An Investigation into the Factors Affecting Probabilistic Criterion for Surf-Riding

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ABSTRACT

The second generation intact stability criteria for broaching are now under development. In this process, several elements should be investigated with nonlinear ship dynamics and stochastic theories for regulatory application. First, the effect of diffraction effects on surf-riding probability was investigated so that the effect is essential for reasonable operational limitation. Second, the effect of estimation of calm-water resistance was examined so that reasonably good fitting of resistance curve is proposed. Third, the effect of different stochastic wave theories was also investigated. These results could provide a base of discussion at the IMO.

Keywords: *Broaching, diffraction effect, IMO, Second generation intact stability criteria, stochastic wave theory*

1. INTRODUCTION

When surf-riding occurs, a ship occasionally suffers broaching, which could results in capsizing. Therefore, the International Maritime Organisation (IMO) circulated its operational guidance for preventing surf-riding (IMO, 1995) and drafted its design criteria for surf-riding (Japan, 2014) as a part of the second generation intact stability criteria. These operational and design requirements are based on global bifurcation analyses, i.e. phase plane analysis and the Melnikov analysis, because surf-riding can be regarded as a global bifurcation of uncoupled surge motion in regular following waves.

Although these approaches were well validated with model experiments, some additional elements should be developed for regulatory criteria. Firstly wave-induced surge force, which induces surf-riding, should be accurately estimated. Secondly, ship calm-water resistance, which could prevent surf-riding, should be practically modelled. Thirdly, a gap between the global bifurcation of periodically excited system and realistic irregular waves should be resolved. Finally the relationship between the surf-riding and capsizing should be established for proper use of direct stability assessment in future. Thus, this paper attempts to provide some guides for these elements for establishing operational and design criteria, following outline of the draft surf-riding criteria at the IMO.

2. OUTLINE OF PROBABILISTIC SURF-RIDING CRITERION

2.1 Surf-riding threshold in regular waves

The draft criterion utilises calculation of surf-riding probability for a given ship in the North Atlantic or its operational area. Firstly, the surf-riding threshold in various regular waves is systematically calculated with the wave- induced surge force, calm-water ship resistance, propeller thrust and displacement. Here the Melnikov analysis is used to determine the bifurcation point where a trajectory starting from one unstable surf-riding equilibrium point coincides with a trajectory from another unstable surf-riding threshold. This means that such trajectory is definitely a periodic orbit but its period is infinite because reaching an unstable equilibrium requires infinite time. Thus this bifurcation point can be regarded as a border between periodic states and the equilibrium which is surf-riding. In this analysis, this bifurcation point is straightforwardly calculated by solving a nonlinear equation without time domain simulation. The Melnikov analysis is applied to this issue by Kan (1990) with linear calm-water resistance model and then Spyrou (2006) proposed to use cubic calm-water modelling. The formula used here allows us to use any order polynomial fitting of ship resistance, which was well validated in model experiments (Maki et al., 2010).

2.2 Surf-riding probability in irregular waves

In the draft criterion, the given ship is judged as vulnerable to broaching if the surf-riding probability in the North Atlantic is larger than the acceptable level. The surf-riding probability is calculated by integrating the probability density of local wave height and wavelength in which operational speed is above the surf- riding threshold as obtained in the section 2.1. This procedure appeared in Umeda (1990) is based on the assumption that irregular waves can be divided into a train of many local waves having different heights and lengths because surf-riding occurs only with one local wave. Indirect validation of this procedure in the light of the Monte Carlo simulation for pitch motion can be found in Umeda et al. (2011). The probability density of local waves can be calculated by Longuet-Higgins's works (1983) or equivalent, assuming that ocean waves are narrow-banded process. Their validation results used the field observation by Goda (2000). Furthermore, by using a wave scattering diagram and the results obtained so far, surf- riding probability for a certain water area can be calculated.

