

Numerical Study towards Physics-Based Criteria for Avoiding Broaching and Capsizing in Following/ Quartering Waves

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1. INTRODUCTION

At the International Maritime Organization (IMO), new-generation intact stability criteria are now under development for allowing the use of first-principle tools for dangerous phenomenon. As a manoeuvring-related problem, broaching is counted in major capsizing modes. For developing the new-generation intact stability criteria, physics-based criteria relating to broaching in following and stern quartering waves have been examined in the light of numerical calculation. For the first step of the criteria relating to broaching, a surf-riding threshold prediction, using a bifurcation analysis in regular following waves having specified steepness and length, was proposed¹⁾. As the next step, for a ship that fails to comply with the first layer criterion, a direct stability assessment calculating capsizing probabilities due to broaching was presented. Here a deterministic analysis of ship motions obtained from numerical simulations is combined with a probabilistic analysis of local waves¹⁾.

Although surf-riding threshold can be used as a vulnerability criterion, it is also understood that increase of rudder area cannot contribute to the compliance with this vulnerability criteria. In other words, good directional stability cannot be evaluated in this criterion. Thus stability safety of a ship designed for higher service speed could often forces her designers to use performance based criteria, i.e. the direct stability assessment. To avoid such difficulties an additional criterion for directional stability during surf-riding is newly proposed in this paper for judging vulnerability of broaching of a surf-ridden ship.

At the direct stability assessment, the method for calculating probability of capsizing requests that the deterministic critical zone of capsizing due to broaching should be identified by repeating the numerical simulation using a coupled surge-sway-yaw-roll model in the time domain. Here it is judged that dangerous zones for broaching could exist not only inside the surf-riding region but also outside. In general, broaching occurs as a result of surf-riding at relatively large forward speed. Therefore, it is important to investigate the role of the capsizing zone outside the surf-riding threshold for practical use of the direct stability assessment.

2. ADDITIONAL VULNERABILITY CRITERION ON BROACHING

2.1 The balance of yaw moment in waves

Earlier works^{2), 3)} concluded that broaching could occur when a ship is surf-ridden and the wave-induced yaw moment exceeds the rudder-induced yaw moment. Thus a vulnerability criterion could be added to request the amplitude of wave-induced yaw moment smaller than the rudder-induced yaw moment at the rudder angle limit.

The wave-induced yaw moment, N^w , can be calculated, for example, as follows:

$$\begin{aligned}
 N^w = & \rho g \zeta_w k \sin \chi \int_{AE}^{FE} \frac{\sin(k \sin \chi \cdot B(x)/2)}{k \sin \chi \cdot B(x)/2} \\
 & \cdot S(x) e^{-kd(x)} x \sin k(\xi_G + x \cos \chi) dx \\
 & + \zeta_w \omega u \sin \chi \int_{AE}^{FE} \rho S_y(x) e^{-kd(x)} x \sin k(\xi_G + x \cos \chi) dx \\
 & - \zeta_w \omega u \sin \chi \left[\rho S_y(x) e^{-kd(x)} x \cos k(\xi_G + x \cos \chi) \right]_{AE}^{FE} \\
 & + (x_R + a_H x_H) \frac{\rho}{2} A_R \frac{6.13\Lambda}{2.25 + \Lambda} \varepsilon (1 - w_p) u \sqrt{1 + \kappa_p \frac{8K_T(J)}{\pi J^2}} \\
 & \cdot \zeta_w \omega \sin \chi \cdot e^{-kz_R} \cos(k\xi_G + kx_R \cos \chi)
 \end{aligned} \tag{1}$$

where ρ : water density, g : gravitational acceleration, ζ_w : wave amplitude, k : wave number, χ : heading angle from the wave direction, ξ_G : horizontal distance of the ship centre from a wave trough, ω wave frequency, AE: ship aft end, FE: ship fore end, x : longitudinal position from the ship centre, $B(x)$: local ship breadth, $d(x)$: local ship draught, $S(x)$: local ship sectional area, $S_y(x)$: local ship added mass in sway, x_R : longitudinal distance of the rudder centre from the ship centre, a_H : interaction factor in sway force between hull and rudder, x_H : longitudinal position of interaction sway force between hull and rudder, A_R : rudder area, Λ : rudder aspect ratio, ε : wake ratio between propeller and hull, w_p : effective propeller wake fraction, u : ship surge velocity, κ_p : interaction factor between propeller and hull, K_T : propeller thrust coefficient, J : propeller advance coefficient, z_R : vertical position of rudder centre from waterline⁴⁾. Here $S_y(x)$ can be calculated analytically using the Lewis form mapping technique.

