quad (1)$$

$$\begin{aligned}&(I_{xx} + A_{44}(\phi))\ddot{\phi} + N_{\dot{\phi}}\dot{\phi} + N_{\dot{\phi}^2}\dot{\phi}\left|\dot{\phi}\right| + A_{43}(\phi)\ddot{\zeta}\\&+B_{43}(\phi)\dot{\zeta} + A_{45}(\phi)\ddot{\theta} + B_{45}(\phi)\dot{\theta}\\&\quad = F_4^{FK}(t,\zeta,\phi,\theta) + F_4^{DF}(t,\phi)\end{aligned} \quad (2)$$

$$(I_{yy} + A_{55}(\phi))\ddot{\theta} + B_{55}(\phi)\dot{\theta} + A_{53}(\phi)\ddot{\zeta} + B_{53}(\phi)\dot{\zeta} + A_{54}(\phi)\ddot{\phi} + B_{54}(\phi)\dot{\phi} = F_5^{FK}(t,\zeta,\phi,\theta) + F_5^{DF}(t,\phi) \tag{3}$$

RESULTS AND DISCUSSION

Numerical simulations were executed for the same conditions of mean wave period, significant wave height, Froude number and number of realization as the model experiment. The comparisons of maximum roll angle between the model experiment and the numerical simulation for $H_{1/3}$=7.82m and Fn=0.0, 0.05, 0.1 are shown in Figs.2-4, respectively. The averages of the maximum roll angles of the experiment and the simulation with respect to Froude number and significant wave height are plotted in Figs. 5-6. Numerical results show reasonably good agreement with the experimental ones in the condition where significant parametric rolling happens while it is not so for the cases of $H_{1/3}$=5.22m and Fn=0.0, and $H_{1/3}$=7.82m and Fn=0.1. From the measured results, it is presumed that these conditions are close to the threshold of parametric rolling. It was pointed out that maximum roll angles of parametric roll scatter near the threshold due to practical non-ergodicity (Bulian et al., 2008). Therefore, the agreement would be improved if a number of realization increases for these conditions. The standard deviations of roll and pitch angles are calculated with $H_{1/3}$=7.82m and Fn=0.0, and plotted in Fig.7. The standard deviation of roll angle scatters significantly due to practical non-ergodicity while that of pitch angle does not. The similar trend can be found in the numerical simulation.

In the experiment, wave elevation was recorded by a wave probe attached to a towing carriage. The incident irregular wave profile is reproduced by the Fourier transformation with the measured data. The numerical simulations were done with the reproduced wave surface train, and the calculated time histories of roll and pitch were compared with the measured ones. An example of the comparisons with $H_{1/3}$=7.82m and Fn=0.0 is shown in Fig.8. Development of parametric rolling can be predicted with reasonable accuracy in the beginning and the end of the time history where largest and 2nd largest parametric rolling were observed.

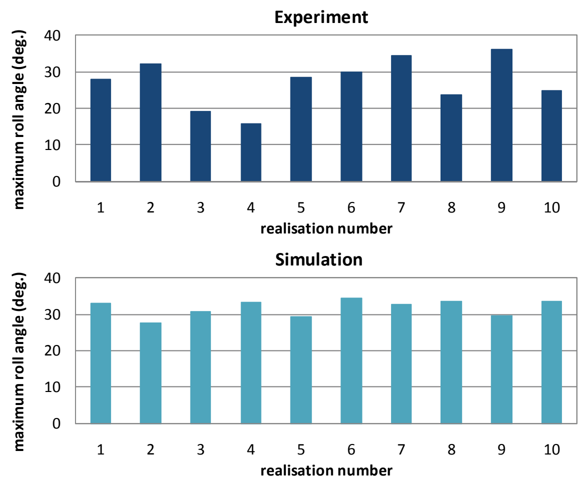

Fig.2 Maximum roll angle of parametric rolling with T_{01}=9.99s, $H_{1/3}$=7.82m and Fn=0.0

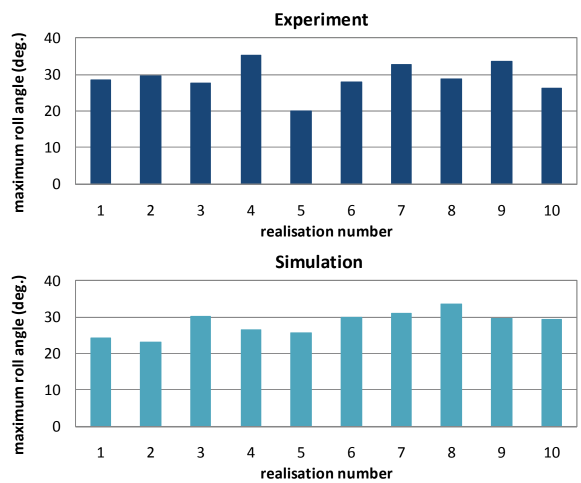

Fig.3 Maximum roll angle of parametric rolling with T_{01}=9.99s, $H_{1/3}$=7.82m and Fn=0.05

