Numerical Simulation of Ship Parametric Roll Motion in Regular Waves Using Consistent Strip Theory in Time Domain

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ABSTRACT

In this paper, a numerical method is proposed to simulate the parametric rolling of ship in regular head seas. The numerical method aims at solving the coupled 3 degrees of freedom heave, pitch and roll together for better modelling of this nonlinear motions. The method is developed in time domain based on strip theory. The concept of impulse response function method is used to take into account the memory effect of fluid due to ship motion generated wave. Via theoretical analysis, a consistent way of estimating the impulse response function using strip theory is presented.

In order to model the nonlinear time variation of restoring force coefficients in wave, the Froude-Krylov forces (incident wave forces) and hydrostatic force are evaluated on the instantaneously wetted surface of the ship. Based on the developed method, the parametrically excited roll motions of C11 containership is simulated and the numerical results are compared with model tests.

Keywords: *Parametric rolling of ship, numerical model, nonlinear ship motions, impulse response function method*

1. INTRODUCTION

In a seaway the parametrically excited roll motion of a ship unexpectedly generated in either following or head sea conditions is quite a dangerous phenomenon due to its occurrence with large rolling amplitudes. Therefore, the quantitative prediction of the parametric roll phenomenon are absolutely essential to ensure the safety of life and property on ships. Authoritative organizations of the maritime industry correspondingly published prediction guidelines (ABS, 2004, ITTC, 2005). The vulnerability criteria on parametric rolling are also under development by the International Maritime Organization (IMO) in the second intact stability criteria.

Parametric rolling in head seas as one of transverse stability problems resulting from time-varying changes in the underwater hull geometry is a nonlinear phenomenon with dynamic pitch and heave motions, which make it difficult to accurately predict parametric rolling in head seas. Before several accidents with ships operating in head seas (France et al., 2003, Hua et al.,2006), parametric rolling is largely handled in the cases of following waves (Kerwin, 1955) or beam waves (Blocki, 1980). In case of following waves the encounter frequency is much lower than the natural frequency of heave and pitch, so that coupling with heave and pitch is not important. As for head seas, however, prediction of parametric rolling is not so easy because parametric roll in head seas is more likely influenced by and coupled with heave and pitch motions, which are typically more pronounced in head waves (Shin et al., 2004). Effect of dynamic heave and pitch motions on parametric rolling was investigated so far by many researchers and is well established that restoring arm variation in head waves depends on dynamic heave and pitch (Taguchi et al., 2006). Nevertheless, the effect of coupling from roll into heave and pitch on parametric rolling in regular head seas is not significant in case the wavelength is equal to the ship length (J. Lu et al., 2012). Naoya Umeda et al. (2003) confirmed that a mathematical model with a roll-restoring moment in waves calculated with the Froude-Krylov assumption could considerably overestimated the danger of capsizing associated with parametric rolling. Neves and Rodriguez (2005) used a two-dimensional analysis for a set of coupled heave, pitch and roll equations of motion with 2nd and 3rd order non-linearities describing the restoring actions. Ahmed et al. (2006, 2008) used a system with 3 degrees of freedom, with the coupled heave and pitch motions providing input to the parametric excitation simulated using a one degree of freedom non-linear roll equation of motion. Levadou and van’t Veer (2006) used coupled non-linear equations of motion in the time domain with 3(heave, roll and pitch) and 5 (sway, heave, roll, pitch and yaw) DOF, where nonlinear excitations are evaluated considering the actual submerged surface whereas diffraction forces are considered linear. Hydrodynamics are calculated in the frequency domain and are incorporated in the time domain by adopting the impulse response functions method. More recently, Ahmed et al. (2010) employed a system with 4 DOF (sway, heave, roll, pitch) to investigate parametric rolling in regular waves. The non-linear incident wave and hydrostatic restoring forces/moments are incorporated considering the instantaneous wetted surface while the hydrodynamic forces and moments, including diffraction, are expressed in terms of convolution integrals based on the mean wetted hull surface. Kim et al. (2010) and Park et al. (2013) also used impulse response function method (IRFM) to predict the parametric roll. Ribeiro e Silva and Guedes Soares (2013) described a time-domain non-linear theory model of ship’s motions in 6 DOF, with the time variations of the restoring force calculated over the instantaneous submerged hull and hydrodynamic effects based on a potential flow strip theory using Frank’s close fit method.

