Study on Vulnerability Criteria for Surf-riding / Broaching with a Model Experiment

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ABSTRACT

The vulnerability criteria for Surf-riding and broaching are currently under development at the International Maritime Organization (IMO) for the second generation intact stability criteria. Firstly, the vulnerability criteria for surf-riding and broaching are introduced, and the calculations of seven sample ships are conducted to analyze the applicability of the current vulnerability criteria. Secondly, a model experiment with a tumblehome vessel for surf-riding and broaching in following and stern-quartering waves is carried out. Four types of ship motions with periodic motion, stable surf-riding, broaching and capsizing due to broaching are observed in the model experiment while broaching is observed three times in one wave case. Finally, the results between the criteria calculations and the model experiment are compared to verify the feasibility of vulnerability criteria for the tumblehome vessel.

Keywords: *Second generation intact stability criteria, Surf-riding, Broaching, Model experiment*

1. INTRODUCTION

The second generation intact stability criteria for five stability failure modes including pure loss of stability, parametric roll, surf-riding and broaching, dead ship condition and excessive accelerations are under development at the International Maritime Organization (IMO) to guarantee sufficient safety of ships in waves (IMO SDC.4, 2017). The second generation intact stability criteria consist of two levels of vulnerability criteria based on simple physical models and direct stability assessment using advanced numerical simulation methods.

Surf-riding occurs when a ship is captured by a wave from the stern and forced to run with wave celerity. During surf-riding, the ship is often unstable and will turn uncontrollably despite keeping maximum rudder angle in the opposite direction, which is defined as broaching. Broaching is considered as one of the most dangerous phenomena in following and stern-quartering waves for high-speed ships, such as destroyers and fishing vessels.

Levels 1 and 2 vulnerability criteria for surf-riding and broaching have been determined at the 3rd session of Sub-committee on Ship Design and Construction (SDC) (IMO SDC.3, 2016a, 2016b). Because surf-riding is usually regarded as a precondition of broaching, the likelihood of surf-riding occurrence is used as vulnerability criteria instead of broaching. Level 1 criterion is simply checked by ship speed and length. The formula of level 2 criterion is obtained by using Melnikov method, the stochastic wave theory and the wave statistics, and the calculated value need to be compared with the safety level set as 0.005 currently.

It’s important to estimate surf-riding thresholds in the level 2 criterion. Recently some approximate formulas based on Melnikov’s method were proposed to predict surf-riding thresholds in following regular waves (Kan, 1990; Spyrou, 2006; Maki et al., 2010, 2014). Maki et al. (2010, 2014) also provided another analytical formula for calculating surf-riding thresholds using a continuous piecewise linear approximation, which is more transparent than Melnikov’s method in obtaining the solution.

The prior task of IMO SDC 4 was drafting the guidelines for the specification of direct stability assessment procedures (IMO SDC.4, 2017). For the numerical simulation of surf-riding and broaching, the numerical approach is required at least a 4 DOF mathematical model of surge-sway-roll-yaw motion, and hydrodynamic forces should consider hydrodynamic lift forces due to the coexistence of wave particle velocity and ship forward velocity.

Umeda and Hashimoto (2002) used a 4 DOF mathematical model of surge-sway-roll-yaw motion to qualitatively explain the capsizing phenomena associated with surf-riding and broaching in regular following and stern-quartering waves. In order to improve the calculation accuracy to realize quantitative prediction, Hashimoto et al. (2004, 2011) took into account several important nonlinear terms in the previous mathematical model.

For the numerical simulation in irregular waves, the issue is how to identify surf-riding and broaching in irregular waves. Belenky et al. (2012) proposed a method to detect surf-riding in irregular waves by the celerity of irregular waves, which is computed by finding the point of maximum wave steepness on the down slope of the wave nearest the ship (Spyrou et al., 2012). They also provided two novel metrics for likelihood of surf-riding and broaching used for evaluating the probability of surf-riding and broaching in irregular waves (Belenky et al., 2016a, 2016b).

