The 14th International Ship Stability Workshop (ISSW), 29 September-1 October 2014, Kuala Lumpur, Malaysia

Experimental and Numerical Study on Roll Restoring Variation Using the C11 Containership

Min Gu, Jiang Lu, Tianhua Wang

China Ship Scientific Research Center, Wuxi, China

Abstract: The vulnerability criteria and direct stability assessment on parametric rolling and pure loss of stability are now under development by the International Maritime Organization (IMO) in the second generation intact stability criteria. Roll restoring variation is a key factor for both criteria and model experiments and simulations are conducted to study the roll restoring variation in waves. Firstly, captive model experiments in which heave and pitch motions are free and other motions are restrained with a constant heeling angle are conducted to measure roll restoring variation in following and head seas for parametric rolling and pure loss of stability. Secondly, the roll restoring variations of Froude-Krylov calculation by a static balance method and a strip method of heave and pitch motions are carried out in following and head seas,and the dynamic effect of radiation and diffraction force on restoring variation are also calculated. Finally,the rule of roll restoring variation in following and head seas is pointed out by experiments and simulations and the numerical methods are also validated through the comparisons between the model experiments and the simulations using the C11 containership for the vulnerability criteria and direct stability assessment on parametric rolling and pure loss of stability.

Key words: Roll restoring variation; pure loss of stability; parametric rolling; vulnerability criteria; direct stability assessment; IMO second generation intact stability criteria

1. Introduction

The vulnerability criteria and direct stability assessment on parametric rolling and pure loss of stability are now under development by the International Maritime Organization (IMO) in the second generation intact stability criteria [1]. The roll restoring variation in waves is allowed to use the Froude-Krylov assumption with static balance in heave and pitch in the vulnerability criteria of parametric rolling and pure loss of stability [2]. The roll restoring variation is a key factor for both criteria of parametric rolling and pure loss of stability . Therefore, it is necessary to conduct model experiments and simulations to validate the reliable of the method proposed in the vulnerability criteria for calculating roll restoring variation in waves and give out reasonable methods for direct stability assessment on parametric rolling and pure loss of stability.

Parametric rolling is induced by restoring arm variation in time. In case of following waves, the encounter frequency is much lower than the natural frequencies of heave and pitch motions so that coupling with heave and pitch is not significant. In addition, added resistance in following waves is generally small. Thus several successful predictions of parametric rolling in following waves were reported [3]. In case of head seas, however, prediction of parametric rolling is not so easy because coupling with heave and pitch is significant and added resistance cannot be simply ignored. Effect of dynamic heave and pitch motions on parametric rolling was investigated so far by many researchers and is well established: restoring arm variation in head seas depends on dynamic heave and pitch motions [4].

*** Corresponding author:** Jiang Lu, Dr., research fields: ship stability in waves and ship hydrodynamics. E-mail: lujiang1980@aliyun.com

Since in a ship seakeeping theory, the effect of roll on heave and pitch motions is small, coupling from heave and pitch to parametric rolling is taken into account but not vice versa in published papers, and here the roll restoring variation consists of two components. One is nonlinear Froude-Krylov component which is calculated by integrating the wave pressure up to the surface of the wave with the heave and pitch motions obtained by a strip theory. The other is the hydrodynamics effect which consists of radiation and diffraction components acting on a heeled hull as linear components with respect to wave height [5, 6, 7, 8, 9].

For validating the method proposed in the vulnerability criteria of parametric rolling and pure loss of stability and providing a reliable numerical method of calculating the roll restoring variation to accurately predict parametric rolling and pure loss of stability on a wave crest, the authors conduct partially restrained experiments with a newly designed equipment to investigate the roll restoring variation of a post Panamax C11 class containership which is provided by an IMO's intersetional corresponding group as one of standard ship for developing second generation intact stability criteria.