Analysis of parametric roll of container ships in regular head waves has been studied extensively. However, the ships do not encounter regular waves in the ocean. So, it is necessary to study how important parametric roll is in irregular seas. The work conducted by Ribeiro e Silva et al.(2003, 2005, 2013) and Bulian et al.(2006) are examples of investigations in this field. Nonetheless, numerical simulations and experimental measurements in regular waves are a useful way of observing and understanding the physics of the parametric roll phenomenon as well as validating numerical methods. According to past research, it is necessary for parametric roll to occur that four certain conditions need to be satisfied, namely, an encounter frequency equal or close to twice the natural frequency of roll, a wave length of the same order as the ship length, a wave height exceeding a critical level and finally, roll damping to be below a threshold value (France et al., 2003). As well known, non-linear damping tends to increase with roll velocity, thus, it will eventually exceed the damping threshold leading to stabilization of the roll motion and reaching a steady roll amplitude. It is worth noting the fact that rationally accounting for non-potential roll damping is of substantial importance for an accurate simulation of parametric rolling.

When the impulse response function method (IRFM) is used, the coefficients and the IRF in Cummins's equation (Cummins, 1962) must be estimated in advance. Liapis et al. (1986) and King (1987) established the complete time domain framework of ship motion with forward speed by 3D time domain potential flow theory in which the coefficients are directly calculated by 3D boundary element method in time domain. While in time domain strip theory using IRFM, the impulse response function is often transformed from frequency domain hydrodynamic coefficients without any extra modification. This transformation seems already being a common practice. Although during the transformation, there are some different methods in the way to estimate the hydrodynamic damping and radiation restoring forces. It looks that people seldom noticed that there is some theoretical inconsistency during the transformation. The hydrodynamic radiation and damping coefficients in Cummins's equation is theoretically derived using the conception of strip theory by us and some of the modification to restoring radiation coefficients is proposed to ensure the consistent transformation.

In this work, the effect of parametric resonance on a containership sailing in head seas is investigated using a partly non-linear numerical model with 3 DOF (heave, roll and pitch). In this model, the incident wave and hydrostatic restoring forces/moments are assumed non-linear and are evaluated at every time step considering the instantaneous submerged surface while hydrodynamic forces and moments are assumed linear. Radiation forces and moments are expressed in terms of convolution integrals and diffraction forces and moments are calculated in the frequency domain by strip method and then incorporated in the time domain. The requisite impulse response functions are obtained from Fourier transforms performed on hydrodynamic coefficients evaluated from STF method (Salvesen et al., 1970) in frequency domain based on the mean wetted surface. Comparisons between numerical and experimental results demonstrate the usefulness and accuracy as well as some limitations of the method proposed.

2. MATHEMATICAL MODEL OF PARAMETRIC ROLLING SHIP MOTIONS IN WAVES

2.1 Ship Motion Equations

A right-handed inertial coordinate system fixed with respect to the mean position of the ship oxyz is established with z in the vertical upward direction and passing through the centre of gravity of the ship and x directed to the bow. The origin is in the plane of the undisturbed free surface. This coordinate moves with the ship but remains unaffected by its parasitic motions. Parallel with oxyz, the inertial coordinate system cx1y1z1 with origin at center of gravity of the ship can also be formed. In order to express the large amplitude rolling motions, the right-handed body-fixed coordinate system cxbybzb, with origin c at the center of mass of the ship is also formed.

The unrestrained 3 DOF rigid body motions of a vessel with or without advancing speed are considered. The ship motions in time domain is formed as followed:

$$\begin{aligned}(M+\mu_{33})\ddot{\eta}_3+b_{33}\dot{\eta}_3+\int_0^t K_{33}(t-\tau)\dot{\eta}_3(\tau)d\tau+(c_{33}+C_{33})\eta_3\\ +\mu_{35}\ddot{\eta}_5+b_{35}\dot{\eta}_5+\int_0^t K_{35}(t-\tau)\dot{\eta}_5(\tau)d\tau+c_{35}\eta_5\\ =F_3^I+F_3^S+F_3^D-Mg\end{aligned}$$

$$
\begin{aligned}
&(I_{44}+\mu_{44})\ddot{\eta}_4 + b_{44}\dot{\eta}_4 + \int_0^t K_{44}(t-\tau)\dot{\eta}_4(\tau)d\tau + c_{44}\eta_4 \\
&\qquad = F_4^I + F_4^S + F_4^D \\
&\mu_{53}\ddot{\eta}_3 + b_{53}\dot{\eta}_3 + \int_0^t K_{53}(t-\tau)\dot{\eta}_3(\tau)d\tau + c_{53}\eta_3 \\
&\quad + (I_{55}+\mu_{55})\ddot{\eta}_5 + b_{55}\dot{\eta}_5 + \int_0^t K_{55}(t-\tau)\dot{\eta}_5(\tau)d\tau \\
&\qquad + c_{55}\eta_5 = F_5^I + F_5^S + F_5^D \quad (1)
\end{aligned}
$$