In order to verify the applicability of vulnerability criteria for surf-riding and broaching, the calculations for seven sample ships including one unconventional ship are conducted. The free running experiment with the unconventional ship is carried out to provide validation data for criteria check.

2. ASSESSMENT ON VULNERABILITY CRITERIA FOR SURF-RIDING AND BROACHING

According to the updated drafts (IMO SDC.2, 2015; IMO SDC.3, 2016a, 2016b), vulnerability criteria for surf-riding and broaching are simply introduced as follows.

Level 1 criterion

A ship is judged to be vulnerable to the surf-riding and broaching failure mode if formula (1) is false:

$$L > 200\text{m or } Fn \leq 0.3 \qquad (1)$$

where, $Fn = V_S/\sqrt{Lg}$ is the Froude number; V_S is service speed of the ship in calm water; L is the length of the ship; g is gravity acceleration. If the ship fails to pass level 1 criteria, a more detailed check of level 2 criteria should be applied.

Level 2 criterion

A ship is judged to be vulnerable to the surf-riding and broaching failure mode if the value C is larger than 0.005:

$$C = \sum_{HS}\sum_{TZ}\left(W2(H_S, T_Z)\sum_{i=1}^{N_\lambda}\sum_{j=1}^{N_a} W_{ij} C2_{ij}\right) \qquad (2)$$

where, $W2(Hs,Tz)$ is the weighting factor of short-term sea state according to wave statistics of the North Atlantic or other sources, H_S is the significant wave height, T_Z is the average zero up-crossing wave period; W_{ij} is a statistical weight calculated with the joint distribution of local wave steepness and lengths; $C2_{ij}$ is calculated for each wave to judge whether surf-riding occurs, which is defined as follows:

$$C2_{ij} = \begin{cases} 1 & if \quad Fn > Fn_{cr}(r_i, s_j) \\ 0 & if \quad Fn \leq Fn_{cr}(r_i, s_j) \end{cases} \qquad (3)$$

where, Fn_{cr} is the critical Froude number corresponding to the surf-riding threshold for the regular wave with steepness s_j and wavelength to ship length ratio r_i, and calculated by using the critical speed u_{cr}, which is determined by solving the following equation:

$$T_e(u_{cr}; n_{cr}) - R(u_{cr}) = 0 \qquad (4)$$

where, T_e is the propulsor thrust in water; R is the calm water resistance of the ship; n_{cr} is the commanded number of propeller revolutions corresponding to the surf-riding threshold, which is estimated based on Melnikov method. The detailed estimation of n_{cr} is introduced in the draft explanatory notes for surf-riding and broaching (IMO SDC.3, 2016b).

Sample ships calculation

The check of level 2 criterion for a fishing vessel is conducted to compare with the example in the draft explanatory notes for surf-riding and broaching (IMO SDC.3, 2016b), and the comparison results of Fn_{cr} and the value C are shown in tables 1 and 2 repectively, which indicate that the software coded by the authors based on the updated vulnerability criteria for surf-riding and broaching (IMO SDC.2, 2015; IMO SDC.3, 2016a, 2016b) has sufficient accuracy. As shown in table 3, the sample calculations for seven ships are conducted to analyze the applicability of the current vulnerability criteria for surf-riding and broaching.

Table 1 Comparison results of Fn_{cr}

λ/L	H/λ	Fn_{cr} in SDC 3	Fn_{cr} in this study	% difference
1.25	0.0504	0.3296	0.3292	-0.121%
1.50	0.0396	0.3563	0.3569	0.168%
1.50	0.0504	0.3428	0.3435	0.204%
1.50	0.0600	0.3325	0.3332	0.211%
1.75	0.0504	0.3577	0.3591	0.391%

Table 2 Comparison results of the value *C*

Fn	*C* in SDC 3	*C* in this study	% difference
0.30	0.000788	0.000810	2.792%
0.35	0.0231	0.0226	-2.165%
0.40	0.0591	0.0577	-2.369%
0.45	0.0877	0.0865	-1.368%
0.50	0.0919	0.0919	0.000%