2. Mathematical Model

The mathematical model for the roll restoring variation of Froude-Krylov component in regular waves is expressed as (1), (2).

$$W \cdot GZ_{FK} = \rho g \int_L y'_{B(x)} \cdot A(x) dx + \rho g \sin\chi \cdot \int_L z'_{B(x)} \cdot F(x) \cdot A(x) \cdot \sin(\zeta_G + x \cdot \cos\chi) d\,x \tag{1}$$

$$F(x) = \varsigma_a k \frac{\sin(k \frac{B(x)}{2} \sin\chi)}{k \frac{B(x)}{2} \sin\chi} e^{-kd(x)} \tag{2}$$

where, *W*: ship weight, GZ_{FK}: Froude-Krylov components of the restoring variation, *L*: ship length, *A(x)*: the submerged area of local section of the ship; $y'_{B(x)}$: the transverse position of buoyancy centre of local section, $z'_{B(x)}$: the vertical position of buoyancy centre of local section, ξ_G: the longitudinal position of a ship's centre of gravity from a wave trough, *x*: the longitudinal position from the ship's centre of gravity. Furthermore, ζa :wave amplitude, *k*:wave number, χ : heading angle, *B(X):*breadth of *x* section, *d(x)*draught of x section, ρ: water density and *g*: gravitational acceleration.

When a ship has a heeling angle, static balance in heave and pitch should be satisfied, and heave and pitch could be calculate by follow static balance methods (3),(4).

$$W - \rho g \int_L A(x) dx + \rho g \cdot \int_L F(x) \cdot A(x) \cdot \cos(\zeta_G + x \cdot \cos\chi) d\,x = 0 \tag{3}$$

$$\rho g \int_L x A(x) dx + \rho g \cdot \int_L x F(x) \cdot A(x) \cdot \cos(\zeta_G + x \cdot \cos\chi) d\,x = 0 \tag{4}$$

A strip method is also used to calculated heave and pitch motions by follow equations (5), (6) as another method.

$$(M + A_{33})\ddot{\varsigma} + B_{33}\dot{\varsigma} + C_{33}\varsigma + A_{35}\ddot{\theta} + B_{35}\dot{\theta} + C_{35}\theta = F_Z \tag{5}$$

$$A_{53}\ddot{\varsigma} + B_{53}\dot{\varsigma} + C_{53}\varsigma + (I_{yy} + A_{55})\ddot{\theta} + B_{55}\dot{\theta} + C_{55}\theta = M_\theta \tag{6}$$

The radiation and diffraction components of the restoring variation are calculated as follows.

$$GZ_{R\&D} = -M_X / W \tag{7}$$

$$M_X = K - (KG - D)Y \tag{8}$$

$$M_X(X_G, t) = M_{Xa} \cos(\omega t - kX_G \cos\chi + \delta_{MX}) \tag{9}$$

$$Y = F_Y - (A_{23}\ddot{\varsigma} + B_{23}\dot{\varsigma} + C_{23}\varsigma + A_{25}\ddot{\theta} + B_{25}\dot{\theta} + C_{25}\theta) \tag{10}$$

$$K = M_\phi - (A_{43}\ddot{\varsigma} + B_{43}\dot{\varsigma} + C_{43}\varsigma + A_{45}\ddot{\theta} + B_{45}\dot{\theta} + C_{45}\theta) \tag{11}$$

where, *KG*: the distance from the keel to the gravity of ship; *D*: draft; M_{Xa}: amplitude of the restoring variation, δ_{MX}: the initial phase of the restoring variation.

Formulae of the wave exciting force, F_Y, and moment M_φ are available in the reference [10] as well as those for coupling coefficients in reference [11].

3. Experiments

The partially restrained experiment with a 1/65.5 scaled model of the post Panamax C11 class containership were conducted at the seakeeping basin (length: 69m, breadth: 46m, height: 4m) of China Ship Scientific Research Center, which is equipped a flap wave maker at the two adjacent sides of the basin. The ship model was towed by the towing carriage in regular head seas and newly designed equipment was used to measure roll restoring variation with pitch and heave motions free. Roll and pitch motions are measure by potentiometer sensor. Heave motions are measured by displacement sensor. Roll moments are measured by a sensors based on electromotive strain gauge.

