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Hydrodynamic Aspects on Vulnerability Criteria for Surf-Riding of Ships

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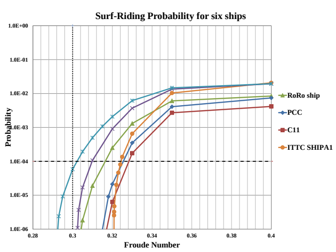
Graphical abstract



Abstract

For developing the International Maritime Organization (IMO) second-generation intact stability criteria regarding broaching, draft vulnerability criteria for surf-riding were agreed at the IMO in 2012. This paper describes their hydrodynamic backgrounds with captive model experiments for seven ships, a hydrodynamic theory and a random process theory. In the first level vulnerability criteria, a ship is required to reduce her Froude number of less than 0.3 in case of severe following waves. For predicting the surf-riding threshold in a global bifurcation theory, it is necessary to precisely estimate wave-induced surge force. Thus, the authors execute captive model experiments for three ships in model basins. As a result, we confirmed that the Froude-Krylov calculation overestimates the amplitude of wave-induced surge force so that an empirical formula for regulatory application is presented. For investigating the reason of this discrepancy, a slender body theory assuming low encounter frequency is applied to the situation where a ship runs with a wave. This theory suggests that change of wave-making resistance due to incident wave could reduce the amplitude of the wave-induced surge force and quantitative agreement with model experiment requires the use of CFD or an empirical formula. Thus, the authors can recommend the use of experimental correction formula for the vulnerability criteria. Based on sample calculation results of surf-riding probability of six ships in the North Atlantic, the safety level to be required in the criteria is proposed.

Keywords: Second-generation intact stability criteria; broaching; surf-riding; slender body theory; surf-riding probability; wave-making resistance

1.0 INTRODUCTION

At the IMO, the second-generation intact stability criteria are now under development for allowing the use of first-principle tools for broaching. It was already agreed that the new criteria should consist of vulnerability criteria and direct stability assessment and be supplemented with operational guidance (IMO, 2008). Then the correspondence group (CG) was established and requested to collect draft criteria together with sample calculation results for sample ships. Responding to this requirement, the delegations of Japan and the United States (2010) jointly submitted draft vulnerability criteria and direct stability assessment method, and then these draft vulnerability criteria for broaching were agreed at the IMO (2012).

Broaching is the phenomenon that a ship cannot keep a constant course despite application of maximum steering effort. Centrifugal force due to such violent yaw motion could result in large rolls. Broaching is often preceded by surf-riding, which occurs when a following wave capture a ship and accelerates the ship to wave-phase speed. A ship can avoid broaching associated with surf-riding if it prevents surf-riding. Thus the draft vulnerability criteria were designed to prevent surf-riding in following waves. Intact stability criteria for broaching is shown in Figure 1.

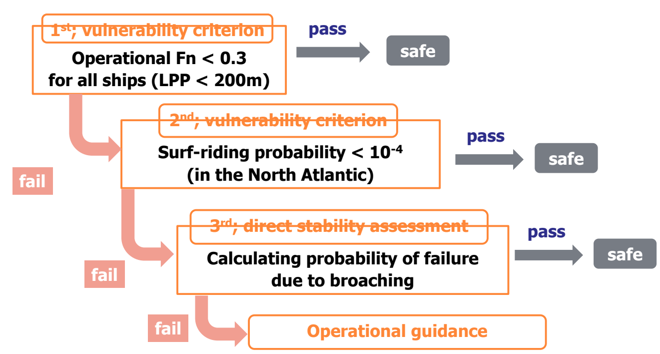


Figure 1 Intact stability criteria for broaching

The first level vulnerability criterion requires operational speed to be smaller than the nominal Froude number of 0.3 for all ships which have length of 200 meters or less. In addition, the second vulnerability criterion requires the ship designer to calculate surf-riding probability in the North Atlantic. Considering these criteria, it is necessary to predict surf-riding threshold, which needs a precisely estimation of wave-induced surge force. Thus in this study we executed captive model experiments for measuring it. The marginally acceptable probability for the second level criterion is requested to be determined. Thus we execute numerical simulations for seven ships in the North Atlantic to determine this value.