3. DIFFRACTION EFFECT ON SURF-RIDING

3.1 Wave-induced surge force

Surf-riding means that a ship runs with a wave. Thus the encounter frequency is zero. For predicting surf-riding, it is essential to accurately predict wave-induced surge forces at zero encounter frequency. If we could ignore disturbance due to a ship, the Froude-Krylov force, which can be easily calculated, could be sufficient. Many comparisons between model experiments and the Froude-Krylov prediction, however, indicate that the Froude-Krylov approach significantly overestimates the experiment (e.g. Ito et al., 2014). An example is shown in Figure 1.

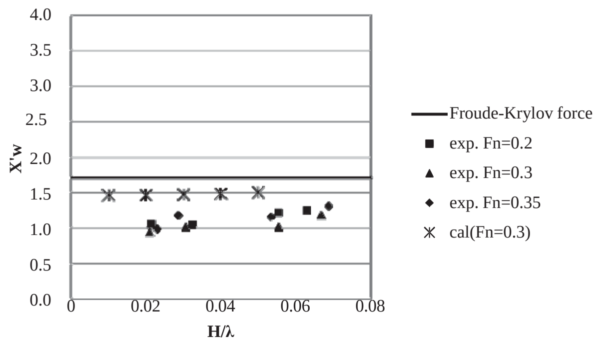

Figure 1 Wave-induced surge force for the ITTC A1 containership with the wavelength to ship length ratio of 1 for different wave steepnesses, H/λ, and the Froude numbers, F_n. Here the wave-induced surge force is normalised with the product of ship weight and wave steepness. (Y. Ito, et al., 2014).

These results indicate that the measured wave- induced surge force is almost linear so that this discrepancy cannot be explained with wave nonlinearity. Thus Umeda (1984) and Ito et al. (2014) applied a thin ship theory and a slender body theory, respectively. Here diffraction effect, i.e. change of wave-making resistance due to periodic change of incident wave profile, is theoretically calculated because the three-dimensional wave pattern due to an oscillatory point source at the zero encounter frequency tends to that due to the Kelvin source. The strength of source distribution can be determined with the hull surface condition with water particle velocity due to waves taken into account. As shown in Figure 1, this diffraction effects explain the discrepancy between the model experiment and the Froude-Krylov prediction to some extent. More quantitative agreement can be achieved with the CFD simulation (Sadat-Hosseini et al., 2011.)

3.2 Diffraction effect on surf-riding probability

It was already published that diffraction effect on surf-riding threshold in regular waves is indispensable to avoid inconsistency between the IMO operational guidance and the draft criteria (Umeda et al., 2011). The critical nominal Froude number for surf-riding estimated with the Froude-Krylov force on its own could be smaller than 0.3, which is requirement of the IMO operational guidance, while that with the measured wave force is larger than 0.3.

As a next step, it is necessary to quantify the diffraction effect on surf-riding probability as the final output of the draft criterion. The comparisons of surf-riding probability with and without diffraction force are conducted as shown in Figures 2-7. The subject ships used here are two containerships, a pure car carrier (PCC), a RoRO ship and two hypothetical war ships. Their principal particulars are shown in Table 1.

Table 1 Principal particulars of the subject ships

	C11 container-ship	ITTC A1 container-ship	RoRo	PCC	ONR- flare	ONR-tumblehome
Length : L_{BP}(m)	262.0	150.0	187.7	192.0	154.0	154.0
Breadth:B(m)	40.0	27.2	24.5	32.26	18.78	18.78
Mean Draught: d(m)	11.5	8.5	6.9	8.18	5.494	5.494
Block coefficient: C_b	0.560	0.667	N/A	0.537	0.536	0.536
Metacentric height: GM (m)	0.56	0.739	1.00	1.25	0.755	2.07

