Investigation of the 2nd Generation of Intact Stability Criteria in Parametric Rolling and Pure loss of Stability

Haipeng Liu, *University of Strathclyde,* h.liu@strath.ac.uk

Osman Turan, *University of Strathclyde,* o.turan@strath.ac.uk

Evangelos Boulougouris, *University of Strathclyde,* evangelos.boulougouris@strath.ac.uk

ABSTRACT

The International Maritime Organisation is developing the second generation intact stability criteria which include parametric rolling, pure loss of stability and the other three failure modes. This paper will focus on the application of the draft parametric rolling and pure loss of stability criteria on the well-known post-Panamax C11 class containership and a high speed containership developed in the FASTPOD project. The roll amplitude calculated from the proposed analytical method in level 2 parametric rolling criteria is compared to experiment results. The influence of the main particulars on the check by the criteria is investigated.

Keywords: *parametric rolling, pure loss of stability, new generation intact stability criteria*

1. INTRODUCTION

The phenomenon of parametric rolling has been known to naval architects for more than 50 years (Paulling & Rosenberg, 1959). The continued study from Paulling demonstrated parametric roll from a model test in following waves in San-Francisco Bay (Paulling, et al. 1972, 1975). In October 1998, a post-Panamax, C11 class containership experienced severe parametric rolling in the North Pacific Ocean and it confronted the largest container casualty in history (France, et al., 2003). After this accident, parametric rolling attracted increased attention from researchers, and since then, many more studies in parametric rolling prediction have been carried out.

Since the 1800s, the stability changes in waves compared with calm water is known to naval architects (Pollard & Dudebout, 1892; Krylov, 1958). Until the 1960s, a series of model tests were carried out in order to calculate the change of stability in waves. During the model experiments in San-Francisco Bay, pure loss of stability was identified (Paulling, et al., 1972, 1975).

Due to some similar accidents which occurred in the Pacific Ocean and the Atlantic Ocean, it was realised that the existing Intact Stability Code (IS Code) couldn't provide enough safety. Therefore, the International Maritime Organisation (IMO) initiated the revision of the existing regulatory framework with the development of the second generation intact stability criteria which will hopefully fill this safety gap. The new intact stability criteria include five stability failure modes as listed below (SLF, 2012)

- Dead ship condition in beam seas
- Surf riding and broaching-to
- Parametric rolling
- Pure loss of stability
- Excessive acceleration

After the new criteria were generated, the process of stability check is suggested in figure 1. In each stability failure mode, it is divided into vulnerability layer of level 1 and level 2 and performance-based layer of level 3. With the level increasing, the procedure is more detailed and accurate. The lower the level it is, the more conservative it is. Currently, the IMO finished the simplest level 1 criterion and is developing level 2 criteria. In the following paragraphs a short description of the background and the procedure of vulnerability layer of the criteria will be presented.

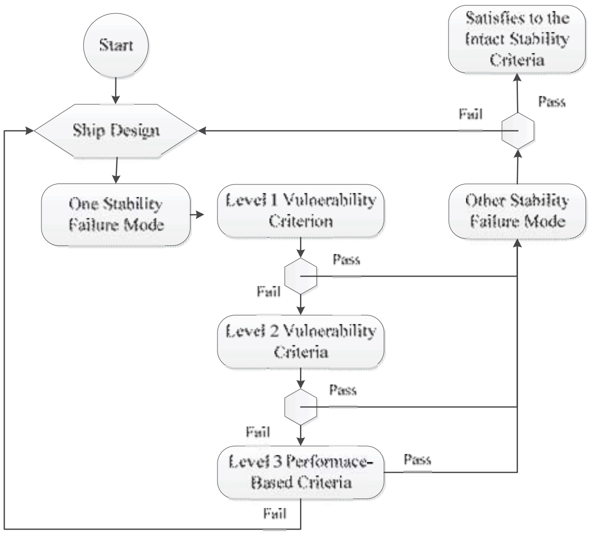

Figure 1 The proposed assessment process for next generation intact stability criteria

- Parametric Rolling

Parametric rolling is the roll amplification which is caused by the periodic change of metacentric height in longitudinal waves under specific conditions (ABS, 2004). The new parametric rolling vulnerability criteria with two levels included are described below.