■2.0 MODIFYING SURGING FORCE

Methodology for estimating surf-riding threshold using nonlinear dynamics was already well established. Since the occurrence of surf-riding is a global bifurcation so that numerical and analytical bifurcation analyses can estimate surf-riding threshold of uncoupled surge model (Makov, 1969; Kan, 1990; Umeda, 1990; Spyrou, 2006; Umeda *et al.,* 2007; Maki *et al.,* 2010). Here a remained issue is hydrodynamic estimation of the wave-induced surge force. The wave-induced surge force is usually estimated with the Froude-Krylov assumption. It can be calculated with the Equation (1) if a ship is in longitudinal waves.

$$X_W(\xi_G/\lambda) = -\rho g \zeta_a k \int_{AE}^{FE} S(x) e^{-kd(x)/2} \sin k\xi_G \, dx \tag{1}$$

where ρ: the water density, g: gravitational acceleration, ζ_a: the incident wave amplitude, k: the wave number, $S(x)$: sectional area, $d(x)$: sectional draught, ξ_G: horizontal distance from a wave trough to the gravitational centre of the ship, λ: the wave length, AE: the ship aft end and FE: the ship fore end.

Since this force is due to change of buoyancy and is proportional to wave height, it can be normalised with displacement and wave steepness as X'_W.

For the Equation (1), captive model experiments were executed in the towing tank of Osaka University. The scaled models were towed by a towing carriage with a constant velocity in regular following waves. Here the surge force was detected by a dynamometer and the wave elevation was measured by a servo-needle wave probe or a capacitance-type wave probe. The models are free in heave and pitch. The wave steepness, H/λ, the wavelength to ship length ratio, λ/L, and the Froude number, F_n, used in the experiments are relevant to typical surf-riding conditions. The comparison between the measured wave-induced surge force and the Froude-Krylov force are shown in Figures 2-4. The ships used here are the ITTC A1 containership (Umeda *et al*., 2008), the modified C11 class containership (Hashimoto *et al.,* 2006) and the car carrier (Hashimoto *et al.,* 2011). In all cases, the Froude–Krylov calculation overestimates measured wave induced surge force and the measured forces are almost proportional to wave steepness. This indicates that the wave-induced surge force can be regarded as linear at least up to the wave steepness of 0.07 but this does not mean that the Froude-Krylov assumption is valid. The speed effect on the wave-induced surge force is not so significant but the force increases when the speed increases.