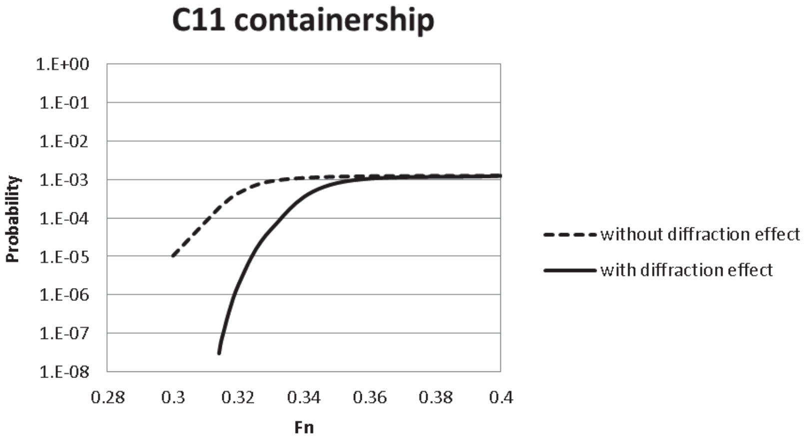

Figure 2 Surf-riding probability for the modified C11 containership with and without diffraction effect.

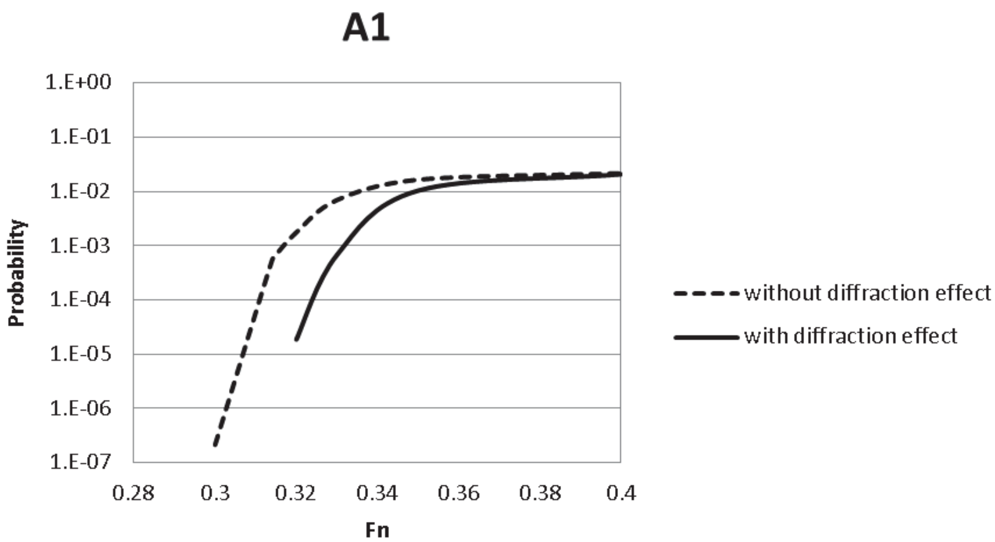

Figure 3 Surf-riding probability for the ITTC A1 containership with and without diffraction effect.