Level 1 Vulnerability Criterion

As defined by current draft criteria (SDC, 2014), if the ratio of GM variation in reference wave (ΔGM/GM) is larger than the standard R_{PR}, the ship is temporary judged as vulnerable to parametric rolling; otherwise it means the vessel doesn't have any potential danger of parametric rolling. Here GM is the metacentric height of the loading condition in calm water including free surface correction and ΔGM is the change of metacentric height which can be estimated using two different methods. In the first method (Option A), two different drafts are used and Simpson’s rule is applied to calculate the moment of inertia and the average GM variation is achieved. This method is not suitable for a tumblehome hullform but it is applicable to a ship without even keel design (SDC, 2014). In the second method (Option B), ΔGM may be determined as one-half difference between the maximum and minimum GM calculated in sinkage and trim on a series of waves with wave length equals to ship length and the wave height equals to 1/60 of wave length. Both of these two methods are utilised herein.

Level 2 Vulnerability Criteria

Level 2 criteria (SDC, 2014) will check the vessel in the aspects of ship speed, metacentric variation and roll amplitude. If either C_1 or C_2 is larger than safety standard R_{PR0} 0.06, the ship is judged to be in danger of parametric rolling (PR) and needs to be checked in performance-based layer, otherwise it passes the criteria. The aspects of speed and metacentric height variation constitute the first check and the aspect of roll angle computation constitutes the second check.

- First Check

The first check aims to test whether the vessel’s speed is within the vulnerable region for PR and GM variation and satisfies the PR safety requirement. The probability of C_1 in the first check is a sum of the product of C_{1i} and the wave weighting factor W_i. The 16 wave series applied in this check are discretisation of the applied wave spectrum (SDC, 2014). The weighting factor is the occurrence probability among the wave series for each wave case. The wave lengths vary from 22.57m to 63.68m and the wave heights vary from 0.35m to 5.95m. The value for criterion 1 in each case, C_{1i} is 0 if both speed check and GM relevant check satisfy with the specific condition as the vessel is considered not vulnerable to PR; otherwise C_{1i} is 1.

Parametric rolling occurs when the encounter frequency is equal to double the natural roll frequency. The speed corresponds to the resonance speed V_{PRi} which is given by the following Equation 1.

$$V_{PRi} = \left| \frac{2\lambda_i}{T_\phi} \cdot \sqrt{\frac{GM(H_i, \lambda_i)}{GM}} - \sqrt{g \frac{\lambda_i}{2\pi}} \right| \quad [1]$$

For GM relevant conditions for avoiding the PR risk region are that $\Delta GM(H_i, \lambda_i)/GM(H_i, \lambda_i) < R_{PR}$ and $GM(H_i, \lambda_i) > 0$. Here, the average metacentric height corresponding to the loading condition under consideration, $GM(H_i, \lambda_i)$; and the one-half of the difference between the maximum and minimum values of the metacentric height GM in wave, $\Delta GM(H_i, \lambda_i)$; are calculated considering the ship balanced in sinkage and trim in the series of waves characteristic by H_i and λ_i.

If total probability of C_1 is greater or equal to the standard value R_{PR0} of 0.06 the ship is judged as potentially vulnerable and it needs to be checked by the second check; otherwise the vessel is not vulnerable and it passes the evaluation of parametric rolling problem.

- Second Check

When C_1 is not smaller than R_{PR0}, the designer should apply the second check. The ship performance is simulated under NO.34 standard wave cases (IACS, 2001). Each wave case has the corresponding weighting factor W_i, which represents the sample wave's occurrence probability among all the 306 wave cases. According to the criteria, if the vessel in each wave case experiences the roll angle which is larger than 25 degrees, the vessel is judged as vulnerable to parametric rolling and C_{2i} is 1, otherwise is 0. An analytical method based on the simplification of Mathieu's equation is used to predict the roll amplitude as given in equation [2] (CGIS, 2014). GM variation in waves is calculated quasi-statically. Ikeda's simplified method, based on an empirical formula, is used for the damping prediction (Kawahara et.al., 2009). It divides the roll damping into the frictional, the wave, the eddy, the bilge keel and the lift damping components.

$$(I_{xx} + J_{xx}) \cdot \ddot{\phi} + R \cdot (\dot{\phi}) + W \cdot GM \cdot \phi = 0 \quad [2]$$

Where Ixx+Jxx: virtual moment of inertia in roll;

R: nonlinear roll damping;

W: ship weight;

GM: metacentric height

For the second check, if the total probability sum C_2 which is the product of C_{2i} and wave weighting factor W_i, is greater than standard R_{PR0} 0.06, the ship is judged to be vulnerable to parametric rolling and the ship should be checked by level 3; if not, the ship passes the parametric rolling failure mode and it should be checked for the other stability failure modes.