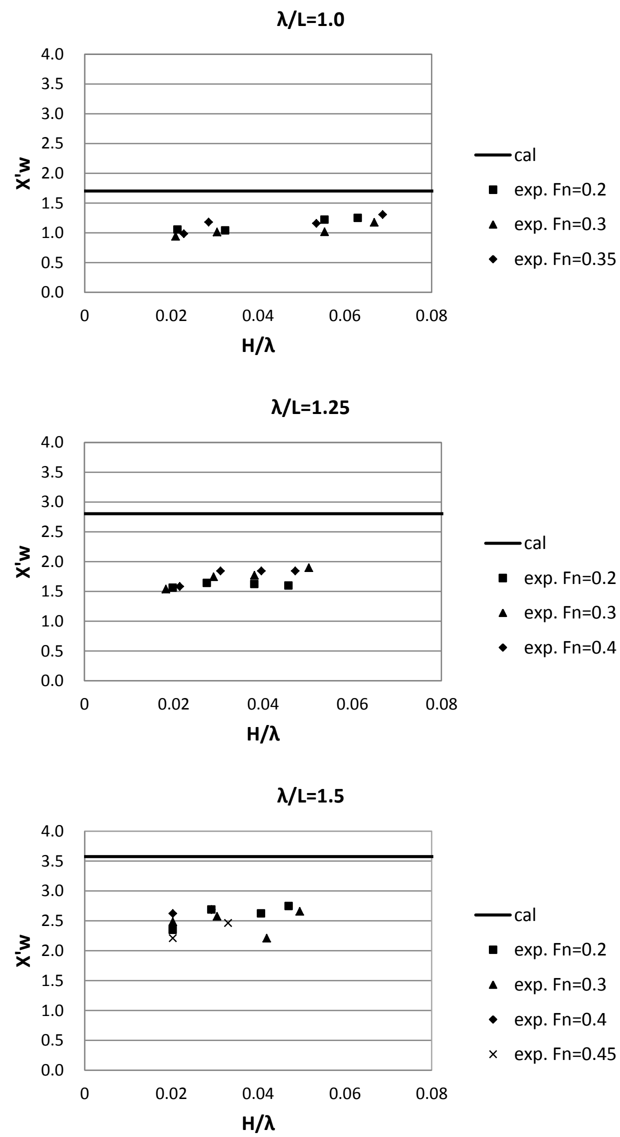


Figure 2 Wave-induced surge force of the ITTC A1 containership

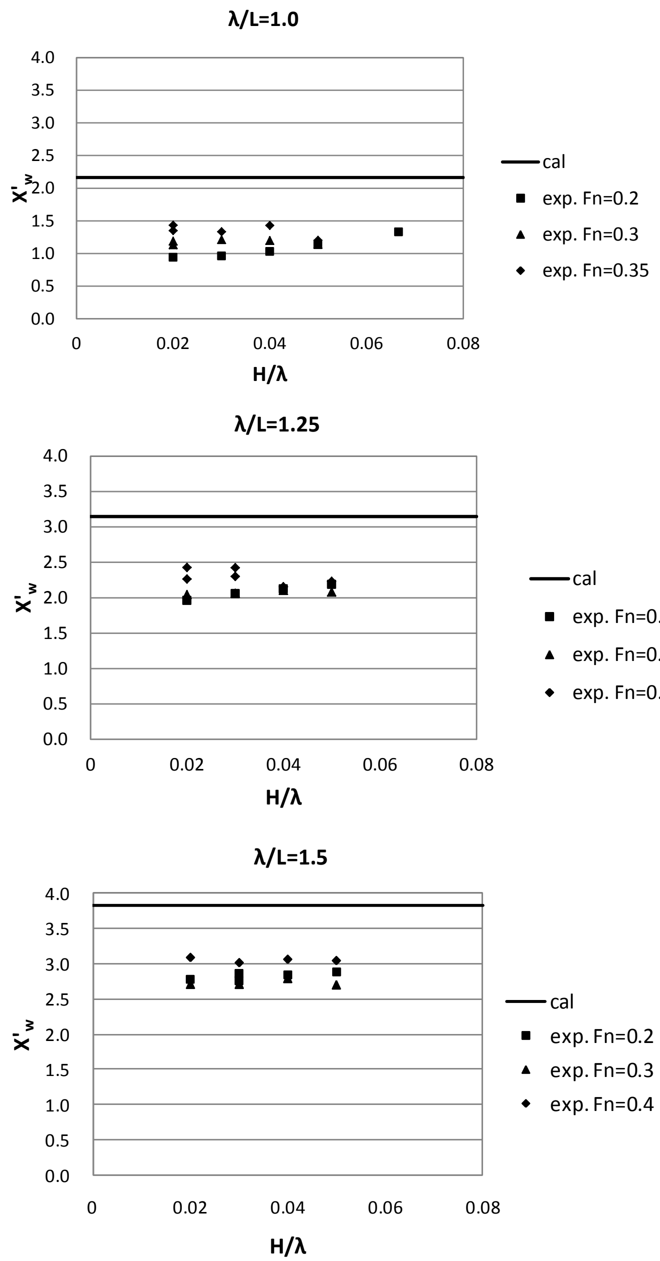


Figure 3 Wave-induced surge force of the modified C11 class containership

As mentioned before, the Froude-Krylov calculation overestimates the measured wave-induced surge force. Thus it is necessary to investigate the reason of discrepancy. Since the measured force is proportional to wave steepness, nonlinearity of hydrodynamics is not relevant. Linear radiation and diffraction forces could have important roles because the Froude-Krylov assumption ignores these. The encounter frequency, however, is very low because of high-speed runs in following waves. As a result, hydrodynamics assuming high encounter frequency, such as a strip theory, is not suitable for this purpose. To overcome this difficulty, Umeda (1983, 1984) applied a thin ship theory to a ship running with waves, e.g. the zero encounter frequency problem, which is directly relevant to surf-riding. He analytically pointed out that periodic changes of wave-making resistance due to incident waves could be comparable to the Froude-Krylov force. This hydrodynamic component is proportional to wave amplitude and has the frequency equal to the encounter wave frequency. Unfortunately, numerical results based on his theory were not good enough to explain the measured results. This is because a thin ship theory is not suitable to quantitatively explain the effect of ship bottom while contemporary ships are beamy.