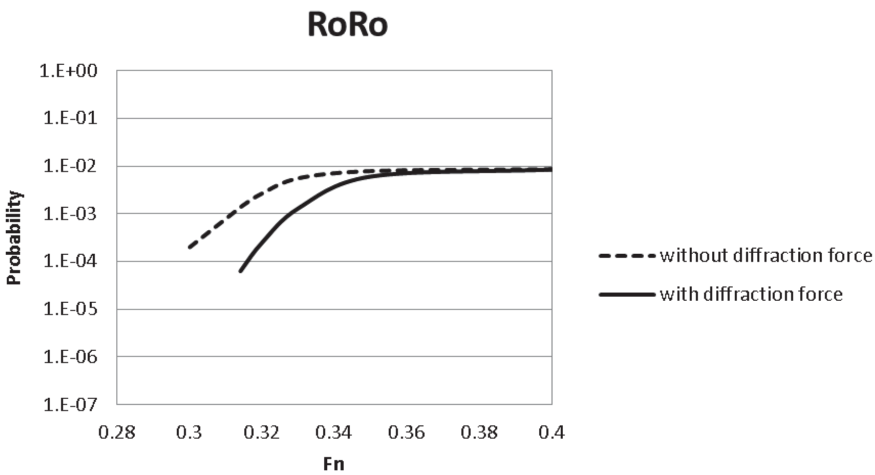

Figure 4 Surf-riding probability for a RoRo ship with and without diffraction effect.

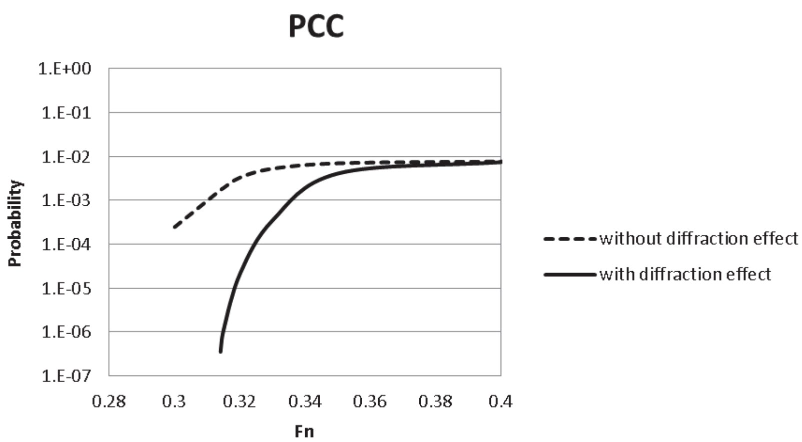

Figure 5 Surf-riding probability for a car carrier with and without diffraction effect.

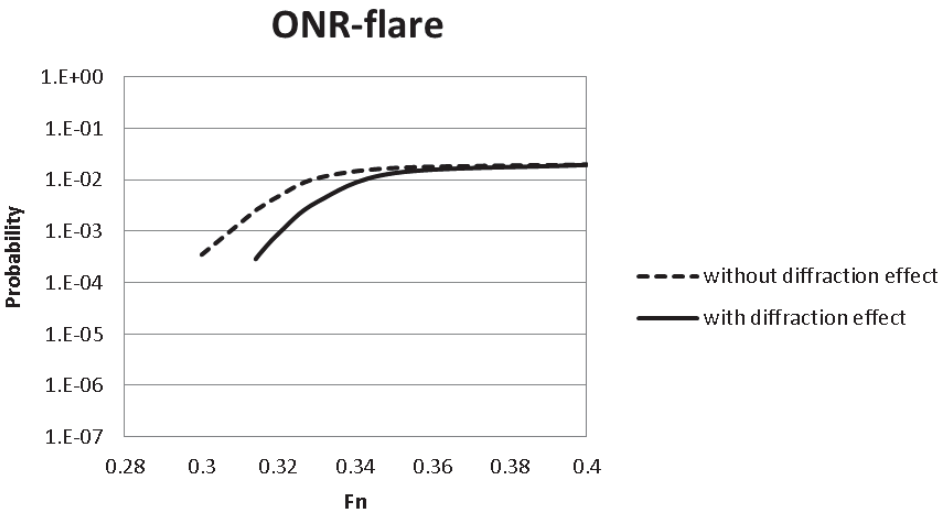

Figure 6 Surf-riding probability for the ONR flare topside vessel with and without diffraction effect.

