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ORIGINAL ARTICLE

An investigation of different methods for the prevention of parametric rolling

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Abstract The parametric rolling of modern containerships is emerging as a serious problem, to the extent that its effects warrant a study into its prevention. In light of this, two methods for reduction of parametric rolling are proposed and examined by physical model experiments. The first is a sponson attached to the side of a ship, the purpose being to decrease the rate of change of the roll-restoring moment. The second is an antirolling tank to increase roll damping. By conducting free-running model experiments for a 6600-TEU post-Panamax container ship with sponsons under typical parametric rolling conditions, it was found that the sponsons could decrease the magnitude of parametric rolling. The antirolling tank could prevent parametric rolling completely in certain conditions, even in severe head seas. Using the damping coefficients from experimentally derived data of a model ship with an antiroll tank, a numerical simulation was established. The numerical model was then compared with the free-running model experiments. The results indicated that the numerical model could qualitatively verify the experimental results. Finally, an attempt to optimise the size of an antirolling tank for preventing parametric rolling for the subject post-Panamax container ship in the North Pacific Ocean is presented.

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Key words Parametric roll · Sponson · Anti-roll tank · Containership

1 Introduction

It has been documented that in 1998 a C11 post-Panamax container ship suffered severe parametric roll in the North Pacific Ocean. A maximum roll angle of about 40° in head seas was reported, which resulted in the loss of 400 containers and damage to as many more.[1] This incident triggered a review of the Intact Stability Code (IS Code) of the International Maritime Organization (IMO). The phenomenon of parametric rolling occurs when the ship roll-restoring moment is affected by a passing wave. When a wave with half the encounter frequency of the ship is coincident with the ship's natural roll frequency, the roll motion is adversely affected. In extreme cases, when the roll frequency is half the encounter frequency, the resulting roll motion is such that cargo damage or even capsize is likely.

Reducing roll motion has been a crucial issue among naval architects for a long time. Bilge keels, antirolling tanks, gyro stabilizers, and fin stabilisers are well developed for this purpose. However, there are only a few pieces of research on their applicability to parametric rolling,[2] and no systematic experimental examination has been reported so far. A theoretical formula to predict the threshold of parametric rolling based on an uncoupled roll model is already established. It is governed by the amplitude of the roll-restoring variation in waves and the linear roll damping coefficient.

Using this formula, prevention of parametric rolling is achieved by reducing the variation in the amplitude of the restoring moment in longitudinal waves and/or by

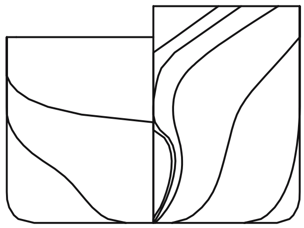

Fig. 1. Body plan of the container ship

Table 1. Principal particulars of the containership

Item	Ship	Model
Length: L_{pp}	283.8 m	2.838 m
Breadth: B	42.8 m	0.428 m
Depth: D	24.4 m	0.244 m
Draught at FP: T_f	14.0 m	0.14 m
Mean draught: T	14.0 m	0.14 m
Draught at AP: T_a	14.0 m	0.14 m
Block coefficient: C_b	0.629	0.629
Pitch radius of gyration: κ_{yy}/L_{pp}	0.244	0.258
Longitudinal position of centre of gravity from the midship: x_{CG}	5.7 m aft	0.057 m aft
Metacentric height: GM	1.06 m	0.0106 m
Natural roll period: T_ϕ	30.3 s	3.2 s

increasing the roll damping. Floats attached to the side of a ship (referred to as sponsons) to reduce the variation in amplitude and an antirolling tank (ART) to reduce the roll damping are examined. Initially, free-running model tests with and without the sponsons or the ART were conducted to examine the applicability of these devices for the prevention of parametric rolling in regular head seas. Then a numerical simulation of the free-running experiments and of water motion in the ART was established. Using numerical simulations for various volumes of ART, it was possible to optimise the size of the tank.

2 Subject ship

A 6600-TEU post-Panamax container ship designed by the National Maritime Research Institute (NMRI) was selected as the subject ship. This post-Panamax container ship has a modern hull form with an exaggerated bow flare and a transom stern and is similar to the C11 post-Panamax container ship that suffered parametric rolling in the North Pacific Ocean. Its principal particulars and body plan are shown in Table 1 and Fig. 1, respectively. The righting arm (GZ) curve in calm water is shown in Fig. 2.