- Pure Loss of Stability

If the stability is reduced for a sufficiently long time, a ship may experience a large roll angle or even capsize, as shown in figure 2 (Belenky, 2008). In the new generated pure loss of stability criteria (SDC, 2014), it mainly concerns the minimum GM value, the vanishing stability and the heel angle under action of specific heeling level. The criteria is proposed to apply to all ships with service speed larger than 0.24.

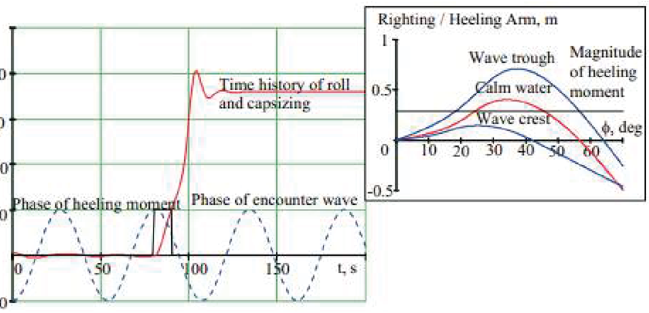

Figure 2: Capsizing due to Pure Loss of Stability (Belenky et.al., 2008)

Level 1 Vulnerability Criteria for Pure Loss of Stability

As proposed, if GM_{min} is greater than R_{PLA} 0.05, the ship is considered not vulnerable; otherwise it has to be checked by the next level (SDC, 2014).

Similar to the method of GM variation prediction in waves in parametric rolling criteria, the minimum value of metacentric height GM_{min} can be calculated either from the simplified method (Option A), or from considering the ship is balanced in sinkage and trim quasi-statically (Option B). In this case, the wave length is equal to the ship length and wave steepness is 0.0334 which is twice of that for parametric rolling.

Level 2 Vulnerability Criteria for Pure Loss of Stability

The procedure is quite similar to level 2 criteria for parametric rolling. It requires the stability calculations in a series of longitudinal sinusoidal waves. Here, the criteria totally include 2 checks which evaluate the ship in vanishing stability and the heel angle under action of specific heeling level. The target is for the angle of vanishing stability to be greater than 30 degrees (referred to C_{R1}), and the angle of heel under action of heeling level specified by R_{PL3} $8(H_i/\lambda)dF_n^2$ (referred to C_{R2}) to be larger than 15 degrees for passenger ship or 25 degrees for other ships. The total sum of probability according to corresponding wave probability in each criterion is C_{R1} and C_{R2}. The ship at its service speed is considered not to be vulnerable to pure loss of stability if the largest value among the two criteria, C_{R1} or C_{R2} is less than R_{PL0}; otherwise, performance-based layer should be applied for further check.

2. SAMPLE VESSELS

2.1 Reference Ship Data

The reference vessels applied with the draft criteria are C11 containership, ITTC ship A-1 and a high speed containership developed in Fastpod project (Turan et. al., 2008). The main particulars of these vessels and geometry are separately listed in table 1-3 and figure 3-5.

Table 1:
Main Parameters of C11 Containership

Item	Value	Unit
Length btw. waterline (L_{pp})	262.00	m
Breadth (B_{DWL})	40.00	m
Depth (D)	24.45	m
Draught (T)	11.50	m
Displacement (Δ)	69,034.40	tons
Block coefficient (C_B)	0.573	/
Transverse metacentric height (GM_T)	1.928	m
Vertical Centre of Gravity (VCG)	18.418	m
Service Speed (Vs)	12.86	m/s
Natural Roll period (T_Φ)	24.49	s