Table 3 Summary of sample calculations

Ship Type	L_{PP} (m)	Maximum service *Fn*	Level 1	Level 2	
			Result	*C*	Result
Fishing ship 1	34.5	0.475	**Fail**	9.19E-2	**Fail**
Fishing ship 2 (Full load)	27.4	0.314	**Fail**	2.12E-3	Pass
Fishing ship 2 (Design load)	27.4	0.319	**Fail**	3.39E-3	Pass
Fishing ship 3	66.0	0.310	**Fail**	2.28E-3	Pass
DTMB 5415	142.0	0.413	**Fail**	2.77E-2	**Fail**
ONR tumble-home ship	154.0	0.397	**Fail**	2.17E-2	**Fail**
Container ship 1	262.0	0.254	Pass	3.50E-9	Pass
Container ship 2	150.0	<0.250	Pass	0.00E+0	Pass

The results of the sample calculations show that five ships fail to pass level 1 criterion, which need to check level 2 criterion, because their Froude numbers are larger than 0.3, while their lengths are less than 200m. Three ships with much higher speed still can't pass level 2 criterion, which need to be checked by the direct stability assessment.

There are no inconsistencies in the checks between two levels vulnerability criteria, which indicate that the mathematical model of the current level 2 criterion is reasonable.

In order to provide validation data for the calculation of vulnerability criteria, ONR tumblehome vessel as an unconventional ship with good performance of propulsion and seakeeping, which is one of standard models for the second generation intact stabiltiy criteria, is used as a subject ship in the following model experiment.

3. EXPERIMENTAL INVESTIGATION

Experiment

The free running experiment of the ONR tumblehome vessel was conducted to assess the surf-riding and broaching phenomena in regular following and stern-quartering waves at the maneuvring and seakeeping basin of China Ship Scientific Research Center (CSSRC). The basin is 69m length, 46m breadth and 4m depth, which is equipped with flap wave makers at the two adjacent sides of the basin. The ship model was equipped with double propellers and double rudders. Ship motions were measured by the MEMS (Micro Electro-Mechanical System)-based gyroscope placed on the ship model.

Table 4 Principal particulars of ONR tumblehome vessel

Items	Ship	Model
Length: L_{BP}	154.0m	3.8m
Breadth: *B*	18.8m	0.463m
Depth: *d*	5.494m	0.136m
Block coefficient: C_b	0.535	0.535
Displacement: *W*	8507ton	0.128ton
Design speed: *V*	15.43 m/s	2.424 m/s
Metacentric height: *GM*	2.068m	0.051m

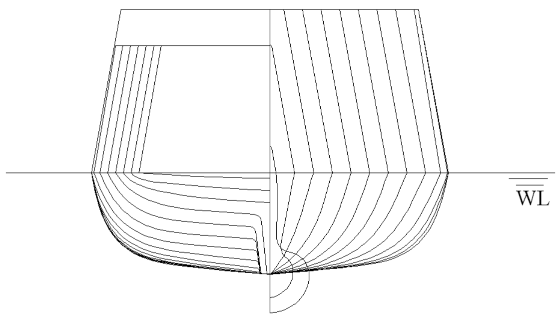

Figure 1: Body plan of ONR tumblehome vessel

The principal particulars and the body plan of the ONR tumblehome vessel are shown in Table 4 and Figure 1.

Results and discussions

As shown in Figures 2 and 3, the ship experiences surf-riding and broaching in two wave conditions respectively. Surf-riding and broaching often occur on the down slope of a wave, and broaching always accompanied with a large heel angle, may lead to stability failure, or even capsizing.

The experiment results in following waves are shown in Figures 4 and 5. The pitch motion of the ship appears periodic at the beginning, and then the amplitude of pitch motion is almost unchanged in later time. While yaw motion is generally small all the time. This reveals that stable surf-riding occurs.