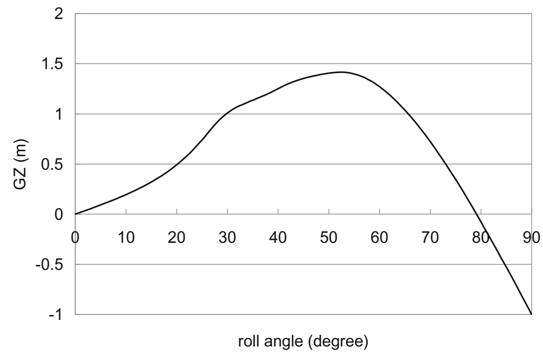

Fig. 2. The righting arm (GZ) curve of the container ship

3 Prevention devices

3.1 Sponsons

Parametric rolling is induced by a time-varying roll-restoring moment due to wave elevation, especially in longitudinal waves. The double amplitude of the restoring moment variation is defined as the difference in the GZ curve between the location of a wave crest and trough amidships. In a large post-Panamax container ship, the restoring moment variation is generally greater than for an ordinary container ship because of their exaggerated bow flare and transom stern, designed for transport efficiency. Thus, the draught at both the bow and stern with a wave crest amidships is lower, which results in a reduction of the secondary moment of the water plane around the centreline. To reduce this effect, additional buoyancy at midship is desirable. This is achieved by attaching sponsons to the side of the ship to increase the restoring moment with a wave crest amidships. The size and shape of the sponsons were determined using an uncoupled roll model with a linear roll-restoring moment in regular longitudinal waves. It has been demonstrated that head seas are more dangerous than waves with a small angle of incidence, such as bow quartering seas.[3]

If the roll motion, ϕ, is described as

$$\ddot{\phi} + 2\alpha\dot{\phi} + \omega_\phi^2(1 + h\cos\omega_e t)\,\phi = 0 \quad (1)$$

the threshold of parametric roll can be obtained as:

$$h > \frac{4\alpha}{\omega_\phi} \quad (2)$$

where α is the linear roll damping coefficient, h is the amplitude ratio of roll restoring , ω_ϕ is the natural roll frequency, ω_e is the encounter frequency, and t is the time.[4] Here, α and h can be obtained using the following two equations:

$$\alpha = \frac{2(a + b\phi_0)}{T_\phi} \tag{3}$$

$$h = \frac{GM_{amp}}{GM} \approx \frac{GZ_{amp}(\phi_0)}{GZ(\phi_0)} \tag{4}$$

where a and b are Froude's extinction coefficients, GM_{amp} is the single amplitude of metacentric height variation, GZ_{amp} is the single amplitude of righting arm variation, ϕ_0 is roll amplitude, and T_ϕ is the natural roll period.

To determine the threshold of parametric rolling, it is sufficient to discuss stability in an upright condition. Thus, nonlinear restoring and nonlinear damping are not included in Eq. 1. Using Eqs. 2–4, the critical amplitude value of GZ variation at a heel angle of 20° can be obtained as the limiting value for preventing parametric rolling of the subject ship.

$$2GZ_{amp} < 0.812\,\text{m} \tag{5}$$

This means that parametric rolling will not occur if the amplitude of GZ variation is less than 0.812 m. The variation amplitude is the difference in the GZ curve when the midship is on a wave crest and when it is in a trough at a heel angle of 20°. It is calculated by integrating the incident wave pressure around the underwater hull up to the wave surface. This means that it is based on the Froude–Krylov assumption and the diffraction effect is not taken into account. The ship is assumed to be free in heave and pitch. The calculated results are shown in Fig. 3. The wave steepness, H/λ, and the wavelength to ship length ratio, λ/L, are assumed to be 0.05 and 1.0, respectively, which is considered to be typical conditions for parametric rolling. The breadth of a sponson is calculated as 11.7% of the ship breadth by using Eq. 5 and Fig. 3. Consideration was also given to avoiding practical problems such as berthing and loading operations.

GZ curves with and without the sponson in longitudinal waves, as well as in calm water, are shown in Fig. 4. The GZ curve with the sponson with a wave crest amidships has higher values than that without sponsons. Nevertheless, the difference in the GZ curve between a wave crest and trough at the heel angle of 20° is close to the calculated value of 0.812 m obtained from Eq. 5. The sponson on the side of the model is shown in Fig. 5.

3.2 Antirolling tank

An antirolling tank (ART) has the effect of additional damping by using the phase lag between the tank water and the ship roll motion. In this investigation, the design of the tank has three water ducts connecting the port and starboard tanks to alter the natural period of the tank water flow. In addition, each tank has a plate with a slit on the bottom to increase the vortex-generating damping effect. Both side tanks are also connected with an air pipe. The ART model is shown in Fig. 6 and its dimensions and definitions are shown in Table 2 and Fig. 7, respectively.