Where η_3 , η_4 , η_5 are heave, roll and pitch motion respectively where η_3 is given along cz$_1$, η_4 , η_5 is given along cx$_b$y$_b$z$_b$ coordinate system. *M, I_{44}, I_{55}* are the mass, inertial moment of the ship along the cx$_b$ and cy$_b$ axis. The radiation forces/moments are expressed by convolution integrals, with accounted for the memory effect. Diffraction forces/moments F_3^D , F_4^D , F_5^D are obtained from strip theory. Both radiation and diffraction forces/moments are represented on cx$_1$y$_1$z$_1$ coordinate system.

The incident wave excitations F_3^I , F_4^I , F_5^I and restoring forces/moments F_3^S , F_4^S , F_5^S are referenced to another right-handed body-fixed coordinate system cx$_b$y$_b$z$_b$, with origin c at the center of mass of the ship.

2.2 Radiation Forces and Moments Modelling

According to Cummins's theory, the added mass and damping coefficients is referenced to an equilibrium axis system, Cummins (1962) showed that the linear radiation forces in time domain can be written as followed:

$$
\begin{aligned}
F_{jk}(t) &= -\mu_{jk}\ddot{\eta}_k(t) - b_{jk}\dot{\eta}_k - c_{jk}\eta_k(t) \\
&\quad - \int_0^t K_{jk}(t-\tau)\dot{\eta}_k(\tau)d\tau \quad (2)
\end{aligned}
$$

where, $\eta_k(t)$ represents the oscillation motion in k -mode and the overdot represents the derivative with respect to time. K_{jk} is the impulse response function (IRF) representing the memory effect of fluid. μ_{jk} and b_{jk} are the asymptotic values of the radiation coefficients at high frequency, and c_{jk} is the radiation restoring force coefficient. The IRF K_{jk} can be directly related to the frequency-domain hydrodynamic coefficient:

$$K_{jk}(\tau) = \frac{2}{\pi}\int_0^\infty (B_{jk}(\omega) - b_{jk})\cos\omega\tau d\omega \quad (3a)$$

$$K_{jk}(\tau) = \frac{2}{\pi}\int_0^\infty \left(\omega\mu_{jk} - \omega A_{jk}(\omega) - \frac{1}{\omega}c_{jk}\right)\sin\omega\tau d\omega \quad (3b)$$

where, ω is the encounter frequency of ship in waves.

By Fourier transformation, Eq. (3) can be written as follows:

$$A_{jk} = \mu_{jk} - \frac{1}{\omega^2}c_{jk} - \frac{1}{\omega}\int_0^\infty K_{jk}(\tau)\sin\omega\tau d\tau \quad (4a)$$

$$B_{jk} = b_{jk} + \int_0^\infty K_{jk}(\tau)\cos\omega\tau d\tau \quad (4b)$$

Eq.3 means that the hydrodynamic impulse response function K_{jk} can be expressed using frequency domain hydrodynamic coefficients without solving the problem directly in time domain. Presently strip theory is used to calculate the hydrodynamic coefficients and estimate IRF. However it's known that this theory is not a fully strict theory to solve the hydrodynamics of ship with forward speed in frequency domain. While Eq. 2 is established using strict 3D hydrodynamic theory in time domain. Because of the discrepant mathematical model described in both domains, the inconsistency may occur if the hydrodynamic coefficients obtained by STF are directly used to calculate the IRF based on Eq. (3a) or Eq. (3b).

With the theoretical analysis followed, the inconsistency can be shown and some modifications are derived.

In the following procedure, the pitch added mass A_{55} and damping B_{55} are taken as example to show the modification. According to STF method, the hydrodynamic coefficients of the ship can be written as follows:

$$A_{55}(\omega) = A_{55}^{0}(\omega) + \frac{u^2}{\omega^2} A_{33}^{0} - \frac{u}{\omega^2} x_A^2 b_{33}^{A}(\omega) + \frac{u^2}{\omega^2} x_A a_{33}^{A}(\omega) \tag{5a}$$

$$B_{55}(\omega) = B_{55}^{0}(\omega) + \frac{u^2}{\omega^2} B_{33}^{0} + u x_A^2 a_{33}^{A}(\omega) + \frac{u^2}{\omega^2} x_A b_{33}^{A}(\omega) \tag{5b}$$