With the wave steepness increasing and the heading changing to stern-quartering waves as shown in Figures 6 and 7, surf-riding occurs quickly. Then the ship can't keep its course even with maximum steering effort, and broaching occurs. At the same time roll angle increases rapidly. But with the action of rudders, the ship is stable at a new heading temporarily. And then the ship is captured again by a new wave and surf-riding and broaching occur once more. At the third broaching event, the roll angle is so large that the ship capsizes at last.

Figure 2: A snapshot of surf-riding in the free running experiment

Figure 3: A snapshot of broaching in the free running experiment

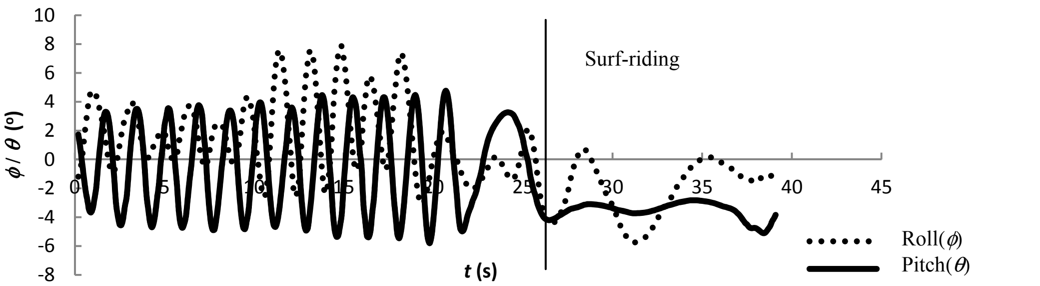

Figure 4: Time histories of roll and pitch (*Fn*=0.4, *λ*/*L*=1.25, *H*/*λ*=0.05, following waves *χ*=0°)

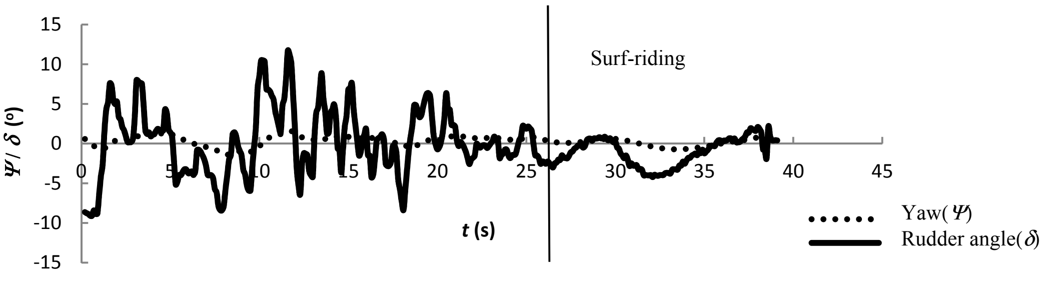

Figure 5: Time histories of yaw and rudder angle (*Fn*=0.4, *λ*/*L*=1.25, *H*/*λ*=0.05, following waves *χ*=0°)

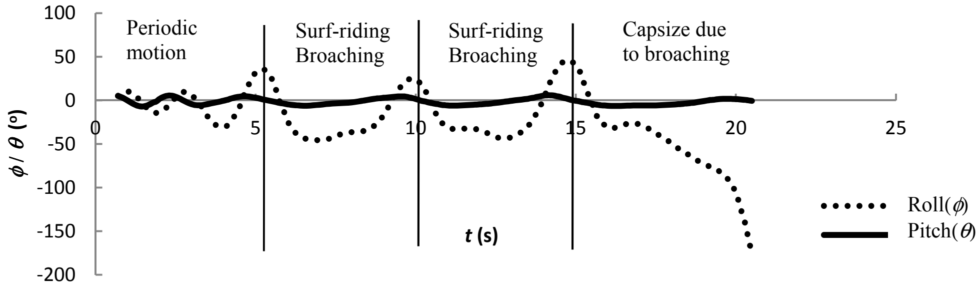

Figure 6: Time histories of roll and pitch (Fn=0.4，λ/L=1.25，H/λ=0.06, stern-quartering waves χ=30°)