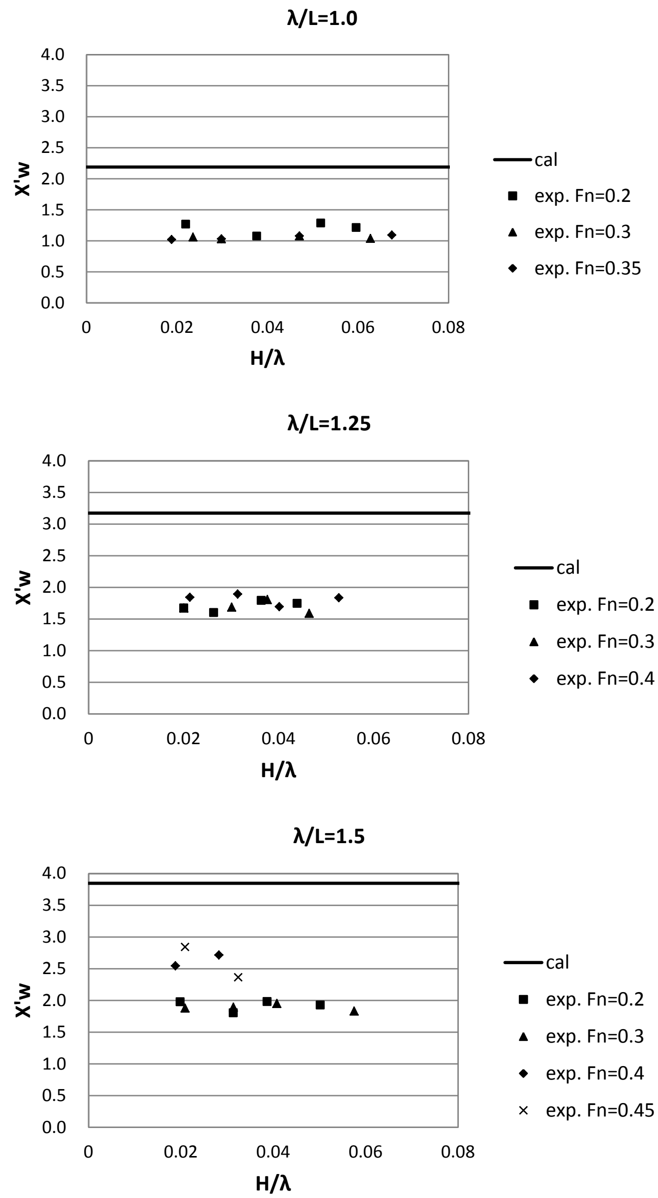


Figure 4 Wave-induced surge force of the car carrier

Therefore, the authors attempt to apply a slender body theory (e.g. Maruo, 1962) to the current problem in place of a thin ship theory. This means that we assume that a ship is slender, the length of ship-generated wave is comparable to ship length, the encounter frequency is zero and fluid can be expressed with a velocity potential. The coordinate systems for this calculation is shown in Figure 5.

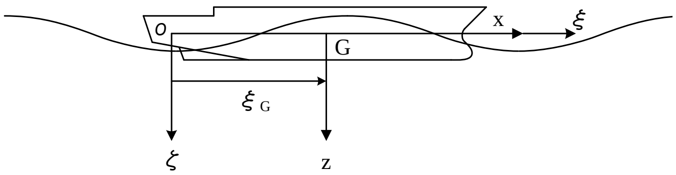


Figure 5 The coordinate systems

In the far field, i.e. flow far from the ship, the velocity potential for flow shall satisfy the continuity equation and the linear free surface condition as follows.

$$[L]: \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \qquad (2)$$

$$[F]: U^2 \frac{\partial^2 \phi}{\partial x^2} - g\frac{\partial \phi}{\partial z} = 0 \quad on \ z = 0 \qquad (3)$$

where$U$ is the ship forward velocity.

Then the velocity potential for interaction between the ship and waves, ϕ, can be determined as follows:

$$\phi = -\int_L m(\xi) G(x, y, z; \xi, 0, 0) d\xi \qquad (4)$$

where $m(\xi)$ is the strength of source distributed in the centreline of the ship and G is the velocity potential of the Kelvin source (Maruo, 1962).