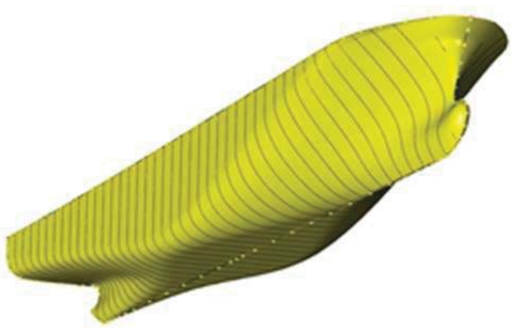

Figure 3: Geometry of C11 Containership

Table 2:
Main Parameters of Ship A-1

Item	Value	Unit
Length btw. Waterline (L_{pp})	150.00	m
Breadth (B_{DWL})	27.20	m
Depth (D)	13.50	m
Draught (T)	8.5	m
Displacement (Δ)	23,751.21	tons
Block coefficient (C_B)	0.668	/
Transverse metacentric height (GM_T)	0.15	m
Vertical Centre of Gravity (VCG)	11.475	m
Service Speed (Vs)	11.50	m/s
Natural Roll period (T_Φ)	43.30	s

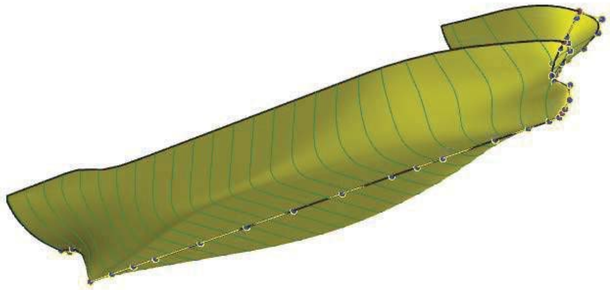

Figure 4: Geometry of ship A1

Table 3:
Main parameters of Fastpod Containership

Item	Value	Unit
Length btw. Waterline (L_{pp})	275.00	m
Breadth (B_{DWL})	30.00	m
Depth (D)	21.65	m
Draught (T)	10.30	m
Displacement (Δ)	49,580.28	tons
Block coefficient (C_B)	0.569	/
Transverse metacentric height (GM_T)	1.926	m
Vertical Centre of Gravity (VCG)	13.678	m
Service Speed (Vs)	18.00	m/s
Natural Roll period (T_Φ)	19.05	s

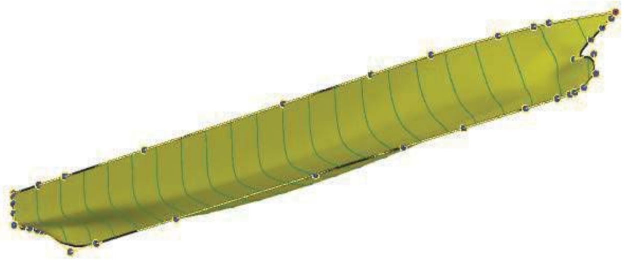

Figure 5: Geometry of Fastpod Containership

3. SECOND GENERATION INTACT STABILITY CRITERIA

The IMO is developing the second generation intact stability criteria of five failure stability modes. In this paper, the application of parametric rolling and pure loss of stability criteria will be introduced in section 3.1 and section 3.2 separately.

3.1 Parametric Rolling

The three sample vessels were tested according to the draft criteria. Roll amplitude results of C11 containership and Fastpod containership were calculated using the analytical methods proposed by the IMO working group and they were compared to model test results. The application of current parametric rolling criteria on the sample vessels is concluded. As C11 containership was tested in danger of parametric rolling, it is useful to investigate the influence of ship parameters on this issue.

- Analytical Method Vs. Experiment

In parametric rolling, the main part is to predict parametric roll amplitude. In level 2 vulnerability criteria, an analytical method is proposed to calculate roll angle (CGIS, 2014). As mentioned, level 2 is more conservative than level 3. If the vessel passes level 2, the vessel won't have any potential danger of parametric rolling. In other words, the roll amplitude calculated from the proposed method in level 2 should be larger than that of the vessel experiencing in practice.

Firstly, the well-known C11 containership is used to carry on the benchmark study. In wave length equals to ship length, wave steepness varies from 0.01 to 0.04 and Froude number changing from 0 to 0.15 in head sea, roll amplitude calculated from analytical method is compared to the experiment result shown in figures 6-9. All these results demonstrate that the analytical method provides a conservative estimate on roll amplitude which matches the purpose of level 2 criteria.