where, A_{55}^{0} and B_{55}^{0} represent added mass and damping coefficients at zero speed, a_{33}^{A} and b_{33}^{A} are stern sectional added mass and damping coefficient, respectively. x_A is the longitudinal distance between stern section and the gravity center of the ship. According to (3a) and (4a):

$$K_{55}(\tau) = \frac{2}{\pi}\int_0^{\infty} (B_{55}(\omega) - b_{55}) \cos \omega\tau d\omega \tag{6a}$$

$$\mathrm{A}_{55} = \mu_{55} - \frac{1}{\omega^2} c_{55} - \frac{1}{\omega}\int_0^{\infty} K_{55}(\tau) \sin \omega\tau d\tau \tag{6b}$$

Substituting (6a) into the third term in the right hand side of (6b) leads to the following equation which is not identical to equation (5a) excluding the additional modification term c_{55plus}.

$$\mathrm{A}_{55} = \mu_{55} - \frac{1}{\omega^2}(c_{55} + c_{55plus}) - \frac{1}{\omega}\int_0^{\infty} K_{55}(\tau) \sin \omega\tau d\tau \tag{7a}$$

$$\mathrm{c}_{55plus} = -u^2 \frac{2}{\pi}\int_0^{\infty} \frac{B_{33}^{0} + x_A b_{33}^{A}}{\omega_1^2} d\omega_1 - u x_A^2 \frac{2}{\pi}\int_0^{\infty} (a_{33}^{A}(\omega) - \mu_{33}^{A}) d\omega_1 \tag{7b}$$

From the above, we can see that the direct transformation from strip theory to get IRF will cause the inconsistency between hydrodynamics in time domain and frequency domain. The modification to the hydrodynamic coefficients like radiation restoring coefficients c_{55plus} is necessary to assure the transformation consistent. The numerical results to be shown in section 4 will demonstrate the necessity of the modification.

2.3 Diffraction Forces Modelling

Similarly, the diffraction forces/moments contribution can also be represented using convolution integrals (King, 1987, Ahmed et al. 2010), which is what we will study in next step. In the present method, the strip theory in frequency-domain is employed to calculate the diffraction force directly. The diffraction forces/moment can be expressed in time-domain as followed:

$$F_j^D(t) = \zeta_a F_{ja}^D \cos(\omega_e t + \varphi_j) \qquad j = 3,4,5 \tag{8}$$

Where ω_e is the encounter frequency of ship in waves. F_{ja}^D, φ_j are amplitude and phase angle of diffraction force transfer function using strip theory, ζ_a is the amplitude of incident regular wave.

2.4 F-K and hydrostatic restoring forces modelling

In order to capture the ship rolling restoring moment variation in wave, the main cause for parametric rolling, the restoring force/moment should be accurately modelled accounting for the exact ship geometry and the position on waves at each time step. In the method presented here, the non-linear incident wave excitation is also incorporated. Together with the corresponding weight contributions, the fluid loads $F_j^I + F_j^S$ from incident wave excitation and hydrostatic restoring force are determined by integration of the incident wave pressure and hydrostatic pressure over the actual submerged part of the hull as shown in Fig. 1.

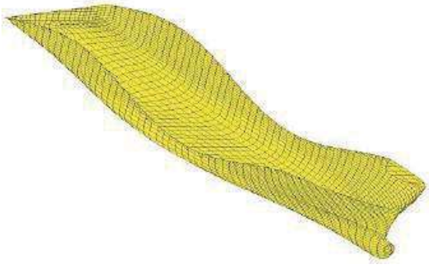

Fig. 1 The instantaneous wetted ship surface under incident wave profile

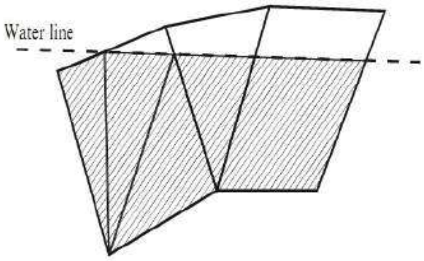

Fig. 2 panels subdivision across the incident wave free surface

The entire surface of the ship hull (up to deck line) is discretised with quadrilateral or triangular panels. At each time step, panels which are above the instantaneous incident wave free surface are directly ignored while panels below the instantaneous free surface are accounted. In particular, panels which are cross the free surface are subdivided and the smaller panels are newly formed, as shown in figure 2. The pressure acting on each panel is assumed uniform and equal to that acting at the centroid of the panel. At each time step, the toll ship rolling moment is given by summing up contributions of all the accounted panels.