Since it is concluded that the developed numerical model has practical accuracy for parametric rolling prediction by comparing with the experimental results. Maximum roll angles of parametric rolling for the C11 containership without forward speed per 1 hour at the North Atlantic were calculated with wave statistics. The time domain simulations were repeated with 10 realizations for each wave condition, and the maximum roll angle is written in the table shown in Fig.9. If a maximum roll angle is beyond 90 degrees, it is regarded as capsize and written as cap. Severe parametric rolling was confirmed for a wide range of wave condition. The probability of parametric rolling exceeding a critical angle is shown in Fig.10. The exceeding probability is very high. This is because numerical simulations were conducted without forward speed and it is the most dangerous condition for suffering severe parametric rolling. The similar calculations should be done with actual ship speed to examine effects of advanced speed on the exceeding probability for practical uses.

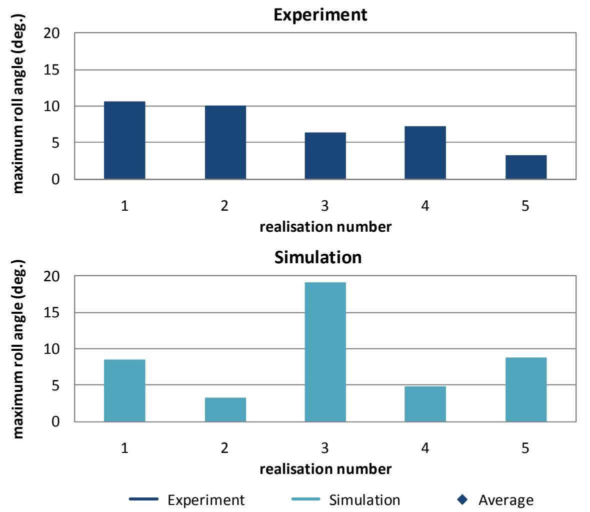

Fig.4 Maximum roll angle of parametric rolling with T_{01}=9.99s, $H_{1/3}$=7.82m and Fn=0.1

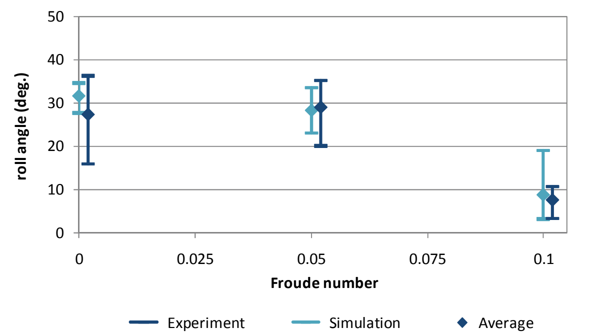

Fig.5 Average of maximum roll angle of parametric rolling for several Froude numbers with T_{01}=9.99s, $H_{1/3}$=7.82m

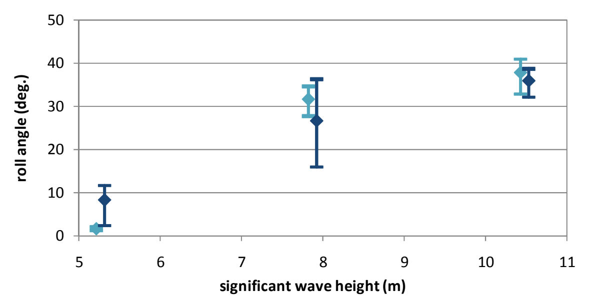

Fig.6 Average of maximum roll angle of parametric rolling for several significant wave heights with T_{01}=9.99s and Fn=0.0

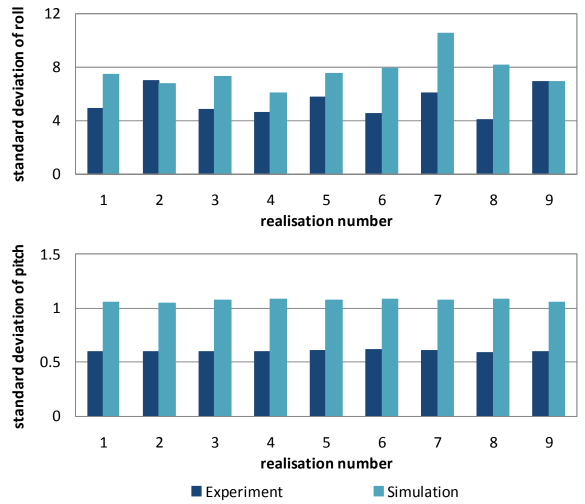

Fig. 7 Standard deviation of roll and pitch angles with T_{01}=9.99 s, $H_{1/3}$=7.82m and Fn=0.0