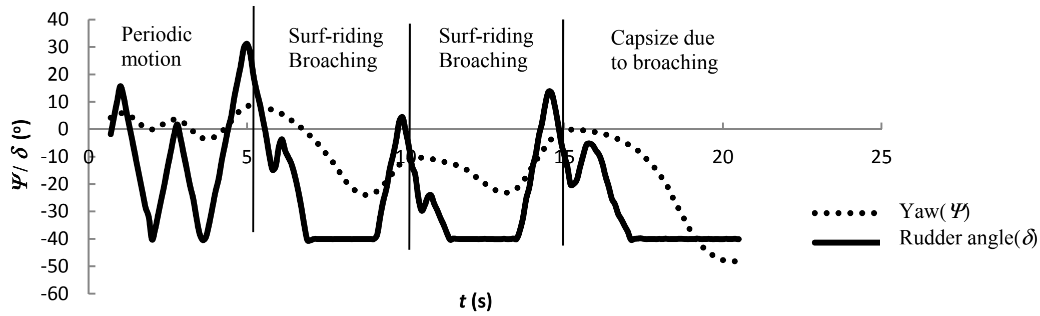

Figure 7: Time histories of yaw and rudder angle (Fn=0.4，λ/L=1.25，H/λ=0.06, stern-quartering waves χ=30°)

In the level 2 criterion for surf-riding and broaching, $C2_{ij}$ is used to judge whether surf-riding occurs in the regular following waves. The calculation results at different Fn are compared with the experiment results as shown in Figures 8 and 9. The comparison indicates that the calculation results are more conservative than experiment results.

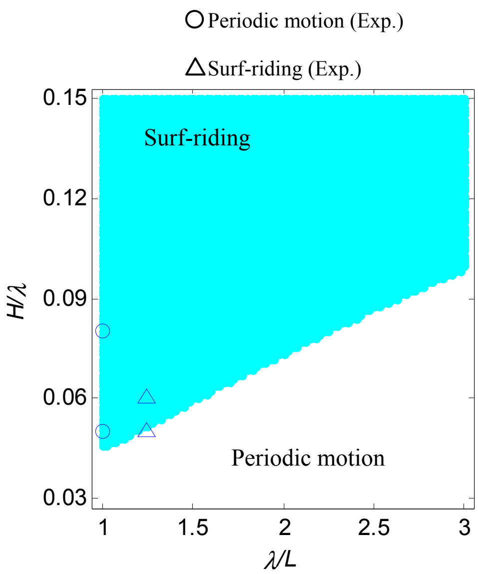

Figure 8: Comparison of the results between calculation and model experiment (Fn=0.3)

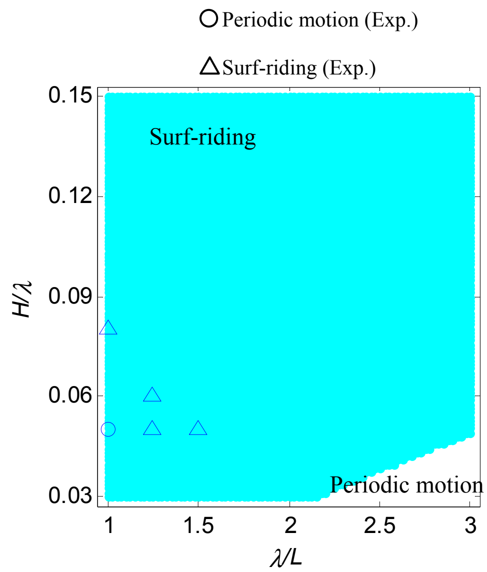

Figure 9: Comparison of the results between calculation and model experiment (Fn=0.4)

In the experiment, the ship doesn't experience surf-riding at the cases with small steepness and wavelength to ship length ratio (Fn=0.3, λ/L=1.0, H/λ=0.05 and 0.08; Fn=0.4, λ/L=1.0, H/λ=0.08), which are inconsistent with the calculation results. It's because that the mathematical model of level 2 criterion is based on a single degree of freedom surge equation with the linear Froude-Krylov force, and could conservatively predict surf-riding for the unconventional ship in waves with small steepness and wavelength to ship length ratio. However, level

2 criterion is practical for its simple and conservative. For the ONR tumblehome vessel, which fails to pass level 2 criterion, the direct stability assessment using the advanced state-of-the-art technology should be performed to avoid over conservative assessments.