Secondly, the study is also applied to a high speed containership used in the Fastpod project (Turan, 2008). The model was tested for different wave heights for wave frequency 0.525 and vessel speed in 17 knots in head sea (Turan, 2008). The result comparison between analytical method and model test is plotted in figure 10. X axis represents the wave heights of regular wave while Y axis represents the roll amplitude. The data meet the conservative purpose as well and the analytical method can achieve larger roll angle and provide a reasonable agreement to model test to some extent.

- Parametric Rolling Criteria Application

After validation of the analytical method, parametric rolling vulnerability criteria were applied to the three sample vessels. The results of level 1 and level 2 compared to the safety standard are shown in table 4. C11 is judged to be in potential danger of parametric rolling, while ship A-1 and Fastpod containership passes the criteria. The calculated result of C11 containership has a relative good agreement with IMO published result. Besides, The roll amplitude of most model tests of C11 containership are larger than the safety limit 25 degree while the largest roll amplitude of Fastpod containership reaches to 24.41 degree which is still smaller than the limit 25 degree. It therefore demonstrates that the parametric vulnerability criteria have good accuracy of parametric rolling occurrence prediction.

- Sensitivity Study

C11 containership was judged as being vulnerable to parametric rolling. It is important to investigate the influence of the main parameters on parametric rolling. To achieve the study, parametric transform method, based on Lackenby hull variation method (Lackenby, 1950) is used to generate new hullform. In this study, only one parameter was changed slightly (e.g. ΔL $\pm$2m; ΔB $\pm$0.4m; ΔT $\pm$0.4m; ΔC_b $\pm$0.01; ΔC_m $\pm$0.005; T_ϕ $\pm$0.5s), keeping the other main parameters constant and leaving the displacement free to vary. Among ship length Lwl, breadth B, draft T, block coefficient Cb, midship coefficient Cm and natural roll period T_ϕ, the small change to all the main parameters doesn't have any influence on C_1 of parametric rolling. In figure 11, it is clear that the small change of ship length doesn't have any influence on C_2 while in figure 12, the increase of breadth and block coefficient could slightly decrease the C_2 value. Compared to these three coefficients, C_m and T_ϕ have a relative larger influence on C_2 value. Overall, increasing draft could decrease the C_2 value but the vessel within this small change still in danger of parametric rolling, as shown in figure 13. From figure 14-15, it demonstrates that decreasing midship coefficient or natural roll period, could reduce the C_2 value and even avoid the vessel from parametric rolling occurrence

3.2 Pure Loss of Stability

In this part, the application of pure loss of stability to the three vessels is applied. The results are listed in table 5. In level 1, the simplified method (option A) seems more conservative. Although most results judged the ship as having a potential danger of pure loss of stability in level 1, all sample vessels still pass the level 2 criteria.

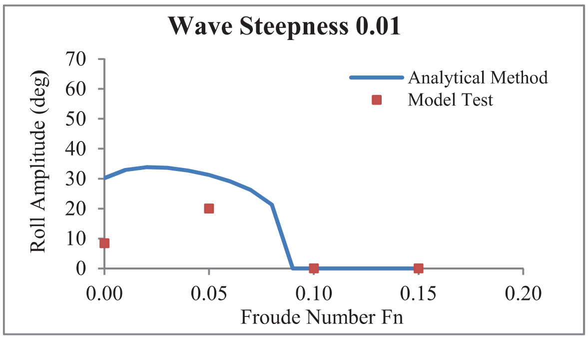

Figure 6 Comparison between Analytical Method and Experiment Result under Wave Steepness 0.01

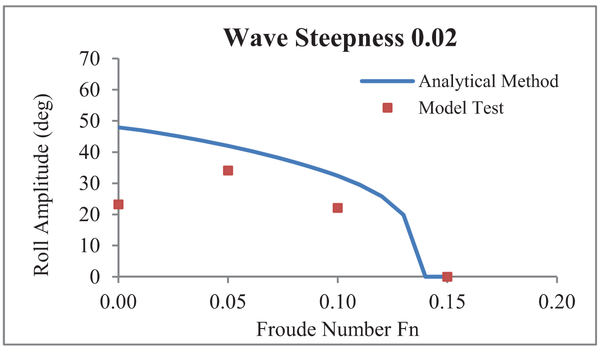

Figure 7 Comparison between Analytical Method and Experiment Result under Wave Steepness 0.02