The rudder-induced yaw moment, N^δ , can be obtained, for example, by ignoring the effect of wave particle velocity, as follows:

$$N^\delta = -(x_R + a_H x_H) \frac{\rho}{2} A_R \frac{6.13\Lambda}{2.25 + \Lambda} \left\{ e^2 (1 - w_p)^2 u^2 (1 + \kappa_p \frac{8K_T(J)}{\pi J^2}) \right\} \delta_{\max} \tag{2}$$

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As an actual procedure, it is recommended to assume $\chi=45$ degrees for simulating the maximum amplitude of N^W and to use $u=c$ for obtaining the minimum magnitude of N^δ during surf-riding. Here δ_{max} is the rudder angle limit, c is the wave celerity and the propeller revolution number for J corresponds to actual one. Then, if the amplitude of N^W is larger than N^δ , a ship is judged as being vulnerable to broaching. Although the formulae of N^δ can be dealt even with a spread-sheet-type calculation, the one of N^W is rather complicated for the criterion. So that the formulae of N^W have to be simplified at calculating particularly $S_y(x)$ in the future works.

2. 2 Sample calculation results

In this paper all sample calculations were executed for a fishing vessel known as the ITTC Ship A2. The principal particulars of the ship are shown in Table. 1. The numerical simulation in the time domain, which is based on a surge-sway-yaw-roll manoeuvring model with linear wave forces and the effect of wave particle velocity on rudder force taken into account ⁴⁾, was applied to this ship for categorising ship behaviours for various wave steepness and wavelength. The initial condition was set to be in a state in dead following waves with sufficiently small forward velocity. Regarding control parameters, the required autopilot course is 10 degrees from the wave direction and the nominal Froude number is 0.35. The autopilot is simulated with a proportional control with the rudder gain of 1.0 and the rudder angle limit is 35 degrees. The results were categorised as periodic motion, stable surf-riding, surf-riding with oscillation, broaching, capsizing and not identified using judging criteria based on nonlinear dynamics ⁴⁾.

Table.1 Principal particulars of the ITTC Ship A2

Items	Ship
Length : L	34.5 m
Breadth : B	7.60 m
Draught : d	2.65 m
Block coefficient : C_b	0.597
Metacentric height : GM	1.00 m
Rudder area : A_R	3.49 m ²

The comparison between the new additional criterion and the numerical simulation result is shown in Fig.1. The surf-riding threshold obtained by a numerical bifurcation analysis in dead following waves is also plotted here. The region the ship fails to comply with the additional criterion includes the regions of broaching associated with surf-riding in the numerical simulation. Therefore, it is concluded that the additional criterion could estimate the danger of broaching associated with surf-riding with a certain margin. Checking the applicability of the additional criterion using other ships designed for higher service speed, e. g. high speed car ferry, and influence of the increase of rudder area could be future tasks.

3. CONSIDERATION ABOUT CAPSIZING IN A LONGER AND HIGHER WAVE AREA

For calculating probability of capsizing in irregular waves, the deterministic critical zone of capsizing due to broaching is

required to be identified in various regular waves with a wide range of wave steepness and length. As shown in Fig.1, the capsizing zone with broaching mainly exists inside her surf-riding threshold obtained by a global bifurcation analysis for the autopilot course of 0 degrees. Because broaching here occurs as a result of surf-riding, this capsizing zone should be used for calculating probability of capsizing due to broaching. However, a capsizing zone also exists outside the surf-riding threshold in longer and higher waves and part of the zone is judged capsizing with broaching. Whether this area should be used for calculating capsizing probability or not is important for developing new-generation intact stability criteria.