In near filed, i.e. flow near the ship, the terms of $\frac{\partial}{\partial x}$ can be regarded as higher order. As a result, the conditions to be satisfied are as follows:

$$[L]: \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \qquad (5)$$

$$[F]: \frac{\partial \phi}{\partial z} = -\zeta_w \frac{\partial^2 \phi_S}{\partial z^2} \quad on \ z = 0 \qquad (6)$$

$$[H]: \frac{\partial \phi}{\partial n} = -U\frac{\partial x}{\partial n} + \frac{\partial \phi_I}{\partial n} + U\theta \frac{\partial z}{\partial n} - (\zeta_G - x\theta)\frac{\partial^2 \phi_S}{\partial n \partial z} \qquad (7)$$

On the hull surface

Here, n: the normal to hull surface, ζ_G: heave displacement due to incident waves, θ: pitch angle due to incident waves, ζ_w: the incident wave elevation, ϕ_S: the velocity potential of flow generated by the ship and ϕ_I: the velocity potential of incident waves.

In a slender body theory, the unknown parameter in far field is determined with the matching of far and near field solutions. In this case, the source strength in far filed is determined with the Equation (8) .

$$m_i(x) = -\frac{1}{4\pi} U \frac{\partial}{\partial x}\left[S_i(x) - \{\zeta_G - x\theta - \zeta_W(x)\} B_i(x)\right] \qquad (8)$$

where $B_i(x)$ is the sectional breadth. This means that the source strength due to incident wave is determined with the relative wave elevation.

Once the velocity potential in far field is determined, the wave making resistance can be calculated with a momentum theory as follows (Maruo, 1962):

$$R = \frac{1}{2}\rho\pi U^2 \int_{\pi/2}^{3\pi/2} \left[\{S(\tilde{\theta})\}^2 + \{C(\tilde{\theta})\}^2\right] \cos^3\tilde{\theta} d\tilde{\theta} \qquad (9)$$

where,

$$\begin{aligned}
S(\tilde{\theta}) &= \frac{4K_0}{U} Q \sec^3\tilde{\theta} \\
C(\tilde{\theta}) &= \frac{4K_0}{U} P \sec^3\tilde{\theta} \\
K_0 &= \frac{g}{U^2} \\
P(\tilde{\theta}) &= \sum m_i \cos\{K_0 p_i \sec^2\tilde{\theta}\} e^{-K_0 z_i \sec^2\tilde{\theta}} \\
Q(\tilde{\theta}) &= \sum m_i \sin\{K_0 p_i \sec^2\tilde{\theta}\} e^{-K_0 z_i \sec^2\tilde{\theta}} \\
p_i &= x_i \cos\tilde{\theta}
\end{aligned} \qquad (10)$$

If the encounter frequency tends to zero, the Equation (8) coincides with Maruo's slender body theory in waves (Maruo, 1966). This means that the change of wave resistance due to incident waves is equivalent to radiation and diffraction forces at the zero encounter frequency. Because of zero encounter frequency, it is impossible to calculate this component with a strip theory.

By using the above theory, the change of wave-making resistance due to incident waves is calculated for the ITTC A1 containership with the Froude number of 0.3 and the sum of this component and the Froude-Krylov component are plotted in Figure 6. The results suggests that the change of wave resistance due to incident waves qualitatively explain the discrepancy between the experiment and the Froude-Krylov force. Considering known difficulty for estimating wave resistance in calm water (Maruo, 1962), for quantitative prediction CFD or model experiments should be used. In fact, Sadat-Hosseini *et al.* (2011) already reported that their CFD can explain the wave-induced surge force but without physical explanation mentioned above.