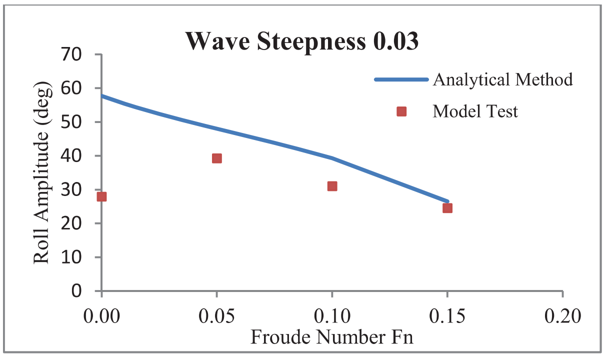

Figure 8 Comparison between Analytical Method and Experiment Result under Wave Steepness 0.03

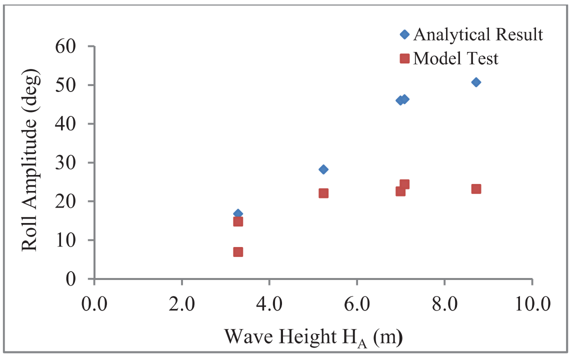

Figure 10 Roll Angle Comparison between the Analytical Method and Experiment Result with Different Wave Height

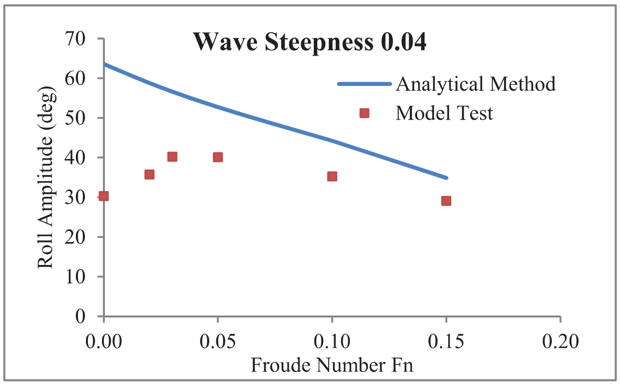

Figure 9 Comparison between Analytical Method and Experiment Result under Wave Steepness 0.04

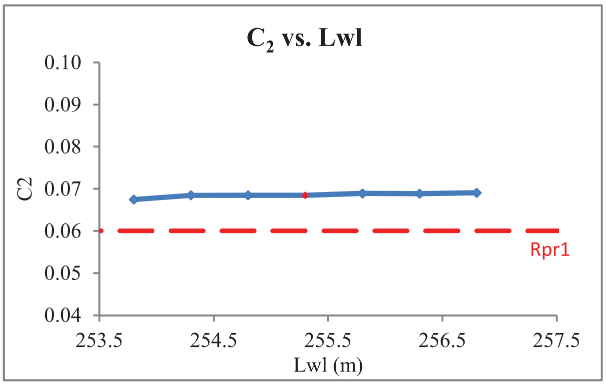

Figure 11 Relationship between ship length and C_2 of Parametric Rolling

Table 4:
Application of Parametric Rolling on Sample Vessels (Non-vulnerable; Vulnerable)

Ship Type	L_{pp} (m)	ΔGM/GM		R_{PR}	C_1	C_2
		Option A	Option B			
C11 from IMO	262	1.056	/	0.356	0.437	0.073
C11	262	1.067	0.852	0.400	0.436	0.068
Ship A-1	150	3.095	2.477	0.627	0.885	0.002
Containership 1	275	0.837	0.399	0.313	0.225	0.001

Table 5:
Application of Pure Loss of Stability on Sample Vessels (Non-vulnerable; Vulnerable)

Ship Type	L_{pp} (m)	F_n	Level 1		Level 2	
			Option 1-A	Option 1-B		
			GMmin-0.05(m)		C_{R1}	C_{R2}
C11	262	0.257	-1.969	-0.046	0.000	0.000
Ship A-1	150	0.3	-0.664	-0.201	0.000	0.000
Containership 1	275	0.345	-1.777	0.383	0.000	0.000