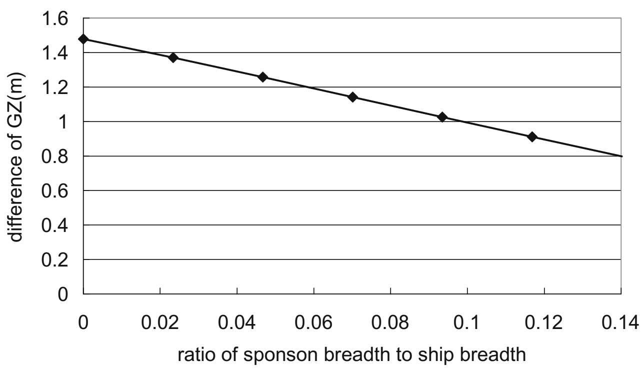

Fig. 3. Ratio of the breadth of sponson and GZ variation with a wave steepness (H/λ) of 0.05 and a wavelength to ship length ratio (λ/L) of 1.0

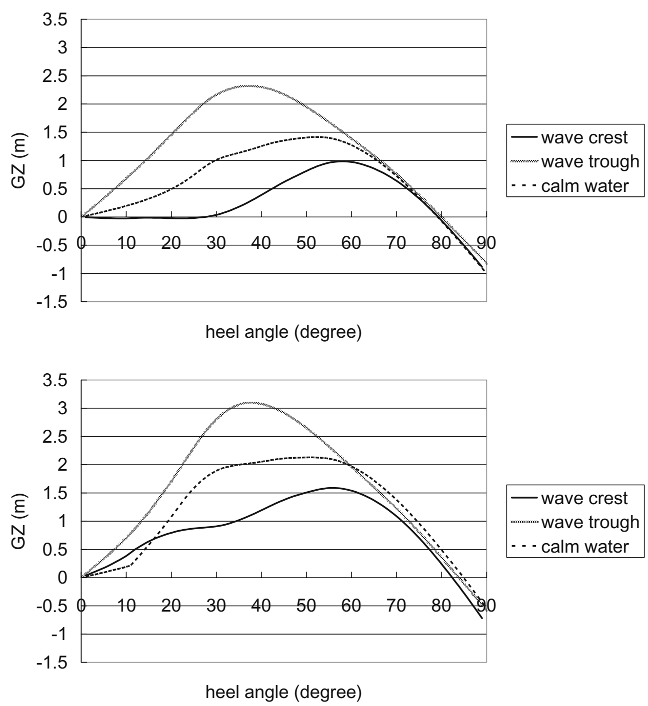

Fig. 4. Comparison of GZ curves without (*upper*) and with (*lower*) the sponson for $H/\lambda = 0.05$ and $\lambda/L = 1.0$

