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The influence of wave surge force on surf-riding/broaching vulnerability criteria check *

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Abstract: This study focuses on the influence of the wave surge force on the assessments of the surf-riding/broaching vulnerability criteria according to the new proposal of the IMO Second Generation Intact Stability Criteria. A code is developed for the criteria check and the sample ship calculations show that the accuracy of the wave surge force estimation has a significant influence on the assessment result. For further investigation, the wave surge force measurement through a captive model test is made for a purse seiner to validate the numerical model, the effects of the wave steepness and the ship forward speed on the wave surge force responses are also discussed. It is demonstrated that the diffraction effect is important for the correct estimation of the wave surge force. Therefore, it is recommended to include this effect in the assessment procedure.

Key words: Intact stability criteria, surf-riding/broaching, sample calculation, wave surge force, captive model test

Introduction

In order to ensure the safety of ships in waves more effectively, the International Maritime Organization (IMO) is currently working on the second generation intact stability criteria to include five new stability failure modes: the pure loss of stability, the parametric roll, the dead ship condition, the surf-riding/broaching and the excessive acceleration[1,2]. Among them, broaching is considered to be the most complicated due to its highly nonlinear and chaotic nature[3,4]. The broaching occurs when a ship cannot keep a constant course despite the maximum steering effort, typically in the following and quartering waves. The surf-riding is usually regarded as the prerequisite of the broaching when a ship is captured by the wave approaching from the stern that accelerates the ship to the wave celerity[5]. Small-size high-speed ships are most vulnerable to this stability failure mode.

The mechanism behind this hazardous phenomenon, was extensively studied both theoretically and experimentally in recent decades. Maki et al.[6,7] and Wu et al.[8] made surf-riding predictions through theoretical formulations based on heteroclinic bifurcation. Umeda et al.[9-11] carried out free running model experiments and demonstrated that a ship complying with the existing IMO stability code can still be capsized as a result of broaching. Hashimoto and Stern[12] and Carrica et al.[13] applied the CFD method for an advanced broaching prediction to identify more details behind this phenomenon. Yu et al.[14] studied the influence of hull parameters on the mitigation of surf-riding. Another breakthrough is the proposal of the analytical formulae based on the Melnikov method and the split-time formulation for predicting the ship surf-riding threshold in the following seas[15,16], which forms the foundation for the development of surf-riding/broaching vulnerability criteria.

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According to the latest IMO draft document[17], a three-level approach is adopted for the assessment of the surf-riding/broaching vulnerability criteria: in the Level 1 evaluation, only the ship length and speed information is required, the Level 2 evaluation is based on a simplified surf-riding model and the probability of the surf-riding occurrence in an irregular seaway is chosen as the criteria for assessment, the Level 3 evaluation involves a direct stability assessment and the detailed procedures are still under discussion[18].

This paper focuses on the influence of the wave surge force on the Level 2 assessment result. Studies concerning the parametric rolling show that the reliability of the wave force estimation plays an important role in the prediction model[19-21]. However, its influence on the assessment result of the surf-riding/broaching stability failure remains an issue to be explored. In the current prediction model, only the Froude-Krylov component of the wave surge force is taken into account. As pointed out in Ref.[17]: for calculating the amplitude of the wave surge force, the Froude-Krylov component on its own might often be over-estimated. Correspondingly, an empirical diffraction effect correction factor is proposed. On the other hand, the current wave force estimation model is based on the linear theory (with the small wave amplitude assumption) and the effect of the ship forward speed is neglected. However, a large wave heights and a high ship speed are necessary for the occurrence of surf-riding/broaching. Therefore, it is meaningful to measure the wave surge forces by the captive model experiment in order to validate this empirical formula and investigate the effect of the wave steepness and the ship forward speed.

1. Vulnerability criteria for surf-riding/broaching

The assessment procedures for the Level 1 and Level 2 surf-riding/broaching stability failure are based on the contents of Annex 32 and Annex 35 in SDC 2/INF.10[17], which is the latest draft document available. The criteria apply to all ships with length equal to, or greater than 24 m. Assessments should be performed for each loading condition of the ship.

$$L > 200\ \text{m} \quad \text{or} \quad Fr < 0.3 \tag{1}$$

where $Fr = V_S / \sqrt{Lg}$ is the Froude number, V_S is the ship service speed in calm water, L is the ship length. If the ship fails to pass the Level 1 criteria, the subsequent Level 2 assessment is needed.

For a ship to pass the assessment of the Level 2 vulnerability criteria, it is required that

$$C < R_{SR} \tag{2}$$

where C represents the probability of the surf-riding occurrence, R_{SR} is the standard value, which is 5×10^{-3}. The value of C is estimated by

$$C = \sum_{H_S}\sum_{T_Z}\left[W2(H_S,T_Z)\frac{\sum_{i=1}^{N_\lambda}\sum_{j=1}^{N_a} W_{ij} C2_{ij}}{\sum_{i=1}^{N_\lambda}\sum_{j=1}^{N_a} W_{ij}} \right] \tag{3}$$

where $W2(H_S,T_Z)$ is the weighting factor of each sea state according to the long-term wave statistics, H_S is the significant wave height, T_Z is the zero-crossing wave period, W_{ij} is the statistical weight of a wave with the steepness $s_j = (H/\lambda)_j$ varying from 0.03 to 0.15, and the ratio of the wave length to the ship length $r_i = (\lambda / L)_i$ varying from 1.0 to 3.0. Details concerning the calculations of these factors are specified in SDC 2/INF.10[17].

$C2_{ij}$ is the key element indicating whether surf-riding/broaching will occur for each wave case, which is defined as:

$$C2_{ij} = 1 \quad \text{if} \quad Fr > Fr_{cr}(r_j, s_i) \tag{4a}$$

$$C2_{ij} = 0 \quad \text{if} \quad Fr \le Fr_{cr}(r_j, s_i) \tag{4b}$$

where $Fr_{cr} = u_{cr} / \sqrt{Lg}$ is the critical Froude number corresponding to the threshold of the surf-riding (when the surf-riding occurs under any initial condition), u_{cr} is the critical ship speed determined by solving the following equation with the critical propeller revolution n_{cr}

$$T_e(u_{cr}, n_{cr}) - R(u_{cr}) = 0 \tag{5}$$

where $R(u)$ is the calm water resistance of the ship approximated by an Nth order polynomial

$$R(u) \approx \sum_{i=0}^{N} r_i u^i = r_0 + r_1 u + r_2 u^2 + \cdots \tag{6}$$

$T_e(u,n)$ is the propeller thrust in calm water, which is modeled by:

$$T_e(u,n) = (1 - t_P)\rho n_{cr}^2 D_P^4 K_T(J) \tag{7}$$

$$K_T(J) \approx \sum_{i=0}^{N} \kappa_i J^i = \kappa_0 + \kappa_1 J + \kappa_2 J^2 + \cdots \tag{8}$$

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