The principal particulars and body plan of the C11 class containership are shown in Table 1 and Fig.1, respectively. The ship model in free running experiment and partially restrained experiment are shown Fig.2 and Fig.3, respectively.

Table 1 Principal particulars of the C11 containership

Items	Ship	Model
Length:L	262.0m	4.000m
Draft:T	11.5m	0.176m
Breadth:B	40.0m	0.611m
Depth:D	24.45m	0.373m
Displ.:W	67508ton	240.2kg
C_B	0.560	0.560
GM	1.928m	0.029m
T_φ	24.68s	3.05s
K_{YY}	0.24L	0.24L

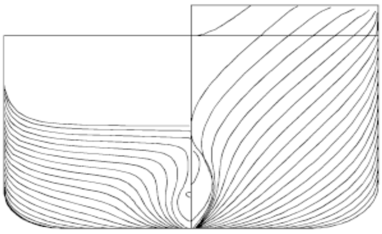


Fig. 1 Lines of C11 containership

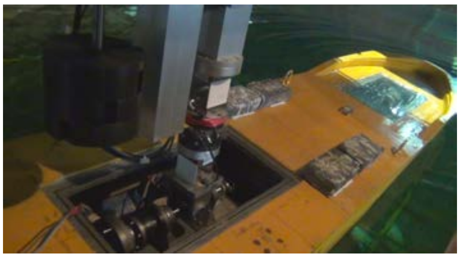
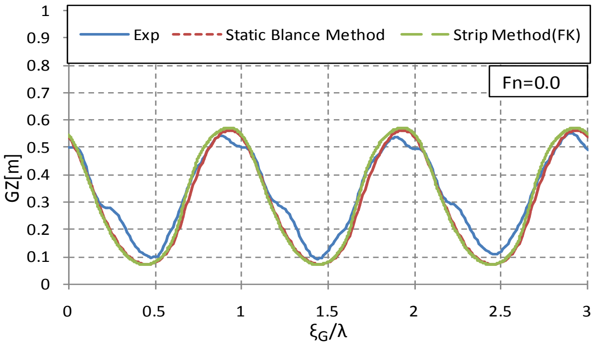
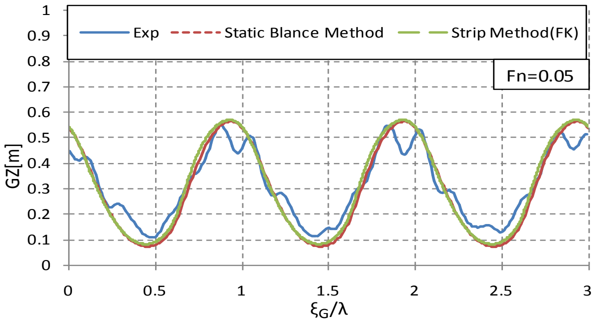