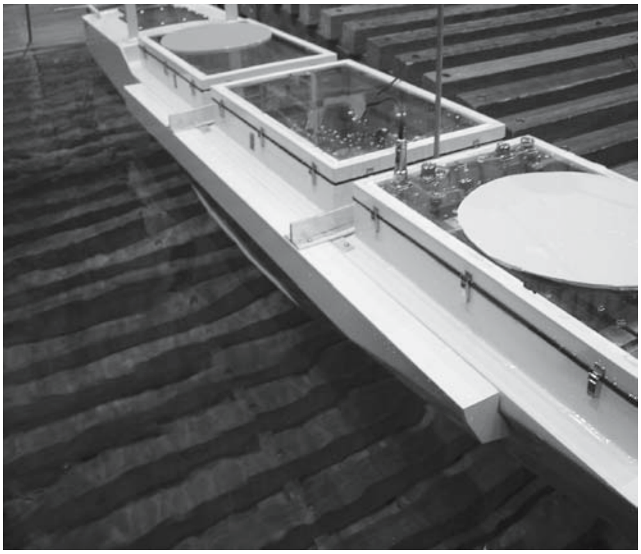

Fig. 5. Sponson on the model ship

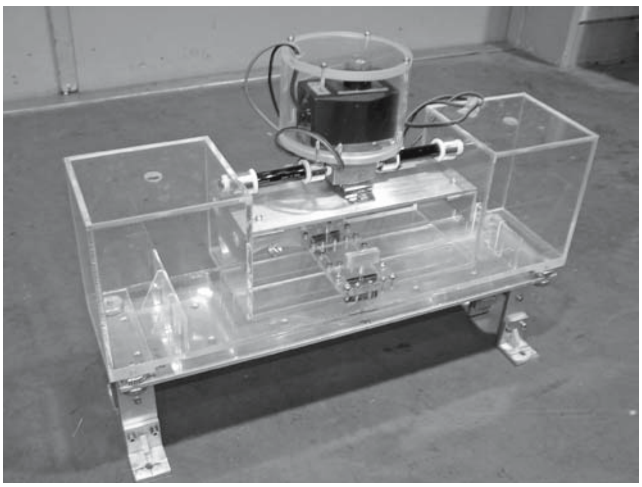

Fig. 6. Antirolling tank (ART) model

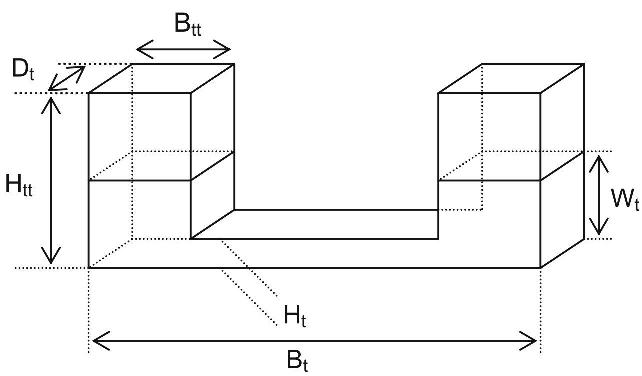

Fig. 7. Definition of ART dimensions

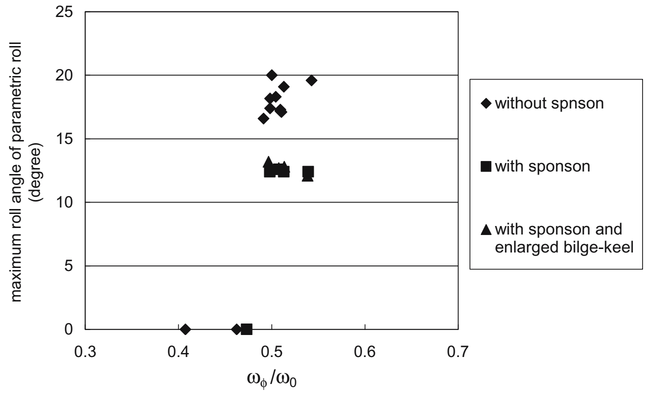

Fig. 8. Experimental results of parametric rolling with and without the sponsons for $H/\lambda = 0.04845$ and $\lambda/L = 1.6$. ω_ϕ, natural roll frequency; ω_0, encounter frequency

Table 2. Dimensions of the antirolling tank model

H_{tt}	0.125 m
D_t	0.09 m
B_{tt}	0.107 m
B_t	0.428 m
H_t	0.018 m
W_t	0.045 m

4 Free-running model experiment

4.1 Sponson

Free-running model experiments with and without the sponson were conducted at the Marine Dynamics Basin of the National Research Institute of Fisheries Engineering (NRIFE). The ship model was propelled by an electric motor with the power supplied by onboard batteries. The propeller RPM was controlled by feedback control and the ship was steered by an autopilot system with the rudder gain set to 1.0. The maximum rudder angle was 35°. The roll, pitch, and yaw angles were measured by an optical gyroscope. The data obtained were stored in an onboard computer and the measured yaw angle was used for the autopilot control.

Model experiments were conducted in regular head seas with a wavelength to ship length ratio of 1.6. The results of measured maximum roll amplitude of parametric rolling with a wave steepness of 0.0485 are shown in Fig. 8. A maximum roll amplitude of 18° was observed without the sponsons for a wave steepness of 0.04845. With the sponsons, the maximum amplitude was approximately 13°. In addition, the bilge keel was increased in size to 1.76 times the original design to increase the damping moment given the same experimental conditions. As shown in Fig. 9, the roll decay tests with the

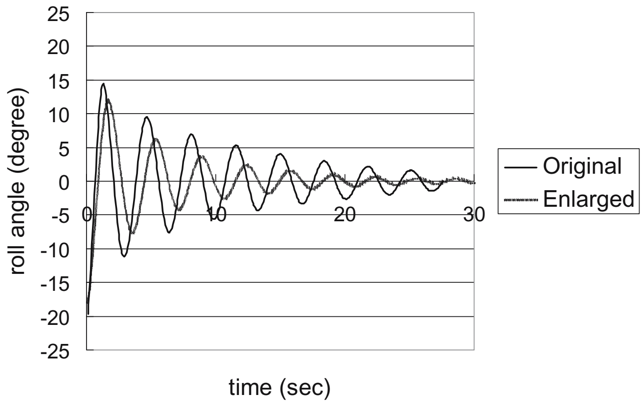

Fig. 9. Comparison of roll decay curves with the original and enlarged bilge keels