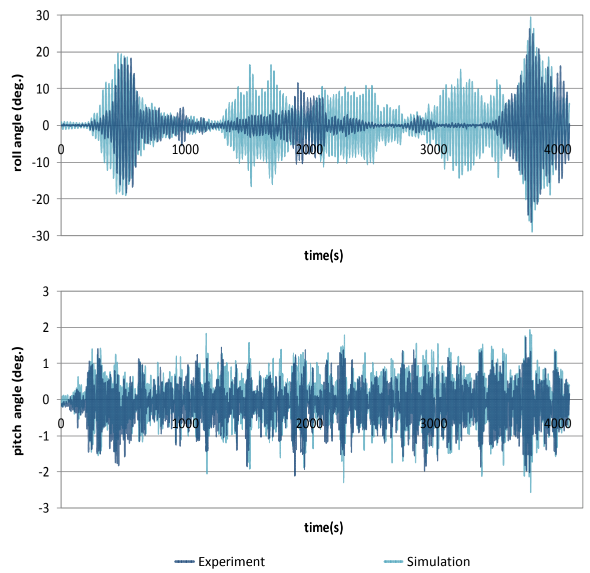

Fig. 8 Time history of roll and pitch angles with T_{01}=9.99s, $H_{1/3}$=7.82m and Fn=0.0

	T_{01} (s)																	
H_{13} (m)	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
0.5			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0						
1.5				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
2.5				0.0	0.3	0.5	4.0	3.0	3.9	4.1	3.2	2.6	2.1	2.2	1.6	1.5		
3.5				1.0	2.1	1.0	8.2	9.0	12.2	10.9	6.8	6.7	5.0	4.5	3.4	3.1	4.3	
4.5					4.4	2.7	13.0	14.9	16.9	16.0	13.1	11.4	9.3	7.1	5.8	6.0	8.2	
5.5					6.5	6.6	17.1	20.5	22.9	21.9	17.9	15.9	15.0	9.9	9.7	11.5	10.6	9.4
6.5					15.5	7.0	19.7	24.9	27.8	27.1	24.0	20.8	19.3	15.2	12.1	14.0	17.4	12.1
7.5						13.9	23.1	28.7	31.5	30.7	28.5	25.5	23.3	20.2	17.7	17.6	20.3	16.8
8.5						cap	24.2	31.9	35.4	33.3	31.1	28.8	28.6	25.0	22.1	22.7	22.6	21.0
9.5						cap	cap	35.6	37.3	35.4	34.4	31.7	30.0	28.2	25.4	25.4	27.7	24.1
10.5							cap	37.6	38.8	37.0	36.0	34.3	32.2	28.7	28.2	27.7	29.2	25.5
11.5							cap	cap	40.6	38.0	36.6	36.8	33.8	30.8	32.0	30.0	29.4	28.2
12.5							cap	cap	42.3	39.5	38.9	36.7	34.9	32.2	33.5	30.4	31.5	
13.5								cap	41.8	40.9	40.6	38.1	35.9	33.2	34.3	29.7	32.1	
14.5								cap	44.1	41.9	39.8	37.7	36.9	34.1	33.6	31.9		
15.5									cap	43.5	40.7	40.0	38.5	35.8	35.7	33.7		
16.5										48.0	43.3	39.1	39.4	36.4	34.7			

Fig. 9 Maximum roll angle of parametric rolling per 1 hour in irregular waves appeared at the North Atlantic

Since the maximum roll angle of parametric rolling of the C11 class post-Panamax containership is sometimes larger than the range of roll decay tests, the rationality of a curve-fitting of extinction curve with linear and quadratic terms could not be guaranteed. Therefore, numerical simulations utilizing the curve-fitting with 3rd order polynomial were attempted. The calculated results are shown in Fig.11. The difference of the numerical results is not negligibly small. Further discussions on this matter are desirable in future.

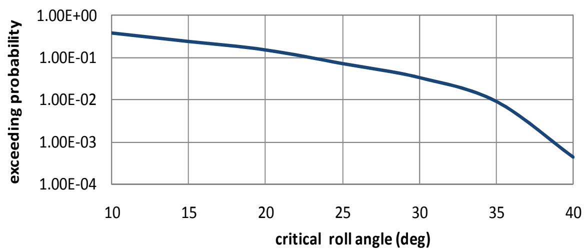

Fig.10 Probability of parametric rolling exceeding a critical roll angle at the North Atlantic