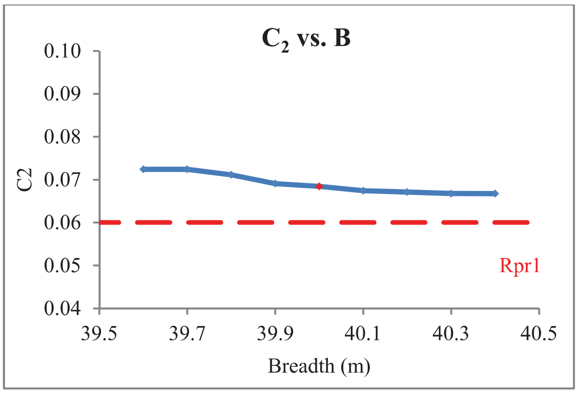

Figure 12 Relationship between Ship Breadth and C_2 of Parametric Rolling

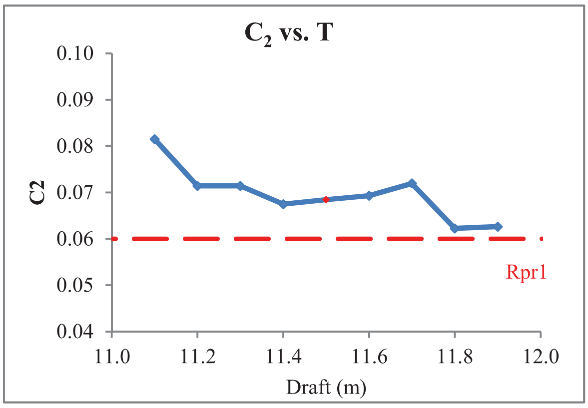

Figure 13 Relationship between Ship Draft and C_2 of Parametric Rolling

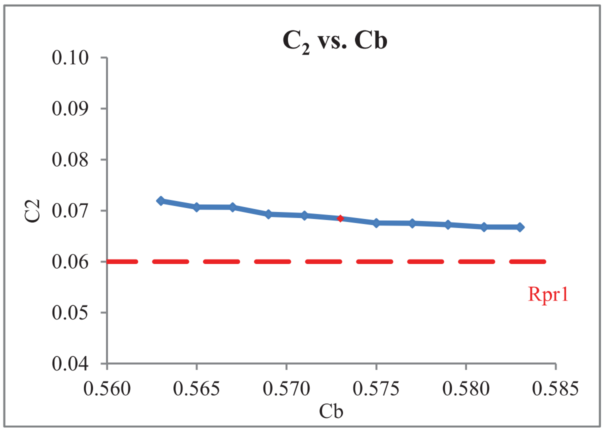

Figure 14 Relationship between Ship Block Coefficient and C_2 of Parametric Rolling

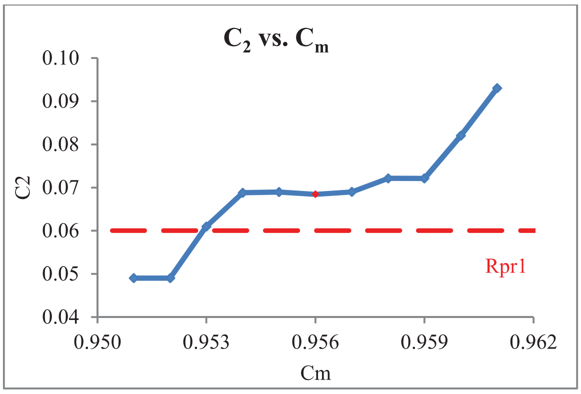

Figure 15 Relationship between Ship Midship Coefficient and C_2 of Parametric Rolling

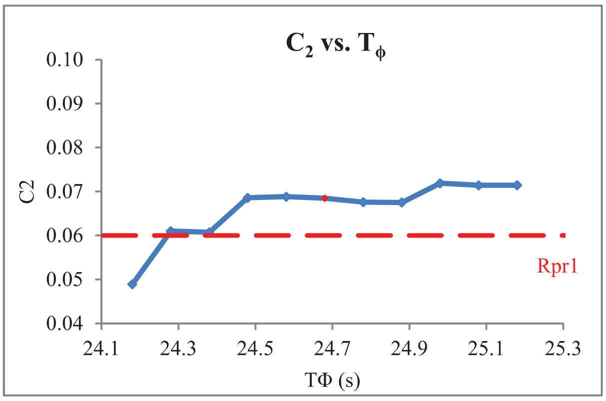

Figure 16 Relationship between Ship Natural Roll Period Coefficient and C_2 of Parametric Rolling