- + broaching without capsize
- capsize with broaching
- capsize without broaching
- stable surf-riding
- surf-riding with oscillation
- periodic motion
- not identified
- bifurcation analysis
- wave-induced yaw moment is smaller than the rudder-induced yaw moment
- × wave-induced yaw moment exceeds the rudder-induced yaw moment

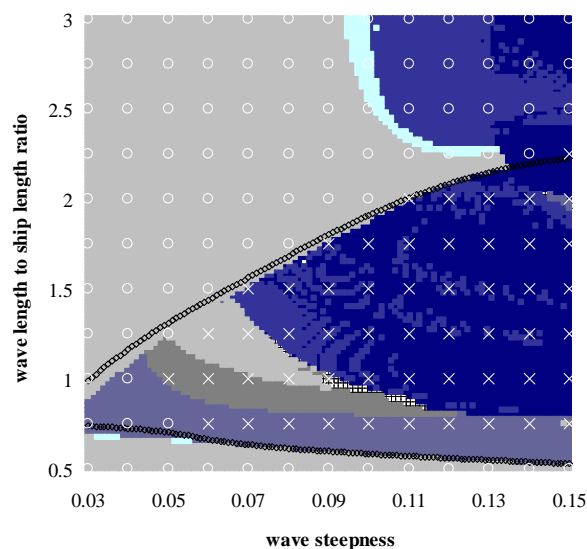


Fig.1 Comparison of the additional criterion and the direct stability assessment for broaching using individual initial conditions with the nominal Froude number of 0.35 and the autopilot course of 10.0 degrees.

Firstly, as a possible reason of this broaching occurrence of *surf-riding under certain initial condition* ⁵⁻⁶⁾, where a point attractor as surf-riding and a periodic orbit coexists under one wave and propeller RPM conditions, is investigated. Although *surf-riding under certain initial condition* cannot occur for a self-propelled ship with a constant propeller RPM in regular waves, in a numerical simulation with unrealistic initial condition could result in such surf-riding ⁵⁻⁶⁾. The numerical simulation shown in Fig.1 uses the initial surge velocity of 10% of the nominal speed and the initial ship centre position of a wave trough. To clarify the effect of the initial condition on surf-riding, numerical simulations for the autopilot course of 0 degrees is executed. The results as shown in Fig.2 indicate obtained surf-riding threshold well agrees with numerical bifurcation analysis. However, the zone of the surf-riding exists also in a longer and higher wave area. For resolving this problem, numerical simulation was systematically executed sweeping the wave condition from a periodic state, which is

used as an initial state for a slightly different wave condition. As a result, periodic states could be continuously traced. The results with this method are shown in Fig.3. The zone of surf-riding outside the surf-riding threshold in a longer and higher wave area completely disappears. This means the surf-riding coexists with periodic motion in this particular zone. Therefore, it can be concluded that a ship running with a constant propeller RPM cannot suffer surf-riding in this larger and higher wave area.

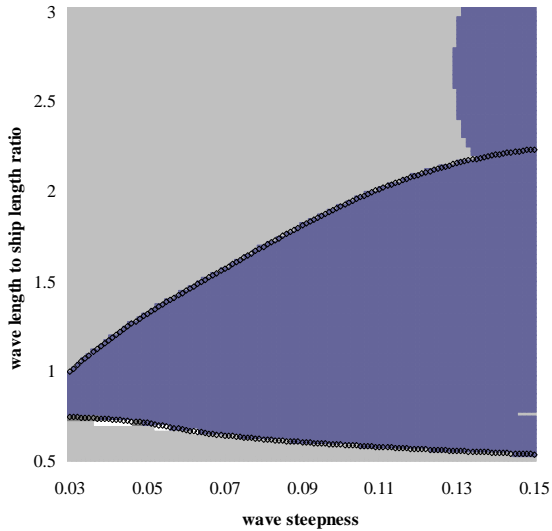


Fig.2 Wave conditions for surf-riding and periodic motion using individual initial conditions with the nominal Froude number of 0.35 and the autopilot course of 0.0 degrees