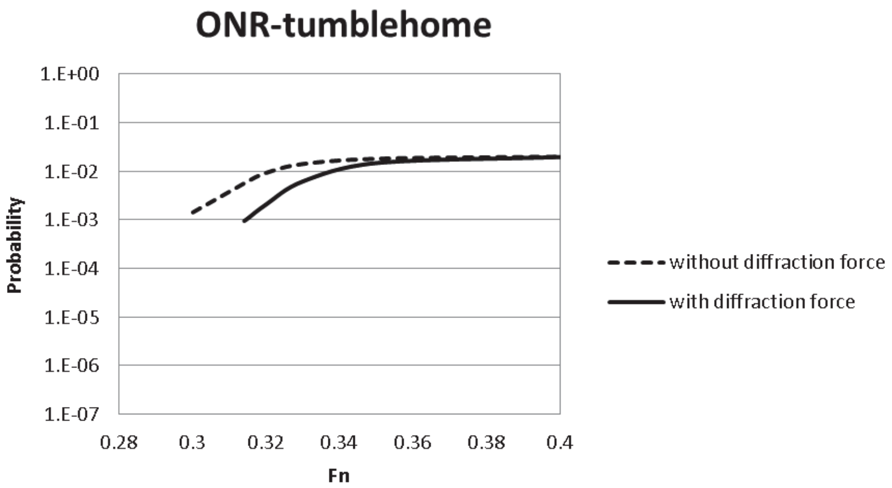

Figure 7 Surf-riding probability for the ONR tumblehome topside vessel with and without diffraction effect.

These comparisons demonstrate that surf-riding probability without diffraction effect is significantly larger than that with diffraction effect. As a result, for avoiding inconsistency with the operational requirement, the acceptable probability level is 10^{-4} with diffraction force and 5 x 10^{-3} without diffraction effect (Japan, 2015).

Then a question could arise: this difference in acceptable probability is crucial or not. It can be quantify with Equation (1).

$$P(T) = 1-(1-p)^{T/T_e} \quad (1)$$

where P: probability of surf-riding within the time interval of T, p: conditional probability of surf-riding when the ship meets a wave and T_e: average of encounter wave period. By using Equation (1), the time interval of non-surf- riding, Ts, can be calculated with Equation (2).

$$T_s = T_e \log(1-p)/\log(1-P) \quad (2).$$

Thus, if we assume T_e=10 s and the confidence level of 5 per cent, p=10^{-4} and 5 x 10^{-3} could result in T_e=1.4 hours and 1.7 minutes, respectively. This result clearly indicates that an estimation without diffraction effect is not practical.

4. EFFECT OF CALM-WATER RESISTANCE SAMPLING ON SURF-RIDING

Other than the wave-induced surge force, calm- water ship resistance is an important factor for estimating surf-riding. Prediction of calm-water ship resistance itself is rather a routine for naval architects for guaranteeing ship speed and for complying with the EEDI (Energy Efficiency Design Index) requirement. Model test for these purposes, however, is not always executed for a given ship design. Thus, it is appropriate to allow the use of speed/power trial. In this case we should examine whether the estimation with only limited number of ship speed is sufficient or not. For providing an answer for this question, the authors attempt to verify the use of speed/power trial in place of model test.

For the sample ships in this paper, we already completed model tests in calm-water up to the Froude number of 0.6. Firstly all available test data was fitted with a quintic curve. Secondly, to simulate speed/power trial we sampled three conditions, i.e. service speed, maximum service speed and maximum speed, from the model test data. We assumed here that the service speed corresponds to 85 per cent of the MCR (Maximum Continuous Rating), the maximum service speed does 100 per cent of the MCR and the maximum speed does 110 per cent of the MCR. Then the speed/resistance curve is fitted with a quadratic model, which requires three unknown parameters.

Figures 8 and 9 show examples of comparisons of fitted calm-water resistances. As a whole, quintic modelling with all experimental data is quite satisfactory. For the ONR tumblehome topside vessel as shown in Figure 8, the sampled speeds coincides with wave celerity range for wavelength to ship length ratio from 1.0 to 1.2 so that quadratic modelling well agrees with the quintic modelling for higher speed range. For the PCC, the sampled speeds are slower but the agreement with the quintic modelling is not so unsatisfactory. This might be because quadratic modelling, which has only one trough, is more robust than cubic modelling or higher order polynomial modelling.