4. CONCLUSION

Based on the sample calculation and the model experiment for surf-riding and broaching, the following conclusions can be summarized.

1) The mathematical model of the current level 2 criterion is reasonable by analyzing the applicability of vulnerability criteria with the sample calculations.

2) Four types of ship motions with periodic motion, stable surf-riding, broaching and capsizing due to broaching are observed in the experiment, while broaching is observed three times in one wave case.

3) With the comparison of results between calculations and model experiment, level 2 criterion for surf-riding and broaching is also applicable to ONR tumblehome vessel.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Belenky V., Spyrou K., Weems K., 2012, "Evaluation of the Probability of Surf-riding in Irregular Waves with the Time-split Method", Proceedings of the 11th International Conference on the Stability of Ships and Ocean Vehicles, pp. 29-37.

Belenky V., Weems K., Spyrou K., 2016a, "On Probability of Surf-riding in Irregular Seas with a Split-time Formulation", Ocean Engineering, 120, pp. 264-273.

Belenky V., Spyrou K., Weems K., 2016b, "On Probability Properties of Surf-riding and Broaching-to in Irregular Seas", 31st Symposium on Naval Hydrodynamics, pp. 264-273.

Hashimoto H., Umeda N., Matsuda A., 2004, "Importance of Several Nonlinear Factors on Broaching Prediction", Journal of Marine Science and Technology, 9, pp. 80-93.

Hashimoto H., Umeda N., Matsuda A., 2011, "Model Experiment on Heel-induced Hydrodynamic Forces in Waves for Realizing Quantitative Prediction of Broaching", Fluid Mechanics and Its Application, 96, pp. 379-398.

IMO 2015, Draft Amendments to Part B of the IS Code with Regard to Vulnerability Criteria of Levels 1 and 2 for the Surf-riding / Broaching Failure Mode, SDC 2/WP.4 Annex3.

IMO 2016a, Amendments to Part B of the 2008 IS Code on Towing, Lifting and Anchor Handling Operations, SDC 3/WP.5.

IMO 2016b, Draft Explanatory Notes on the Vulnerability of Ships to the Surf-riding/ Broaching Stability Failure Mode, SDC 3/WP.5 Annex 5.

IMO 2017, Draft Guidelines of Direct Stability Assessment Procedures for Use with the Second Generation Intact Stability Criteria, SDC 4/WP.4 Annex 1.

Kan M., 1990, "A Guideline to Avoid the Dangerous Surf-riding", Proceedings of the 4th International Conference on Stability of Ships and Ocean Vehicles, pp. 90–97.

Maki A., Umeda N., Renilson M., Ueta T., "Analytical Formulae for Predicting the Surf-riding Threshold for a Ship in Following Seas", Journal of Marine Science and Technology, 15, pp. 218-229.

Maki A., Umeda N., Renilson M., Ueta T., 2014, "Analytical Methods to Predict the Surf-riding Threshold and the Wave-blocking Threshold in Astern Seas", Journal of Marine Science and Technology, 19, pp. 415-424.

Spyrou K.J., 2006, "Asymmetric Surging of Ships in Following Seas and its Repercussion for Safety", Nonlinear Dynamics, 43, pp. 149–172.

Spyrou K., Belenky V., Themelis N., Weems K., 2012, "Conditions for Surf-riding in an Irregular Seaway", Proceedings of the 11th International Conference on the Stability of Ships and Ocean Vehicles, pp. 23-28.

Umeda N., Hashimoto H., 2002, "Qualitative Aspects of Nonlinear Ship Motions in Following and Quartering Seas with High Forward Velocity", Journal of Marine Science and Technology, 6(2), pp. 111-121.