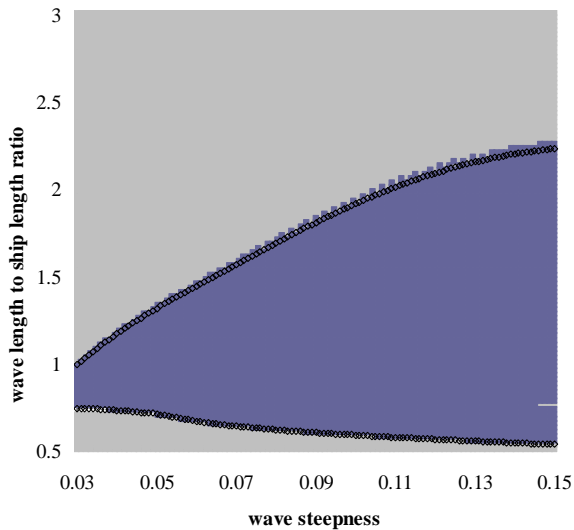


Fig.3 Wave conditions for surf-riding and periodic motion tracing periodic states with the nominal Froude number of 0.35 and the autopilot course of 0.0 degrees

Following the success of the autopilot course of 0 degrees, the same method is applied to the case of the autopilot of 10 degrees. The results as shown in Fig.4 show that the capsizing zone in longer and higher waves is only partly removed. In other words, existence of capsizing outside the surf-riding threshold is not only the effect of inappropriate initial conditions.

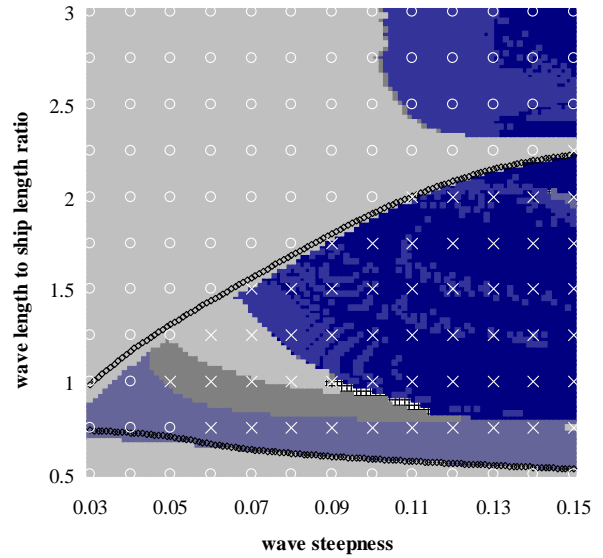


Fig.4 Wave conditions for qualitatively categorised ship motions from the numerical simulation tracing periodic states using the proportional gain of 1.0 and no differential gain with the nominal Froude number of 0.35 and the autopilot course of 10.0 degrees

To investigate ship behaviours in the capsizing zone outside the surf-riding thresholds, the ship motion trajectories here are plotted as the function of the longitudinal position of the centre of the ship gravity, ξ_G , normalised with the wavelength, λ . Fig.5 shows the ship velocity in the wave direction and Fig.6 does the roll and yaw angles. The ship velocity in the wave direction here is always smaller than the wave celerity so that this ship behaviour is not relevant to surf-riding. The oscillatory roll angle gradually develops and finally results in capsizing. It is noteworthy here that periods of roll and yaw angles are twice as long as the encounter frequency.

This phenomenon was theoretically explained with a simplified model as parametric oscillation due to wave exciting yaw moment depending on heading angle ⁷⁾, which can be regarded as a kind of time-dependent restoring term, and can be removed with the increase of differential gain of the autopilot ⁷⁾. Thus numerical simulations with the proportional gain of 1.0 and the different differential gains are executed and the results with the differential gain of 5.0 seconds are shown in Fig.7. Here the capsizing zone outside the surf-riding threshold becomes sufficiently smaller and only exists with excessively high wave steepness. Further increase of the differential gain induces to rather enlarge the capsizing area. Thus further decrease of the capsizing area outside the surf-riding zone could be realised by application of an optimal control theory ⁸⁾. That could be a future task. The comparison between Figs.4 and 7 indicates that the capsizing zone inside the surf-riding zone does not depend on the differential gain very much but the region of broaching without capsizing enlarges with the increase of the differential gain. This is because the magnitude of rudder action under surf-riding increases with the differential gain but does not efficiently change ship yaw motion under surf-riding ⁹⁾. Considering the above points, it seems to be reasonable that capsizing zone inside the surf-riding threshold are used for calculating probability of capsizing due to broaching.