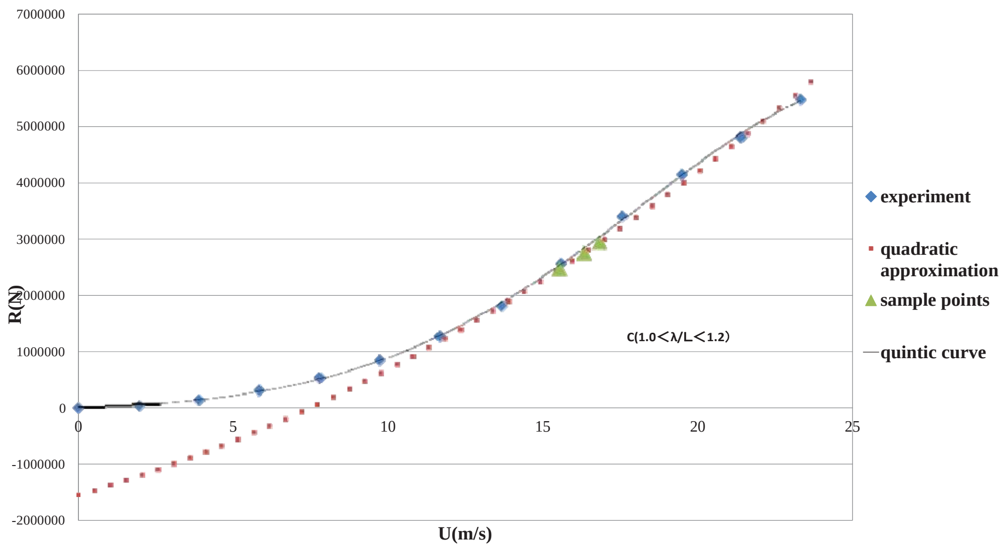

Figure 8 Calm-water resistance of the ONR tumblehome topside vessel

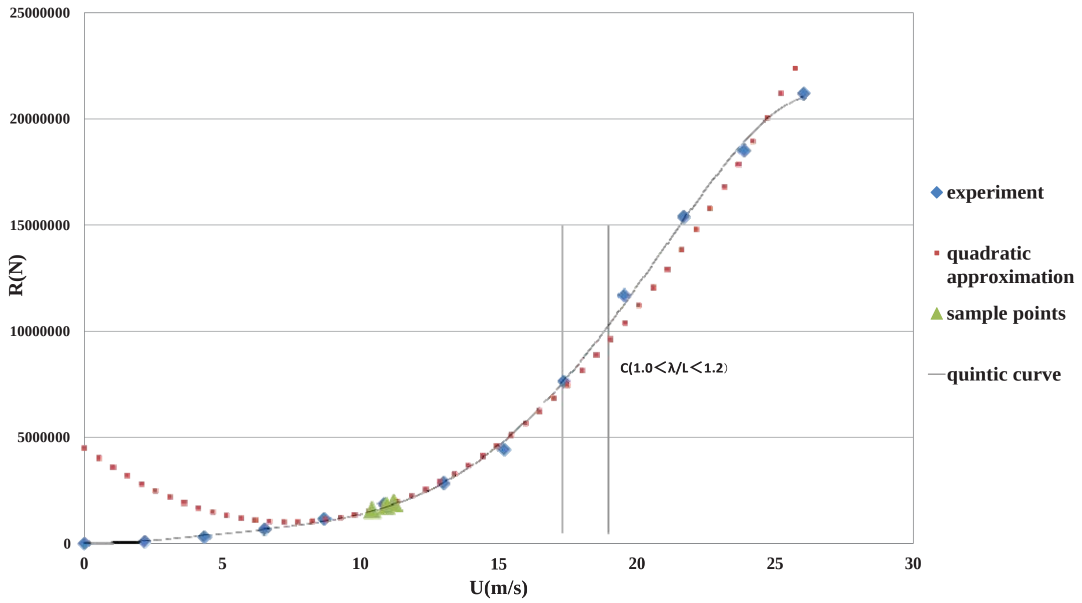

Figure 9 Calm-water resistance of the PCC

Furthermore, surf-riding probabilities of the sample ships are calculated with different calm-water modelling. The results shown in Figures 10-15 demonstrate that surf-riding probabilities with three speed sampling well agree with those with full range sampling. This could be because good agreement of calm- water resistance in the wave celerity range for wavelength to ship length ratio from 1.0 to 1.2, which is responsible for surf-riding prediction.

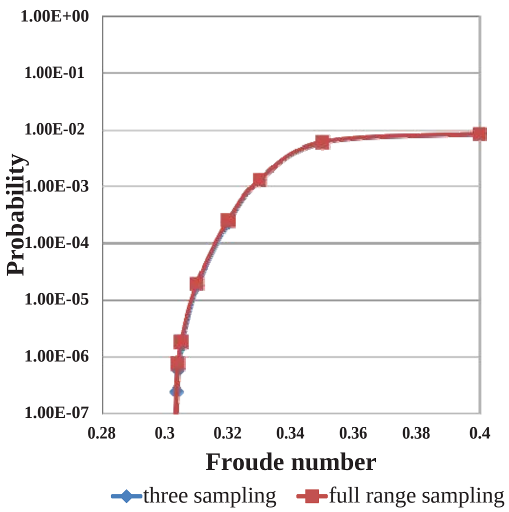