2.5 Ship roll damping modelling

In general, ships rolling on the free surface of the sea are subjected to the damping of the water where the viscous effect contributes quite large amount and can't be calculated using traditional potential flow theory. The most accurate way to account for the damping moment is to conduct experiments on models or actual ships. In this study, a series of free-decay experiment with different advancing speed are conducted on a scaled model of C11 class containership.

In order to confine the case to the problem of non-linear roll damping, the following roll equation are considered, where the original damping term is expressed as a series expansion of $\dot{\eta}_4$:

$$(I_{44}+\mu_{44})\ddot{\eta}_4 + b_{44}\dot{\eta}_4 + b_{441}\dot{\eta}_4 + b_{442}\dot{\eta}_4^3 + \int_0^t K_{44}(t-\tau)\dot{\eta}_4(\tau)d\tau + c_{44}\eta_4 = F_4^I + F_4^S + F_4^D \quad (9)$$

where b_{441} is the linear damping term, and b_{442} is the cubic damping term. The terms b_{441} and b_{442} can be determined by analyzing the free-decay rolling experimental data.

3. THE MODEL TEST ABOUT THE PARAMETRIC ROLLING FOR C11 CONTAINERSHIP

The free running experiment with a 1/65.5 scaled model of the post Panamax C11 class containership in regular waves is conducted at the seakeeping basin of China Science Research Center in China, in which the ship model is propelled by one propeller whose revolution is controlled to keep the same mean speed with the tow carriage (J. LU, 2012). The principal particulars and the line plan of the C11 class containership are shown in Table 1 and Fig. 3.

Table 1 Main particulars of C11 class containership

Principal particular	Value
Length between perpendiculars (L_{pp})	262.0 m
Breadth (B)	40.0 m
Mean draught (T)	11.5 m
Block coefficient (C_b)	0.560
Pitch radius of gyration (κ_{yy})	$0.24L_{pp}$
Longitudinal position of center of gravity from amidship (x_{CG})	5.483 m aft

Transverse metacentric height, still water (GM)	1.952 m
Natural roll period (T_φ)	24.20 s

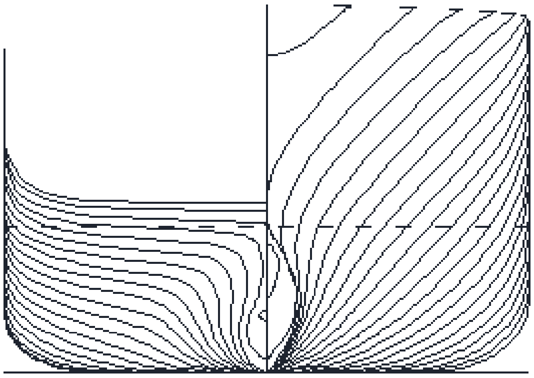

Fig.3. Lines plan for the C11 class containership

The test carried out covering a range of Froude numbers of 0.0, 0.05, 0.1, 0.15 and a range of wave steepness varying from 0.01 to 0.04. And the wavelength is equal to ship length between perpendiculars. Roll damping is determined directly from free roll decay tests at different speed based on extinction curve method. For example, the time history of a free-decay test with Froude number of 0.1 is illustrated in Fig. 4, imposing the largest heeling angle of 19.25°. Then the extinction curve obtained by regressive analysis and demonstrated in Fig. 5 can be calculated as follow:

$$\Delta\eta_4 = a\eta_{4m} + b\eta_{4m}^3 \tag{10}$$

where η_{4m} and $\Delta\eta_4$ are mean roll amplitude and roll amplitude decrement per half cycle, respectively.

After obtaining the coefficients a and b, the roll damping then can be calculated. The method is based on the concept that the rate of change of the total energy in roll motion equals to the rate of energy dissipated by the roll damping.