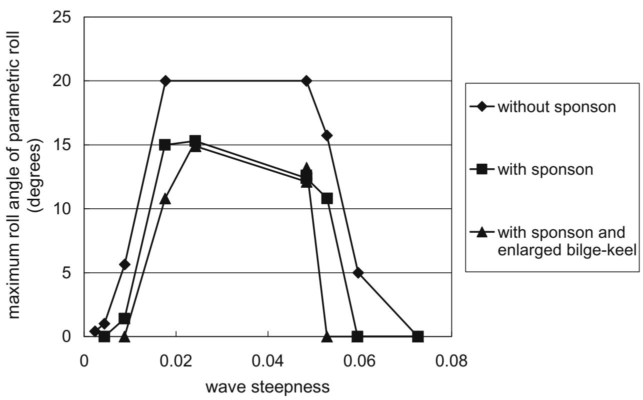

Fig. 10. Experimental results of parametric roll as a function of wave steepness for $\lambda/L = 1.6$

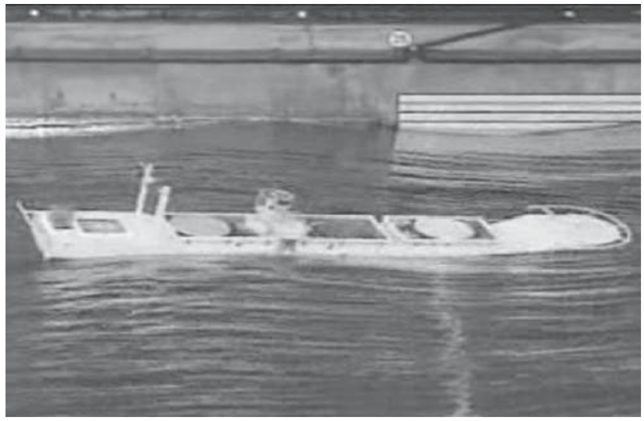

Fig. 11. Photo of running ship model with an ART

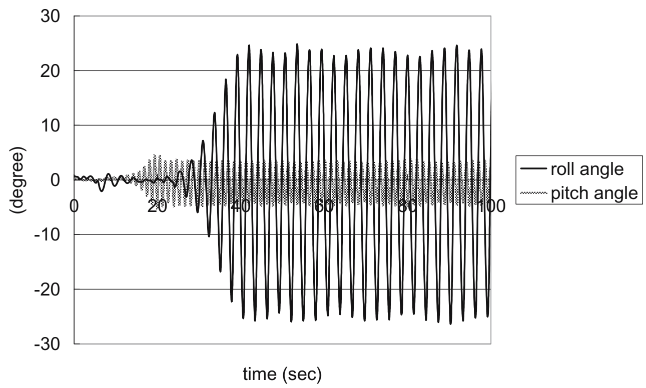

Fig. 12. Time series of model run without the ART for $\lambda/L = 1.3$ and $H/\lambda = 0.03$

original and enlarged bilge keels showed that the enlargement of the bilge keel resulted in an increase of about 80% in linear roll damping coefficient. This did not affect the maximum roll angle or the occurrence range.

The maximum angles of parametric rolling with and without the sponson are shown as a function of wave steepness in Fig. 10. The propeller RPM was adjusted to realize the relationship of parametric rolling that half the encounter frequency is equal to the natural roll frequency. In all conditions tested, the sponsons reduced the maximum roll angle. The recently published American Bureau of Shipping Guide regarding the prevention of accidents due to parametric rolling states that the maximum roll angle is to be less than 15°.[5] Therefore, the experiment confirms that the sponsons tested reduced the maximum roll angle to less than 15°. The results also indicate that increasing the roll damping by increasing the size of the bilge keel is less effective in preventing parametric rolling and can only reduce its occurrence. This indicates that the sponson is effective in reducing severe parametric rolling, but additional enlargement of the bilge keel has minimal effect.

4.2 Antirolling tank

Free-running model experiments with and without an ART were conducted in regular head waves with wavelength to ship length ratios of 1.0, 1.3, and 1.6. The antirolling tank model was attached above the main deck near the midship position; this is shown in Fig. 11. Initially, model runs were conducted with no water in the tank, which corresponds to the case without the ART. As before, the propeller RPM was adjusted to satisfy the typical parametric rolling condition. As a result, parametric rolling with a maximum amplitude of 23° and a roll period of twice the wave encounter period was clearly observed, as shown in Fig. 12. Model runs with the tank water level at 100% in the same conditions are shown in Fig. 13. The results show that parametric rolling has completely disappeared. The free surface effects of the ART were taken into account by the use