Figure 10 Effect of calm-water resistance modellng on surf-riding probability of the RoRo ship

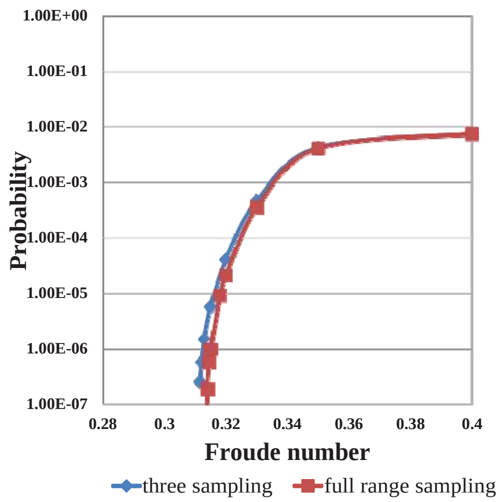

Figure 11 Effect of calm-water resistance modellng nn surf-riding probability of the PCC

5. EFFECT OF STOCHASTIC WAVE THEORIE

In the draft criterion, it is necessary to calculate the joint probability density function of wave height and wavelength in a stationary seaway specified as a wave spectrum with Longuet- Higgins's work (1983) or equivalent. In 1957 Longuet-Higgins derived the formula by using the joint probability density of amplitude and phase of wave envelope. Here the relationship between the local wave period,