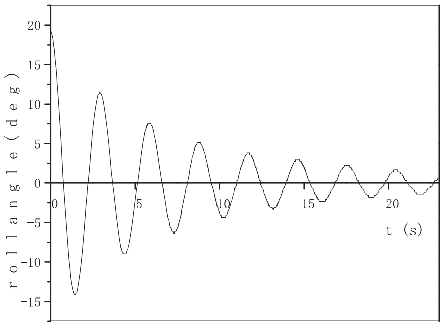

Fig.4. Time history of free roll decay test with Froude number of 0.1

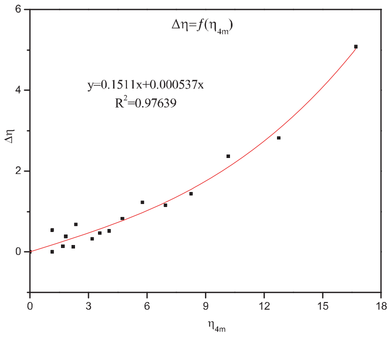

Fig.5. The extinct curve of the corresponding free roll decay test

4. NUMERICAL RESULTS AND DISCUSSIONS

4.1 The numerical results and discussion on the modification of radiation restoring coefficients using IRF method

The comparison of linear hydrodynamics-radiation pitch moment with or without considering the term $c_{55\text{plus}}$ -for C11 containership using Eq. 2 and numerical result using strip theory in frequency domain is illustrated in Fig. 6. In the plot, the results are obtained assumed that the ship is performing harmonic pitch motion with unit amplitude. Obviously, the result from "new transformation" considering the term $c_{55\text{plus}}$

keeps highly consistence with that from STF method.

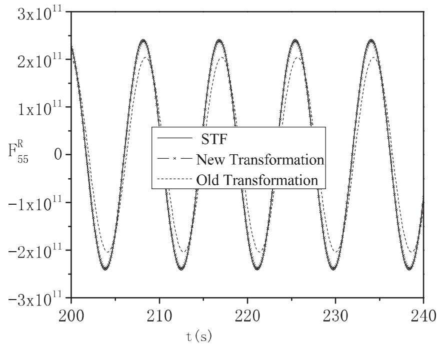

Fig.6 The comparison of radiation pitch moment between strip theory and time domain hydrodynamics using IRF

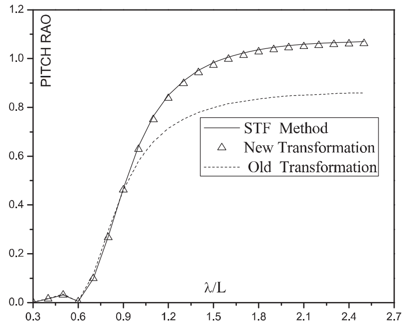

Fig.7 The comparison of pitch motion between strip theory and time domain solution using IRF

To further show the influence of the modification to hydrodynamic coefficients like term $c_{55\text{plus}}$ using IRF method, The comparison of linear pitch motion- between time domain calculation and strip theory results in frequency domain are demonstrated in Fig. 7. It is evident that the present method can provide consistent results with those from original strip theory.

4.2 The numerical simulation of parametric rolling and compared with model test using 3 DOF coupled method in time domain

Based on the numerical model for parametric rolling prediction, the time-domain simulation of vessel's motions is carried out using fourth order Runge-Kutta method. As mentioned before, only three degrees of freedoms are considered, i.e., heave, roll, pitch.

In table 2, Experimental and numerical results for C11 class containership are presented. The table provides the final steady roll amplitudes comparisons between numerical predictions and experimental data. From the comparison, it's seen that the numerical code generally presents quite well predictions on the steady amplitude of parametric rolling. While it can also be observed that the numerical code fails to predict properly in four cases where three of them fail to predict its occurence and one of them overestimated the steady magnitude. From the discussion by Belenky et. al. (2011) about the influence of roll damping on parametric rolling, it is known that the linear damping will make the instability zone narrower and increase the threshold value of minimum GM variation. Therefore the possible reason of numerical code unable to predict the occurrence of parametric roll is related to damping. The numerical damping used in simulation is a little larger and consequently move the system out of the instability region. For the case Test No. 1 where the numerical code overestimate the experiment value, the possible reason is not clearly yet.

Table 2. Experimental and numerical results for the C11 class containership

Test No.	Fr. #	Wave steepness	Experimental Roll Amp.(deg.)	Numerical Roll Amp.(deg.)
1	0.0	0.01	8.12	30.65
2		0.02	24.77	33.46
3		0.03	28.61	33.91

4		0.04	30.23	34.52
5	0.05	0.01	17.77	0.0
6		0.02	30.6	37.15
7		0.03	34.7	42.87
8		0.04	39.97	44.69
9	0.10	0.01	0.0	0.0
10		0.02	21.16	0.0
11		0.03	31.07	37.1
12		0.04	34.43	48.33
13	0.15	0.01	0.0	0.0
14		0.02	0.0	0.0
15		0.03	21.89	0.0
16		0.04	28.13	36.89

The following Fig. 8 presents the comparison of time history between numerical code and model test. The model test case is referred to Test No.11 in Tab. 2. where the Froude number is 0.1, the wave height is H_W=7.86 m and incident wave period is 12.95s.