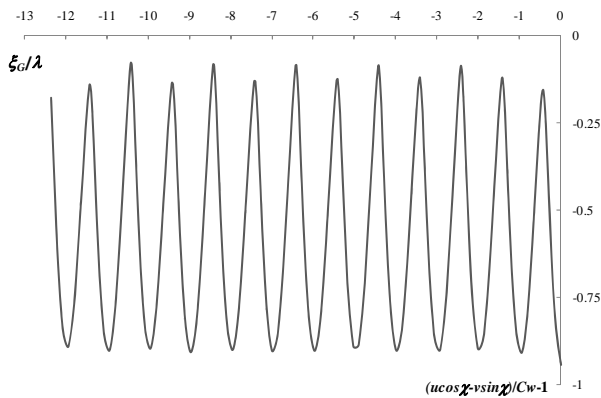


Fig.5 Ship velocity in the wave direction as the function of longitudinal ship position at the wavelength to ship length ratio of 2.5 and the wave steepness of 0.1068.

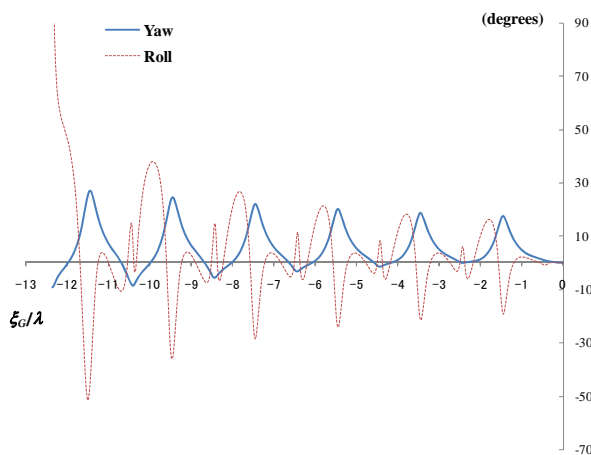


Fig.6 Yaw and roll angles as the function of longitudinal ship position at the wavelength to ship length ratio of 2.5 and the wave steepness of 0.1068.

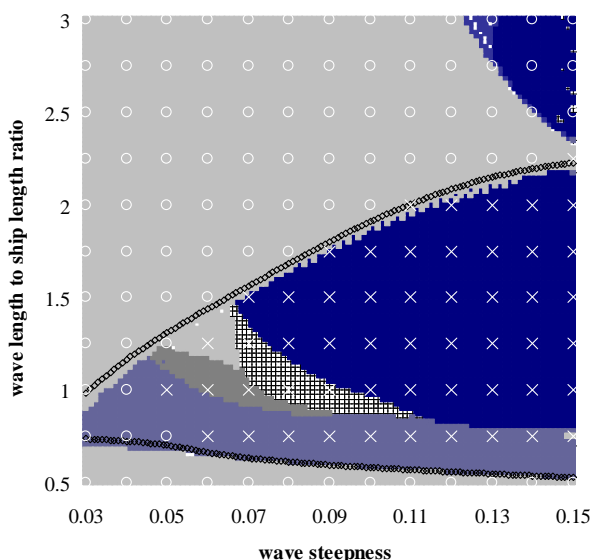


Fig.7 Wave conditions for qualitatively categorised ship motions from numerical simulation tracing periodic states using the proportional gain of 1.0 and the differential gain of 5.0 seconds with the nominal Froude number of 0.35 and the autopilot course of 10.0 degrees

4. CONCLUDING REMARKS

A criterion for avoiding broaching under surf-riding is proposed using comparison of the wave-induced yaw moment amplitude and rudder-induced yaw moment and is verified with the direct numerical simulation.

For calculating probability of capsizing due to broaching associated with surf-riding, it is justified that only deterministic capsizing zones inside the surf-riding threshold should be used as dangerous zones with numerical simulation.

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