Fig.2 The ship model in partially restrained experiment

4. Results and Discussions





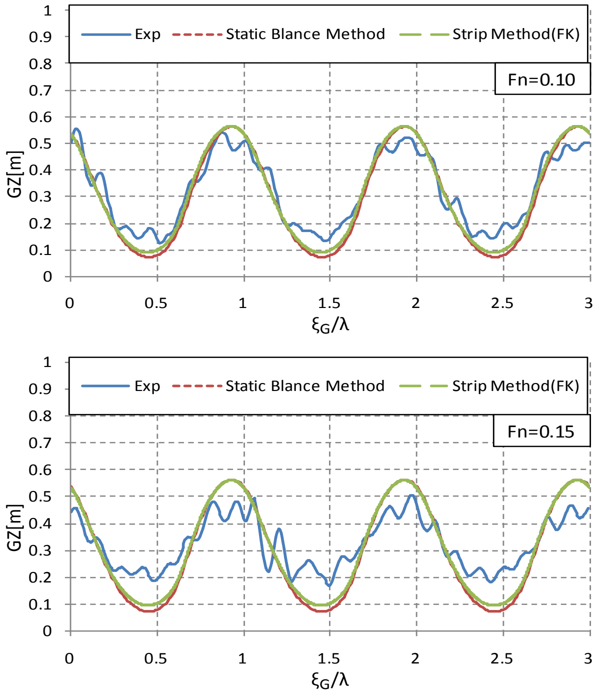
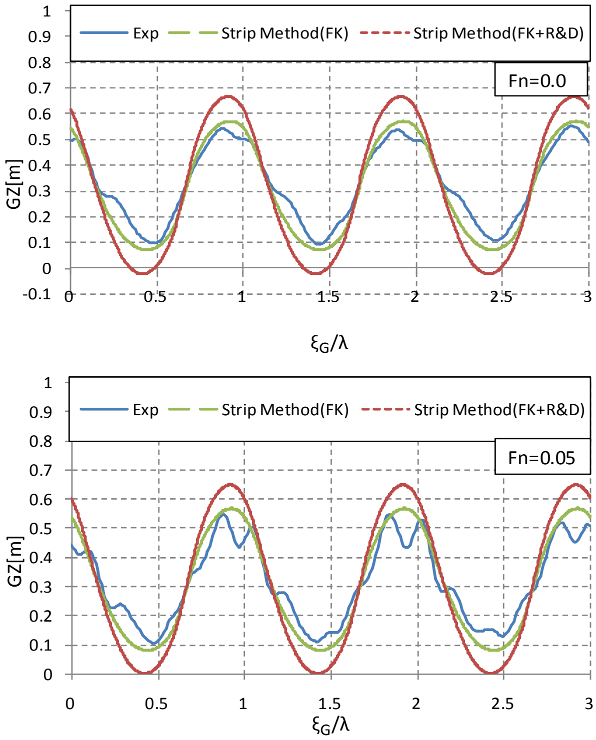


Fig.3 Comparison of roll restoring variation as the function of relative position of ship to wave between the experiment and the Froude-Krylov calculations with λ/L_{pp}=1.0, H/λ=0.02, χ=0^0, Φ =8^0.



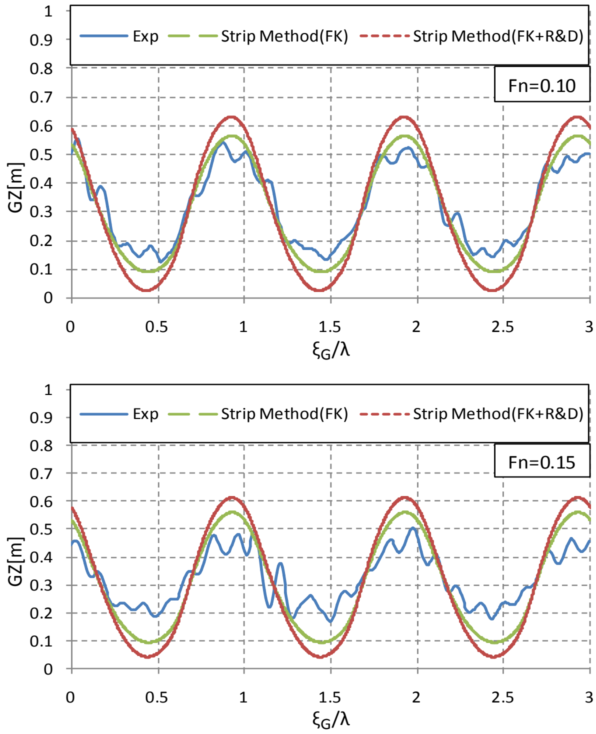
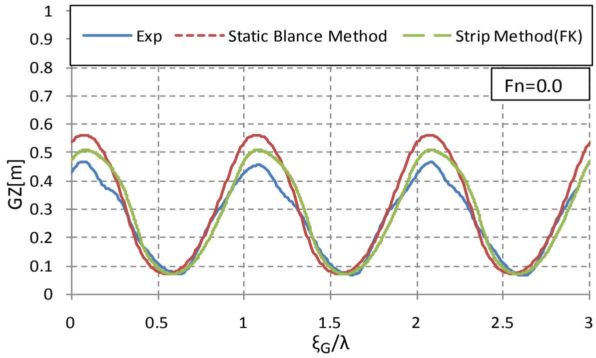


Fig.4 Comparison of roll restoring variation as the function of relative position of ship to wave between the experiment and the calculations with λ/L_{pp}=1.0, H/λ=0.02, χ=0^0, Φ =8^0.