As we can see, the parametric roll stabilizes at a roll angle of about 37 degrees, which is close to the experimental result of 31.07 degrees. The successful prediction justifies the usefulness and accuracy of the presented method. The associated heave acceleration and pitch motions are also illustrated. In term of numerical predictions for heave and pitch motions itself, it's seen that there is a increase in heave and a very slight decrease in pitch motions accompanied with parametric rolling compared with those when ship roll motions is not excited. These phenomena should be the influence of non-linearity from fluid loads and coupling between heave-roll-pitch.

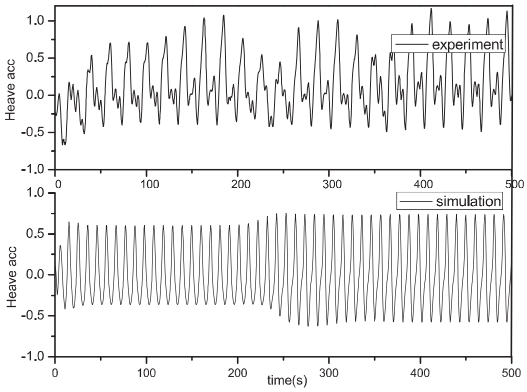

Fig. 8a Time history of heave acceleration

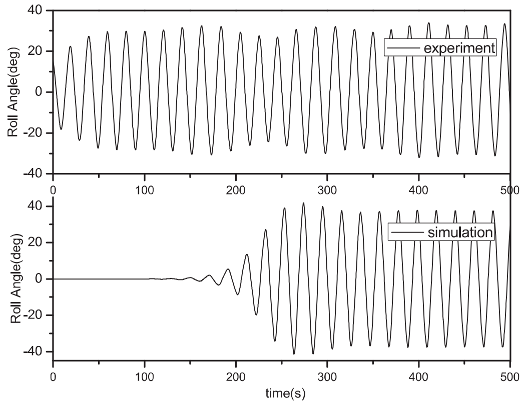

Fig. 8b Time history of roll angle

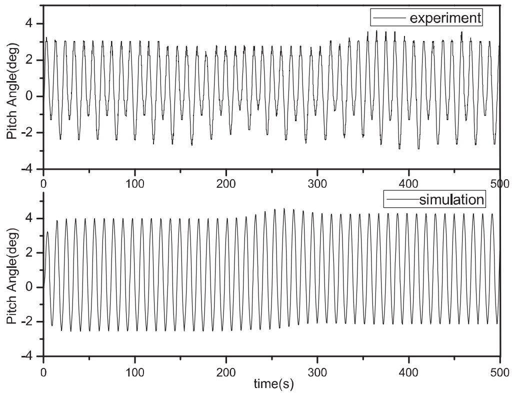

Fig. 8c Time history of pitch angle

Fig. 8. Time history comparison for test No. 11 obtained from numerical simulations and experimental measurements

5. CONCLUSION

In this paper, a partly non-linear time-domain numerical model is presented and utilized to simulate parametric excited rolling resonance in regular head waves. In the present numerical model, the impulse response function method is used to model the time domain radiation forces of ship motions. The impulse response function is obtained from strip theory. Via theoretical analysis, consistent transformation from frequency domain to time domain has been performed. Results obtained for C11 class containership demonstrate that the method succeeds in obtaining steady roll angles of parametric roll that mostly compares reasonably well with experimental data. In addition, it should be noted that the presented model undesirably fails to predict the occurrence of parametric ship rolling under some cases. The possible reason is due to the numerical modelling of rolling damping which will influence the occurrence of parametric rolling. Further developments needed to improve the capability of the presented method will include: considering the hydrodynamic coupling effects from heave and pitch to rolling and vice versa, the numerical modelling of parametric rolling in irregular wave.

6. ACKNOWLEDGEMENT

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7. REFERENCES

Ahmed, T.M., Ballard, E.J., Hudson, D.A., and Temarel, P., 2006, “Prediction of parametric roll resonance in longitudinal regular waves using a non-linear method”, Proceedings of the Ninth International Conference on Stability of Ships and Ocean Vehicles STAB’06, vol. 1, Rio de Janeiro, Brasil, pp.89–97.

Ahmed, T.M., Ballard, E.J., Hudson, D.A., and Temarel, P., 2008, “A non-linear numerical method for the simulation of parametric roll resonance in regular waves”, Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering OMAE 2008, Estoril, Portugal.

Ahmed T M, Hudson D A, Temarel P. 2010, “An investigation into parametric roll resonance in regular waves using a partly non-linear numerical model”, Ocean Engineering, 37(14): 1307-1320

Bulian, G. Francescutto, A.,2006, “On the effect of stochastic variations of restoring moment in long-crested irregular longitudinal seas”, Proceedings of the Ninth International Conference on Stability of Ships and Ocean Vehicles (STAB’06), vol. 1, pp. 131–146.