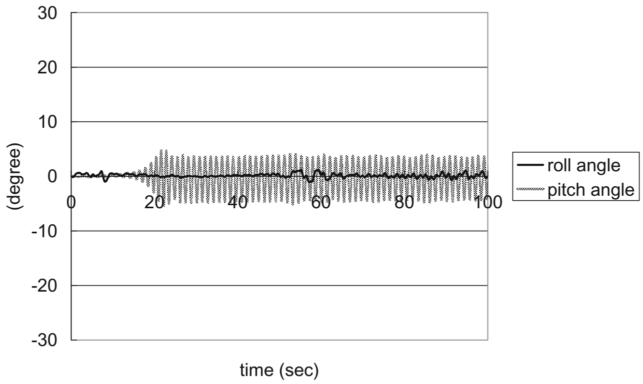

Fig. 13. Time series of model run with the ART (100% full of water) for $\lambda/L = 1.3$ and $H/\lambda = 0.03$

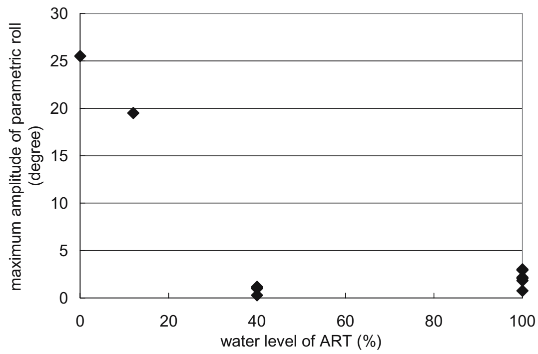

Fig. 14. Parametric roll amplitude with different water levels in the ART for $\lambda/L = 1.3$ and $H/\lambda = 0.03$

of ballast weights to ensure the same metacentric height (GM) as the ship's GM.

Experimental results of the maximum angle of parametric rolling with differing water levels in the tank are shown in Fig. 14. This is for a wavelength to ship length ratio of 1.3 and $H/\lambda = 0.03$ with the as-designed GM. It shows that parametric rolling is prevented if the water level in the tank is greater than 40%. The roll decay tests of the model ship showed that the linear roll damping coefficient analysed as an uncoupled roll model for the ship with the ART having a 40% water level is about 3.3 times that without the ART.

5 Numerical simulation

5.1 Mathematical model

To reproduce the experimental results numerically, a mathematical model of the water tank effect[6] was combined with an uncoupled ship roll model.[7] Since the amplitude of parametric rolling is of interest, nonlinear restoring and damping are taken into account. The wave exciting roll moment is zero because the condition is based upon head seas.

For the ship:

$$\begin{aligned}&(I_{xx}+J_{xx})\ddot{\phi}-K_p\dot{\phi}-K_{ppp}\dot{\phi}^3+mg\left(GM\phi+C_3\phi^3+C_5\phi^5\right)\\&\quad+mg\left\{\left(a_1\zeta_{ae}+a_2\zeta_{ae}^2+a_3\zeta_{ae}^3\right)\right.\\&\quad+\left.\left(b_1\zeta_{ae}+b_2\zeta_{ae}^2+b_3\zeta_{ae}^3\right)\cos\omega_e t\right\}\\&\quad\left\{\phi-\left(1/\pi^2\right)\phi^3\right\}+J_{st}\ddot{\eta}+K_{st}\eta=0\end{aligned} \tag{6}$$

where I_{XX} is the moment of inertia in roll; J_{XX} is the added moment of inertia in roll; K_p is the linear roll damping coefficient; K_{ppp} is the cubic roll damping coefficient; g is the gravitational acceleration; GM is the metacentric height; C_3 and C_5 are the constant coefficients of nonlinear restoring moment in still water; a_1, a_2, a_3 are the constant coefficients of the average of variation of the roll-restoring moment; b_1, b_2, b_3 are the constant coefficients of the amplitude of variation of the roll-restoring moment; λ is the wave length; J_{st} is the coefficient of inertia coupling of the tank water and the ship; K_{st} is the coefficient of static coupling of the tank water and the ship; and ζ_{ae} is the amplitude of Grim's effective wave.[7]

For the tank water:

$$J_{st}\ddot{\phi}+K_{st}\phi+J_t\ddot{\eta}+B_t\dot{\eta}+K_{st}\eta=0 \tag{7}$$

where J_t is the inertia coefficient of tank water, B_t is the tank water damping coefficient, and K_{st} is the restoring coefficient of tank water.

To determine the restoring variation, the systematic calculations of metacentric height were carried out for a wavelength to ship length ratio of 1.0 and several different wave heights, and the regression formula of the restoring variation for different wave amplitudes was obtained. Then, by utilizing Grim's effective wave concept,[7] the variation of the roll-restoring moment was modelled for an arbitrary combination of wavelength and wave height. Here, the roll-restoring moment was assumed to be zero when the roll angle was 180°. The damping coefficient of the ship was estimated from a roll decay test in calm water with no forward velocity. The damping of the water in the ART was numerically estimated to fit the time history of the roll decay within the first half cycle, as shown in Fig. 15.