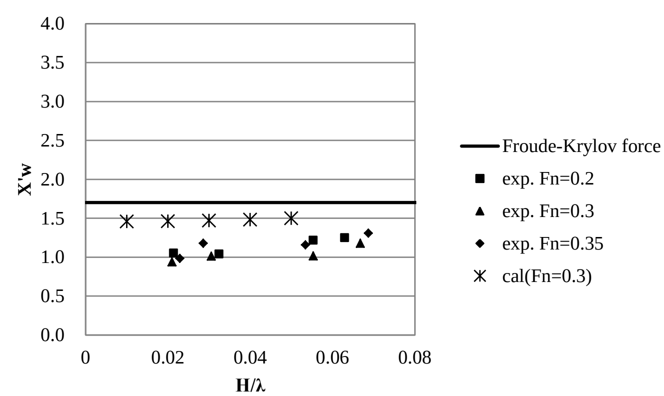


Figure 6 The wave-induced surge force calculated with the slender body theory for the ITTC A1 containership with the wavelength to ship length ratio of 1

■3.0 LEVEL 1ST VULNERABILITY CRITERIA FOR BROACHING

For vulnerability criteria, however, the use of CFD or captive model experiments for each ship is prohibitive. Thus, the authors attempted to propose an empirical formula for the wave-induced surge force using data not only for the subject ship here but also for other published data. The ships used here include the two containership, the car carrier, a RoRo ship, a fishing vessel and two war ships. The ratios of measured values to the Froude-Krylov prediction are plotted in Figure 7. Then it can be found that this factor depends on the block coefficient, C_b, and the midship section coefficient, C_m. As a result, the following formula can be proposed:

$$X_W(\xi_G/\lambda) = -\alpha\rho g\zeta_a k\int_{AE}^{FE} S(x)e^{-kd(x)/2}\sin k\xi_G dx$$
$$\alpha = \begin{cases} 1.46C_b - 0.05 & \text{if} \quad C_m > 0.9 \\ 1.06C_b - 0.05 & \quad\;\; C_m < 0.9 \end{cases} \tag{11}$$

By using this empirical formula and numerical bifurcation analysis (Umeda *et al.*, 2007), we calculated the surf-riding threshold for four different ships in regular following waves with the wave steepness of 1/10, which can regarded as a practical limit of wave steepness. The results shown in Figure 7 indicate that the critical Froude number of 0.3 used in the Level 1 criterion is reasonable.

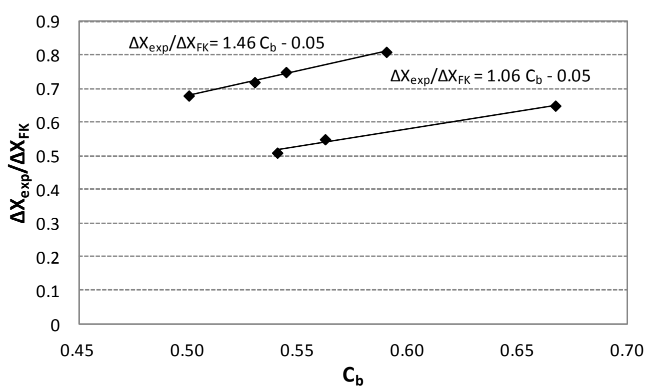


Figure 7 Correction factors of wave-induced surge force for seven ships

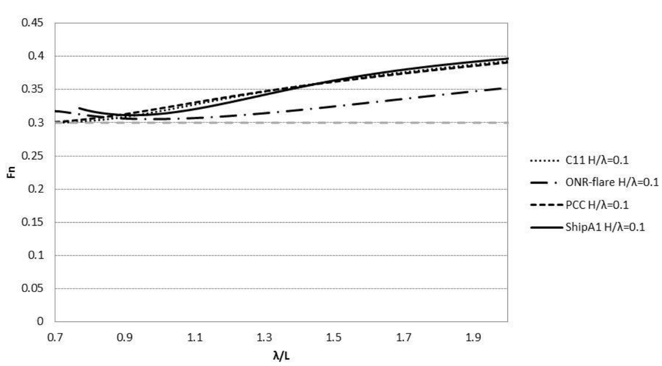


Figure 8 Critical Froude numbers for surf-riding for four different ships estimated by numerical bifurcation analyses in regular waves with the wave steepness of 1/10