Blocki W., 1980,“Ship Safety in Connection with Parametric Resonance of the Roll”, International Shipbuilding Progress, 27:36-53.

Cummins, W. E., 1962, “The impulse response function and ship motions”, DTMB-1661. David Taylor Model Basin Washington DC.

France, W.N., Levadou, M., Treakle, T.W., Paulling, J.R., Michel, R.K. and Moore, C. ,2003, " An investigation of head-sea parametric rolling and its influence on container lashing systems", Marine Technology, Vol. 40, pp. 1-19

"Guide for the assessment of parametric roll resonance in the design of container carriers", 2004, American Bureau of Shipping, Houston, TX. USA.

Hua, J., Palmquist, M. and Lindgren, G.,2006, "An analysis of the parametric roll events measured onboard the PCTC Aida", Proc. STAB 2006, pp. 109-118

Kerwin J.E., 1955, "Note on Rolling in Longitudinal Waves",International Shipbuilding Progress, 2(16): 597-614.

Kim, T.Y. and Kim, Y., 2010, "multi-level approach of parametric roll analysis", The 7th International Workshop on Ship Hydrodynamics. ITTC Workshop on Seakeeping, Seoul, Korea, Oct. 19-21

King, B., 1987, "Time-domain analysis of wave exciting forces on ships and bodies.", Ph.D. Thesis, The University of Michigan.

Liapis, S. J., 1986, "Time-Domain Analysis of Ship Motions", Ph.D. Thesis, University of Michigan.

Levadou, M. van 't Veer, R.,2006, "Parametric roll and ship design". Proceedings of the Ninth International Conference on Stability of Ships and Ocean Vehicles (STAB'06), vol. 1, pp. 191–206.

LU J., GU M., Umeda N., 2012, "Numerical Approaches on Parametric Rolling in Head Seas", 10th International Conference on Hydrodynamics, St. Petersburg, Russia.October 1-4, 2012.

Neves, M., Rodriguez, C., 2005. "A non-linear mathematical model of higher order for strong parametric resonance of the roll motion of ships in waves", Marine Systems & Ocean Technology 1 (2), 69–81 .

Park, D. M., Kim, Y., Song, K. H., 2013. "Sensitivity in numerical analysis of parametric roll", Ocean Engineering, 67, 1-12.

Ribeiro e Silva S, Guedes Soares C. 2013, "Prediction of parametric rolling in waves with a time domain non-linear strip theory model", Ocean Engineering, 72: 453-469.

Ribeiro e Silva, S., Santos, T. Guedes Soares, C. 2003, "Time domain simulation of a fully coupled parametrically excited roll response in regular and irregular head seas", Proceedings of the Eighth International Conference of Ships and Ocean Vehicles (STAB'03), Madrid, Spain, pp. 349–360.

Ribeiro e Silva, S., Santos, T.A., Guedes Soares, C.,2005, "Parametrically excited roll in regular and irregular head seas", International Shipbuilding Progress 52, 29–56.

Salvesen, N., Tuck, E. O., Faltinsen, O. M.. "Ship motions and sea loads", SNAME, 1970

Shin, Y.S., Belenky, V.L., Paulling, J.R., Weems, K.M., Lin, W.M., 2004. "Criteria for parametric roll of large containerships in longitudinal seas". Transactions of SNAME 112, 14–47.

"Testing and Extrapolation Methods Loads and Responses, Stability Predicting the Occurrence and Magnitude of Parametric Rolling", Revision 00, 2005, ITTC-international towing tank conference 7.5-02-07-04.3,

Taguchi H., Ishida S., Sawada H. and Minami, M,2006, "Model Experiment on Parametric Rolling of a Post-Panamax Containership in Head Waves",Proceedings of the 9th

International Conference of Ships and Ocean Vehicles, COPPE Univ Fed Rio de Janeiro, 147-156

Umeda N, Hashimoto H, Vassalos D, et al ,2003, "Nonliner dynamics on parametric roll resonance with realistic numerical modelling", Proceedings of the 8th International Conference on Stability of Ships and Ocean Vehicles, Madrid, pp 281–290.

Belenky V., Bassler C.C., Spyrou K.J., 2011, "Development of Second Generation Intact Stability Criteria", NSWCCD-50-TR-2011/065, Hydromechanics Department Report, Naval Surface Warfare Center, Carderock Division.