5.2 Numerical results

Comparisons between the free-running model experiment and the numerical simulation were conducted, as shown in Fig. 16. In the case of 100% water level in the

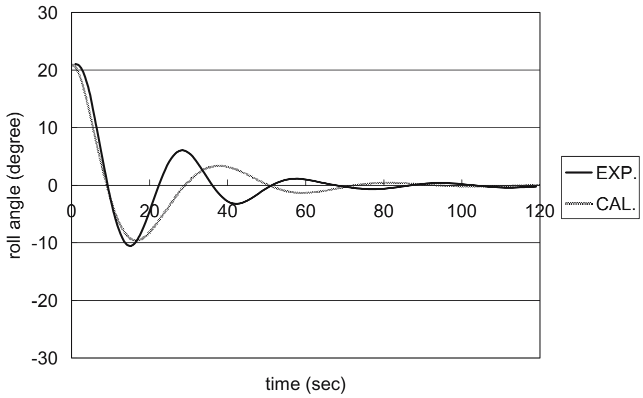

Fig. 15. Comparison between roll decay tests with the ART (*EXP.*) and the numerical simulation (*CAL.*)

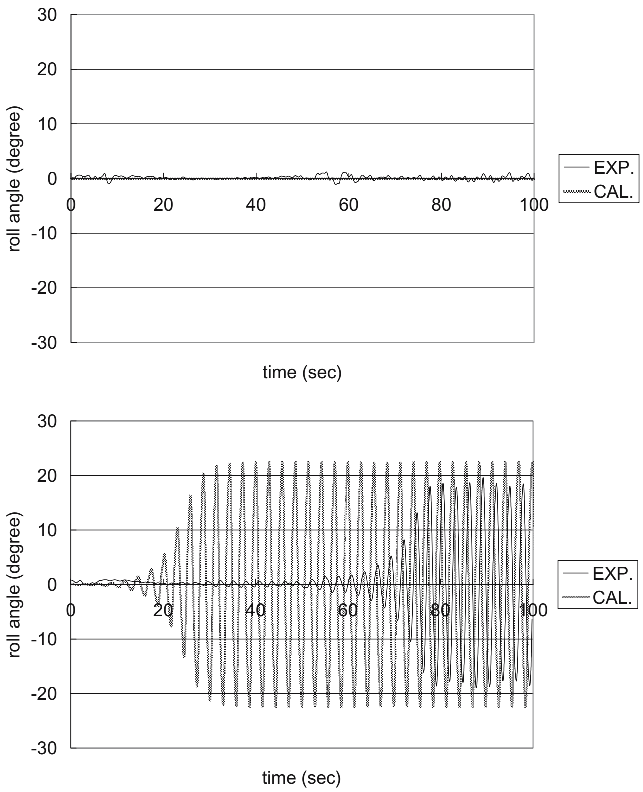

Fig. 16. Comparison of roll angles between experiment and calculation with the ART at 100% water level (*upper*) and 11% water level (*lower*) for $\lambda/L = 1.3$ and $H/\lambda = 0.03$

ART, the numerical simulation can predict the experimental results, i.e., no parametric rolling occurs. For 11% of water in the ART, the numerical results agree with the experiment for the steady amplitude and the development rate of parametric roll. Further comparisons are shown in Fig. 17 with different wavelengths and wave steepness. The comparisons demonstrate that the mathematical model can qualitatively predict parametric rolling of a ship with an ART

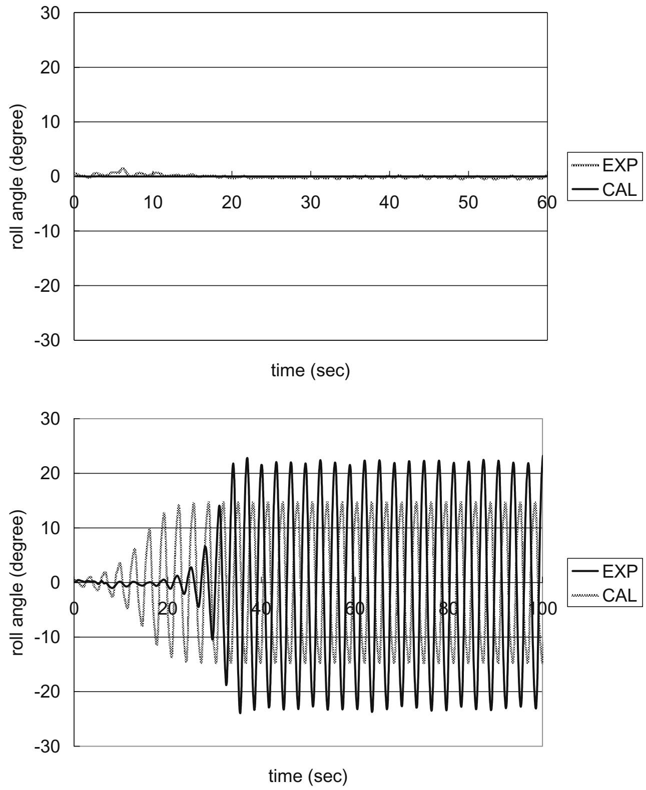

Fig. 17. Comparison of experiment and calculation with ART at 40% water level (*upper*) and 0% water level (*lower*) for $\lambda/L = 1.6$ and $H/\lambda = 0.025$