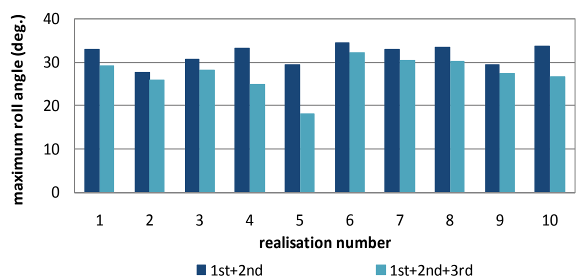

Fig.11 Maximum roll angle of parametric rolling with 2nd and 3rd order polynomial curve-fittings of extinction curves

REASONS OF LARGE AMPLITUDE

Since severe parametric rolling is observed both in the model experiment and the numerical simulations, we have investigated the reason why the C11 class post-Panamax containership could suffer such severe parametric rolling from view points of roll restoring variation and roll damping by comparing them with other post-Panamax containership. The body plan and the principal particulars of this containership can be found in the literature [Hashimoto and Umeda, 2010].

Roll Restoring Variation

Since roll restoring variation is an essential factor as well as roll damping for parametric rolling, the amplitude of roll restoring variation in regular head waves was calculated for the C11 and other post-Panamax containerships. The calculated amplitudes of roll restoring variation for the C11 containership is larger than that of other containership by 26% as shown in Fig.12. Therefore, it is concluded that the C11 class post-Panamax containership has a worse hull form from the view point of parametric rolling occurrence.

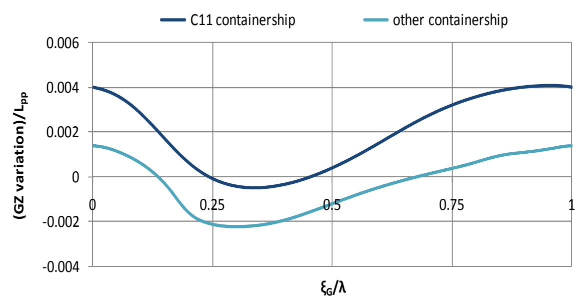

Fig.12 Roll restoring variation at 20 degrees of heel angle in regular head waves with H/λ=0.03, λ/L=1.0 and Fn=0.0

Roll Damping

Since the C11 class post-Panamax containership has the small bilge keel, time domain simulations were conducted with the roll damping of other Post-Panamax containership to examine effects of bilge keel. The bilge keel size compared here is shown in Table 2. The bilge keel area of the C11 class post-Panamax containership is smaller than half of that of other post-Panamax containership. Fig.13 shows the comparison of experimentally obtained extinction coefficients for both ships. Fig.14 indicates that the maximum roll angle of parametric rolling drastically reduces if the roll damping of other containership is adopted. This numerical result clearly demonstrates that the small size of the bilge keel leads to significant parametric rolling.

Table 2 Bilge keel size

	C11 containership	other containership
Bilge keel area: A_{BK}	30.6 m^2	84.3 m^2
$\frac{A_{BK}\times 100}{L_{pp}\times B}(\%)$	0.58	1.38

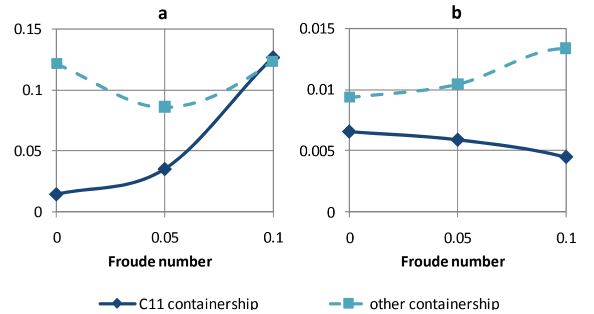

Fig.13 Linear and quadratic extinction coefficients determined from roll decay tests

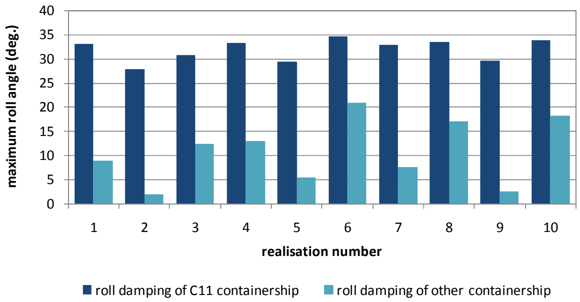

Fig.14 Maximum roll angle of parametric rolling with the roll damping of the C11 and other post-Panamax containerships with T_{01}=9.99 s, $H_{1/3}$=7.82 m and Fn=0.0

CONCLUSIONS

For providing a benchmark data, the model experiment of the C11 class post-Panamax containership was conducted and significant parametric rolling was observed in irregular head waves. It was demonstrated that this is mainly because the height of bilge keel is much smaller than usual containerships. The newly-extended 3 DoF numerical model shows reasonably good agreements with measured parametric rolling in irregular waves for the C11 class containership.

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