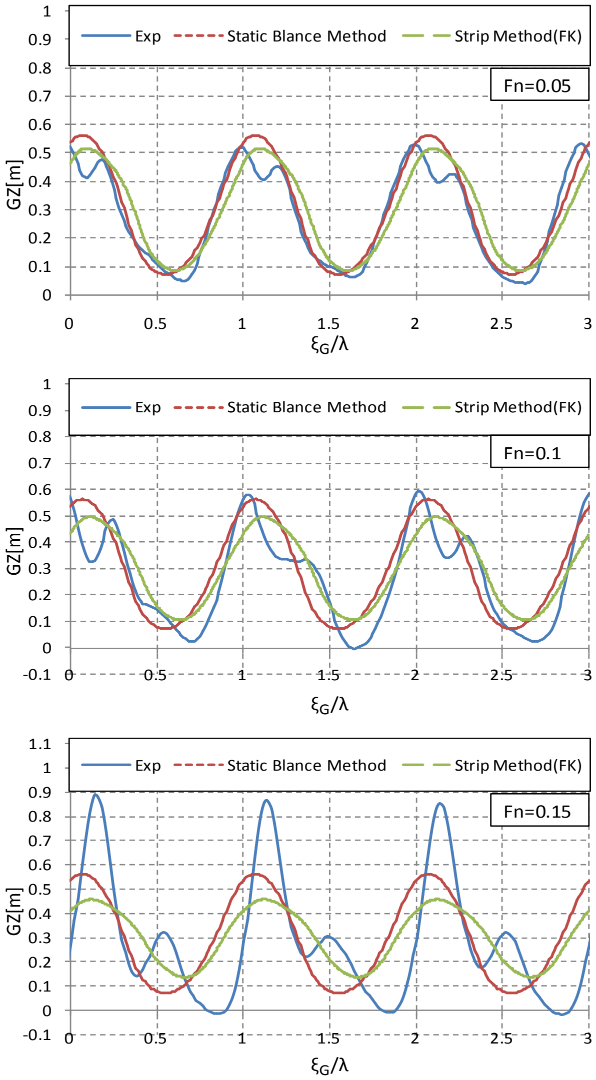
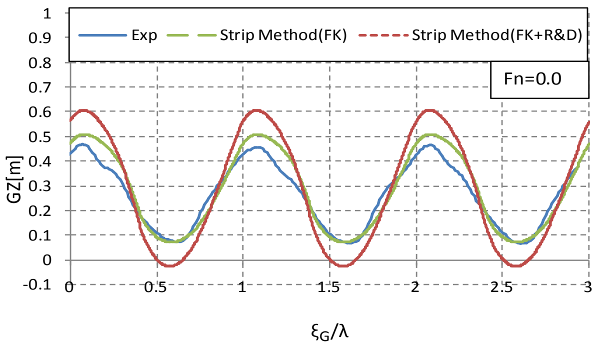


Fig.5 Comparison of roll restoring variation as the function of relative position of ship to wave between the experiment and the Froude-Krylov calculations with λ/L_{pp}=1.0, H/λ=0.02, χ=180^0, Φ =7.3^0.