6 Optimisation of the ART

The comparisons between the free-running model experiment and the numerical simulation demonstrate that the mathematical model expressed by Eqs. 6 and 7 can predict the roll motion with the ART. By optimising the size of the ART using numerical analysis, it is possible to minimise the resultant reduction of onboard containers (to counter the effect of the tank on the displacement and GM). Repeating the time domain simulations and systematically changing the length of the ART, which is defined as D_t in Fig. 7, the threshold of wave steepness for parametric rolling was obtained, as shown in Fig. 18. The threshold of parametric rolling for each water level in the ART was obtained by plotting the instantaneous roll angle when the ship's centre of gravity passed a wave crest. This is the Poincare mapping technique,[7] and parametric rolling can be identified when there are two points for one wave steepness, H/λ. An example of the Poincare mapping is shown in Fig. 19, where the threshold of parametric rolling is $H/\lambda = 0.052$. With increasing wave steepness, symmetry breaking, period doubling, chaos, and capsizing are identified.

The wave statistics for the North Pacific Ocean[8] show that the probability of a wave height of 14.75 m or greater

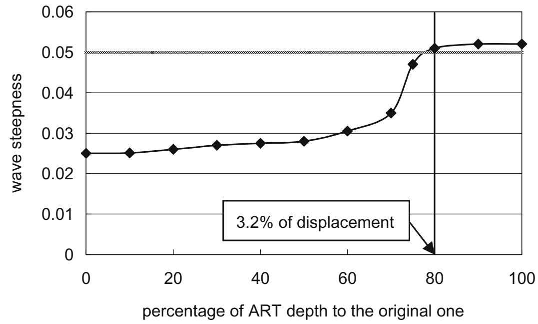

Fig. 18. Relation between ART length and critical wave steepness for parametric rolling for $\lambda/L = 1.0$

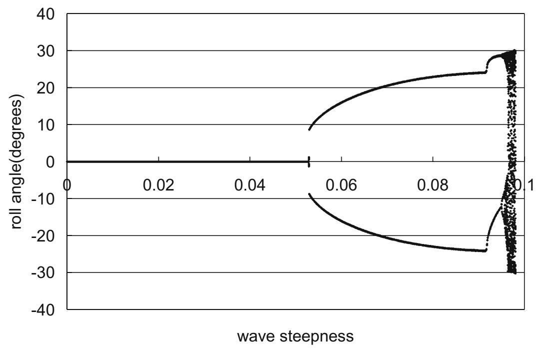

Fig. 19. Roll angle obtained by Poincare mapping with 100% ART water level for $\lambda/L = 1.0$

is 0.0035%. This corresponds to a wave steepness of 0.05 if the wavelength to ship length ratio of 1.0 is assumed for the subject ship. Figure 18 indicates that the anti-rolling tank can prevent parametric rolling in exceptionally high waves if the tank length is larger than 80% of the original designed value. This corresponds to 0.88% of the ship's displacement.

7 Conclusions

The effectiveness of using sponsons or an ART to prevent parametric rolling was assessed experimentally. Numerical simulations were then performed to optimise the size of the ART, based on correlations between the experimental and numerical analysis:

1. By installing a sponson with a width of 11.7% of the ship's breadth, the maximum roll amplitude of parametric rolling decreased from 20° to 15° for a wavelength to ship length ratio of 1.6.
2. With an ART installed, parametric rolling can disappear completely with a wavelength to ship length ratio of 1.6.
3. Numerical simulation of the roll motion with an ART using experimentally obtained damping coefficients can predict parametric rolling with satisfactory accuracy.
4. Optimisation resulted in an ART volume corresponding to 0.88% of the ship's displacement. This ART was shown to prevent parametric rolling for the subject post-Panamax container ship operating in the North Pacific Ocean.

This study demonstrated that both the sponson and the ART are effective in preventing parametric rolling. However, sponsons may not been a practical solution owing to the resulting increased difficulty in berthing and loading. The ART is effective in reducing parametric rolling; however, the total number of onboard containers must be decreased to counter the effects of the tank on displacement and GM. This proposal requires an investigation into the economics of container reduction on earning capacity.

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