4. CONCLUSIONS

In this paper, the current parametric rolling and pure loss of stability criteria are applied to three sample vessels. C11 containership is judged as vulnerable to parametric rolling while ITTC ship A-1 and Fastpod containership are judged as non-vulnerable to parametric rolling. All the vessels passed the pure loss of stability criteria. Meanwhile, the analytical method from Mathieu equation provides a conservative estimate on the roll angle in comparison to experiments and to some extent; it has a relatively good prediction on the trend. Besides, the sensitivity study demonstrates that among ship length, breadth, draft, block coefficient, midship coefficient, natural roll period, when only one parameter is changed and the other main parameters are left constant, C_1 is not sensitive but C_2 of parametric rolling is much influenced by draft, midship coefficient and natural period.

5. ACKNOWLEDMENTS

This project was funded by Lloyd's Register. All internal information relevant to second generation of intact stability was kindly provided by the Royal Institution of Naval Architects. The support from Lloyd's Register and the Royal Institution of Naval Architects is gratefully acknowledged.

The experiment of high speed containership was carried out under the European Commission Research Project FASTPOD (GRD2-2001-50063). The efforts from Dr Zafer Ayaz are very much appreciated.

6. REFERENCES

American Bureau of Shipping (ABS), 2004, "Guide for the Assessment of Parametric Roll Resonance in the Design of Container Carriers", Houston, Texas.

Belenky, V., Kat, H.O.D., and Umeda, N., 2008, "Toward Performance-Based Criteria for Intact Stability", Marine Technology, Vol.45, No.2, pp. 101-123.

Correspondence Group on Intact Stability (CGIS), 2014 "Working Version of Draft Explanatory Notes on the Vulnerability of Ships to the Parametric Rolling Stability Failure Mode", Sub-Committee on Ship Design and Construction, SDC 2/INF.10 Annex 17, pp. 59-74.

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, Number 1, pp.1-19.

International Association of Classification Societies (IACS), 2001, "No.34 Standard Wave Data".

Lackenby, H., 1950, "On the Systematic Geometrical Variation of Ship Forms", RINA-Transaction, Vol 92, pp. 289-315.

Kawahara, Y., Maekawa, K., and Ikeda, Y., 2009, "A Simple Prediction Formula of Roll Damping of Conventional Cargo Ships on the Basis of Ikeda's Method and Its Limitation", The 10th International Conference on Stability of Ships and Ocean Vehicles, St. Petersburg, Russia.

Krylov, A.N., 1958, Selected Papers, USSR Academy of Sciences, Moscow.

Paulling, J.R., Kastner, S., and Schaffran, S., 1972, "Experimental Studies of Capsizing of Intact Ships in Heavy Seas", U.S. Coast Guard Technical Report

Paulling, J.R., Oakely, O.H., and Wood, P.D., 1975, "Ship Capsizing in Heavy Seas: The Correction of Theory and Experiments", Proceedings of 1st International Conference on Stability of Ships and Ocean Vehicles, Glasgow.

Paulling, J.R. and Rosenberg, R.M., 1959, "On Unstable Ship Motions Resulting from Nonlinear Coupling", Journal of Ship Research, Vol. 3, pp.36-46.

Pollard, J. and Dudebout, A., 1892, "Theorie Du Navire", Paris.

Sub-Committee on Stability and Load Lines and on Fishing Vessels Safety (SLF), 2012, "Summary of the Methodologies for the Second Generation Stability Criteria Available for SLF 54", SLF 54-WP, Annex 3.

Sub-Committee on Ship Design and Construction (SDC), 2014, "Draft Amendments to Part B of the IS Code with

Regard to Vulnerability Criteria of Levels 1 and 2 for the Parametric Rolling Failure Mode", Development of Second Generation Intact Stability Criteria – Development of Amendments to Part B of the 2008 IS Code on Towing and Anchor Handling Operations: Report of Working Group (Part 1), SDC 2/WP.4, Annex 2.

Turan, O., Ayaz, Z., Aksu, S., Kanar, J. and Bednarek, A., 2008, "Parametic Rolling Behaviour of Azimuthing Propulsion-driven Ships", Ocean Engineering, 35(13), pp. 1339-1356.