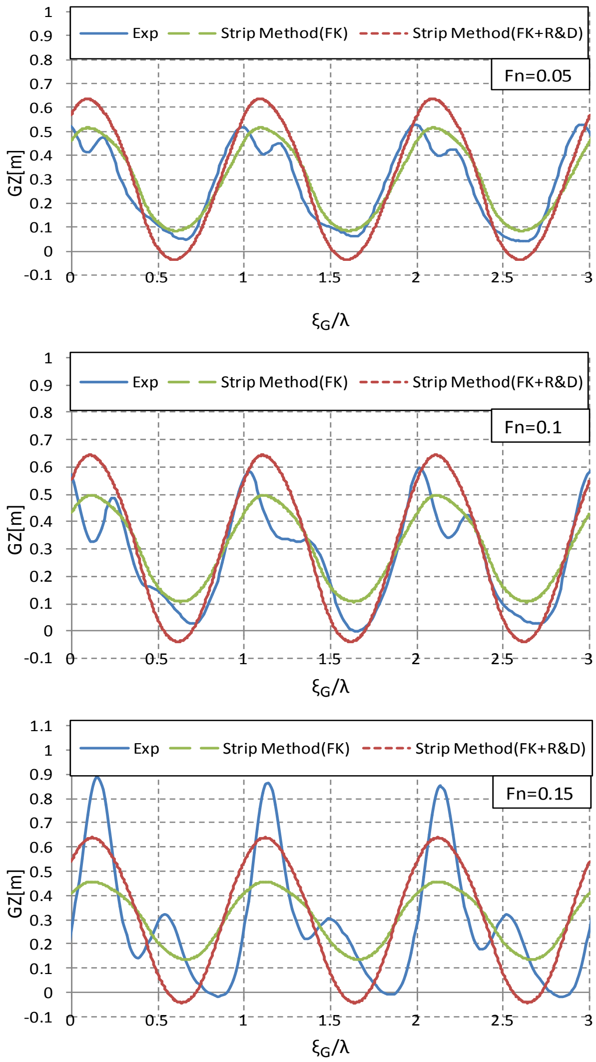


Fig.6 Comparison of roll restoring variation as the function of relative position of ship to wave between the experiment and the calculations with λ/L_{pp}=1.0, H/λ=0.02, χ=180^0, Φ =7.3^0.

The results of experiments indicate the roll restoring variations become small in following seas as ship forward speed increase and they could like first harmonic cosines curve although the signals are affected by the vibration of the carriage as shown in Fig.3. The roll restoring variations of Froude-Krylov calculation by the static balance method and the strip method are near same in following seas and they are also near same with that in experiment at zero ship forward speed while they are small larger than that in experiment as ship forward speed increase as shown by Fig.3. The radiation and diffraction components of the restoring variation are also calculated. The roll restoring variations with he radiation and diffraction component become larger than that with Froude-Krylov on its own and that in experiment as shown by Fig.4. So the roll restoring variations of only Froude-Krylov calculation by static balance method and strip method should be allowed to predict parametric rolling and pure loss of stability in following seas while the roll restoring variations of only Froude-Krylov calculation by static balance method could be more suitable for providing a simple and conservative vulnerability criteria of parametric rolling and pure loss of stability in follow seas.

In case of head seas, prediction of parametric rolling is not so easy because coupling with heave and pitch is significant and heave and pitch motions are also distinct affected by parametric rolling [12, 13].The results of experiments indicate the roll restoring variations become large in head seas as ship forward speed increase and become complicated at a hight ship forward speed as shown in Fig.5. The roll restoring variations of Froude-Krylov calculation by static balance method and strip method are near same with that in experiment at zero ship forward speed while they are smaller than that in experiment as ship forward speed increase as shown by Fig.5. The radiation and diffraction components of the restoring variation are also calculated. The restoring variation with the radiation and diffraction component become larger than that with the Froude-Krylov on its own and also larger than that in experiment except Froude number 0.15 as shown by Fig. 6. This could be the reason why the parametric rolling with Froude-Krylov, radiation and diffraction components is larger than that in experiment while that with the Froude-Krylov on its own is near same with that in experiment[13]. So the dynamic effect of radiation and diffraction force should be taken into account for conservatively predicting parametric rolling in head seas with ship forward speed. However, the roll restoring variations of only Froude-Krylov calculation by static balance method could be also suitable for providing a simple vulnerability criteria of parametric rolling in head seas and keeping consistent with the method used in following seas .