■4.0 LEVEL 2ND VULNERABILITY CRITERIA FOR BROACHING

A ship which failed to comply with the 1st vulnerability criterion has to be examined with the 2nd vulnerability criterion. In the 2nd vulnerability criterion, surf-riding probability in irregular following waves shall be calculated. Firstly, combinations of wave height and wave length leading to surf-riding are determined by numerical global bifurcation analysis (Umeda, *et al.*, 2007). The results of this calculation are shown in Figures 8-9 as examples. When the nominal Froude number is larger than that of surf-riding threshold, a ship motion is judged as surf-riding. Then, the probability of encountering these waves in a stationary sea state is evaluated by applying the Longuet-Higgins theory (Longuet-Higgins, 1983). By integrating the sum of probability in each stationary sea state and joint probability density of the significant wave height and the mean wave period in the North Atlantic, the probability of surf-riding when the ship meets a zero-crossing wave in the North Atlantic can be calculated. Here the value of surf-riding probability depends on the minimum wave length used in the calculation for stationary sea states. Generally speaking, short waves may not induce broaching so that surf-riding due to short waves can be ignored. According to model experiments in the Haslar basin (Renilson, 1982), the minimum wavelength to ship length ratio for broaching is about 1.0. Therefore, the waves whose lengths are shorter than the ship length are ignored in calculations.

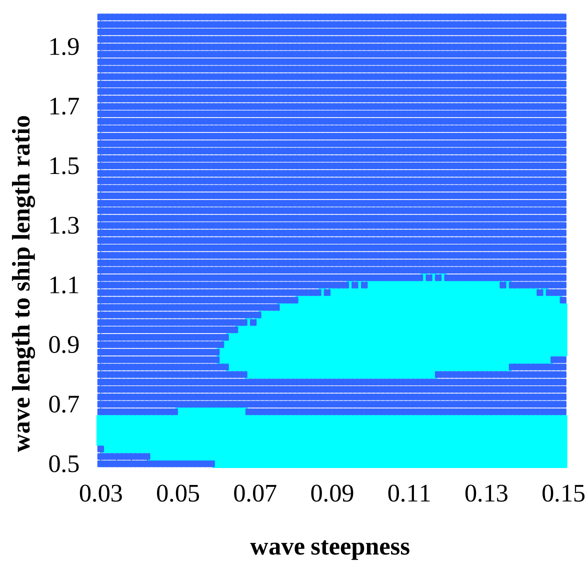


Figure 9 Wave conditions for surf-riding in regular waves with the nominal Froude number of 0.32 for ITTC A1 containership

The results of surf-riding probability in the North Atlantic for six ships are shown in Figure 10. The ships used here include the two containership, the car carrier, the RoRo ship and the two war ships. When the nominal Froude number increases, the probability of surf-riding also increases. If we select 10^{-4} as the marginally acceptable probability, the critical Froude number for each ship is larger than 0.3, which is ship-independent critical Froude number in the Level 1 criterion. This means that the Level 2 criterion is less stringent than the Level 1 criterion. In other words, if we apply the Level 2 criterion, the operational speed range could increases.

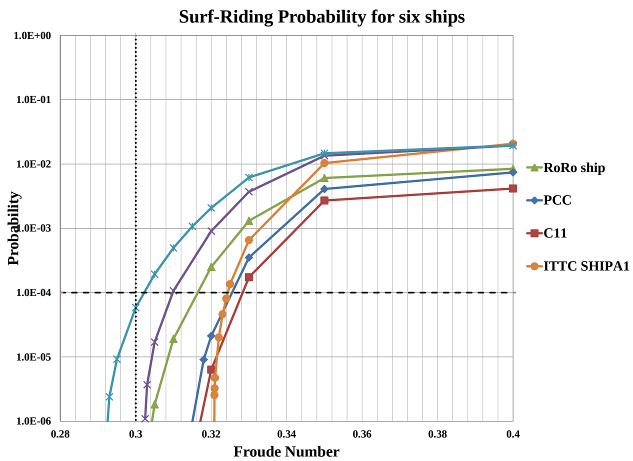


Figure 10 Surf-riding probability for six ships in the North Atlantic

■5.0 CONCLUSION

The draft level 1st and 2nd level vulnerability criteria are validated by captive model experiments, global bifurcation analysis, and numerical simulation. For accurately estimating the wave-induced surge force, we should take account of not only the Froude-Krylov force but also the change of wave-making resistance due to incident waves, which can be dealt with a slender body theory with zero encounter frequency. For regulatory uses, an empirical formula is proposed based on captive model tests for seven ships. Furthermore, as the marginally acceptable surf-riding probability in the Level 2 criterion the value of 10^{-4} is proposed based on sample calculation for six ships.

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