5. Conclusions

As a result of experimental and numerical studies on the roll restoring variations in regular following and head seas, the following remarks and recommendations are noted:

1) The roll restoring variations become small in follow seas and become large in head seas as ship forward speed increase and they could like harmonic cosines curves in following seas while they become complicated in head seas at hight speeds.

2) The roll restoring variations of only Froude-Krylov calculation by the static balance method and the strip method should be allowed to predict parametric rolling and pure loss of stability in following seas, and the static balance method could be more suitable for providing a simple and conservative vulnerability criteria of parametric rolling and pure loss of stability in following seas.

3) The roll restoring variations of dynamic effect of radiation and diffraction force should be taken into account for conservatively predicting parametric rolling in head seas and the roll restoring variations of only Froude-Krylov calculation by the static balance method could be also suitable for providing a simple vulnerability criteria of parametric rolling in head seas and keeping consistent with the method used in following seas .

Acknowledgments

Part of this research was once supported by China Scholarship Council [No.2008606031] for J. Lu's visit to Osaka University. The research is supported by Ministry of Industry and Information Technology of China (No. [2012] 533). The authors sincerely thank the above organizations.

References

[1] IMO SDC 1/WP.5, Development of Second Generation Intact Stability Criteria, Report of the working group. 2014.

[2] IMO SLF55 1/IN.10, Draft Vulnerability Criteria on Parametric Rolling and Pure Loss of Stability with Their Sample Calculation Results, Submitted by Japan. 2010.

[3] A. Munif, N. Umeda, Modeling Extreme Roll Motions and Capsizing of a Moderate-Speed Ship in Astern Waves. Journal of the Society of Naval Architects of Japan, (2000) 187: 405-408.

[4] H. Taguchi, S. Ishida, H. Sawada, M. Minami, Model Experiments of Ship Capsize in Astern Seas. Journal of the Society of Naval Architects of Japan, (1995)177: 207-217.

[5] J. Lu, N. Umeda, K. Ma, Modeling Parametric Rolling in Regular and Irregular Head Seas with Added Resistance Taken into Account. Proceedings of the 5th Asia-Pacific Workshop on Marine Hydrodynamics, Osaka Pref Univ, (2010)93-98.

[6] N. Umeda, H. Hashimoto, F. Stern, S. Nakamura, H. Sadat-Hosseini, A. Matsuda, P. Carrica, Comparison Study on Numerical Prediction Techniques for Parametric Roll. Proceedings 27th Symposium on Naval Hydrodynamics, Seoul Nat Univ, (2008) 5-10.

[7] N. Umeda, A. Francescutto, Performance-Based Ship Operation. Proceedings 2nd International Workshop on Risk-Based Approaches in Maritime Industry, Univ. Strathclyde, (2008)2.2.1-2.2.9.

[8] J. Lu, N. Umeda, K. Ma, Predicting Parametric Rolling in Irregular Head Seas with Added Resistance Taken into Account . J Mar Sci Technol, (2011)16:462-471.

[9] J. Lu, G. Min, N. Umeda, Numerical Approaches on Parametric Rolling in Head Seas. The 10th International Hydrodynamics, Petersburg, Russia, (2012)83-88.

[10] M. Fujino, S. Sakurai, On the Evaluation of Wave Exciting Roll Moment by strip Method, J the Society of Naval Architects of Japan, (1982) 152: 125-137(in Japanese).

[11] M.C. Lee, K.H. Kim, Prediction of Motion of Ships in Damaged Condition in Waves, the 2nd STAB, the Society of Naval Architects of Japan, (1982)13-26.

[12] J. Lu, G. Min, N. Umeda, A Study on the Effect of Parametric Rolling on Heave and Pitch Motions in Head Seas. Proceedings of the 13th International Ship Stability Workshop, Brest, France. (2013)185-191.

[13] J. Lu, G. Min, N. Umeda, Experimental and Numerical Study on Predicting method of Parametric Rolling in Regular Head Seas. Proceedings of the 14th International Ship Stability Workshop, Kuala Lumpur, Malaysia. (2014).