T, and wave envelope phase, ϕ, was simplified as

$$T = 2\pi/(\bar{\sigma} + \dot{\phi}) \quad (3)$$

$$\approx T_{01}(1 - \dot{\phi}/\bar{\sigma}) \quad (4)$$

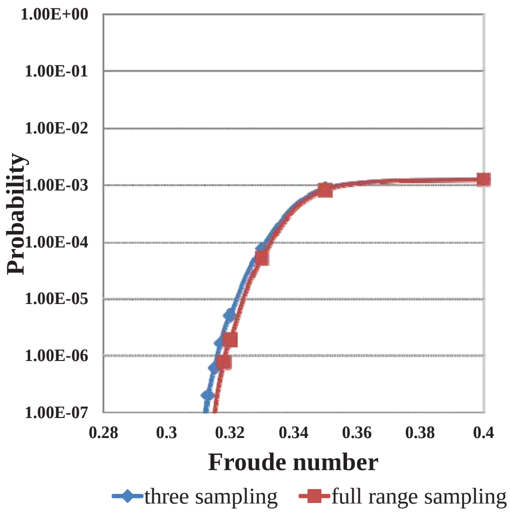

Figure 12 Effect of calm-water resistance modellng on surf-riding probability of the C11 class containership

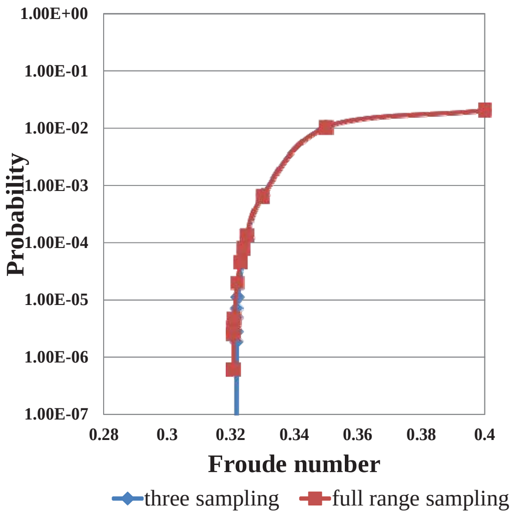

Figure 13 Effect of calm-water resistance modellng on surf-riding probability of the ITTC A1 containership

where T_{01} is the mean wave period, σ is the mean wave circular frequency and a dot indicates differentiation with time. Later on it was pointed out that this formula cannot explain the physically observed fact that short local waves have smaller wave local height. Then, in 1983, Longuet-Higgins revised his own formula with more precise relationship between the local wave period and wave envelope phase, i.e. Equation (3) in place of Equation (4). As a result, he resolved the draw back of his original formula.

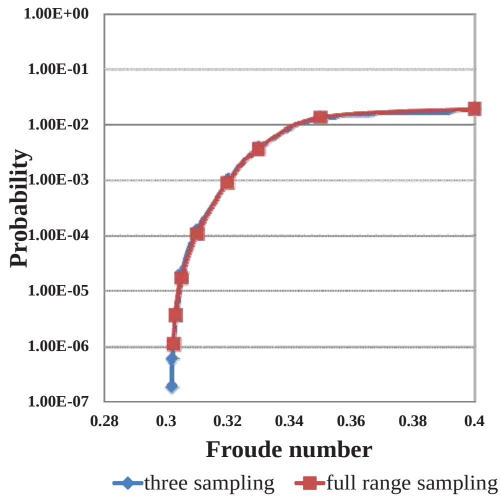

Figure 14 Effect of calm-water resistance modellng on surf-riding probability of the ONR flare topside vessel

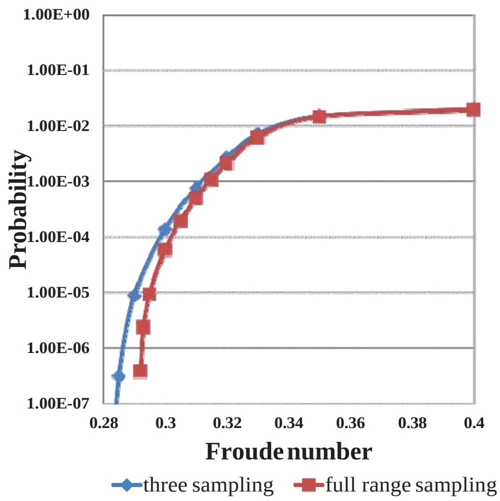

Figure 15 Effect of calm-water resistance modellng on surf-riding probability of the ONR tumblehome topside vessel

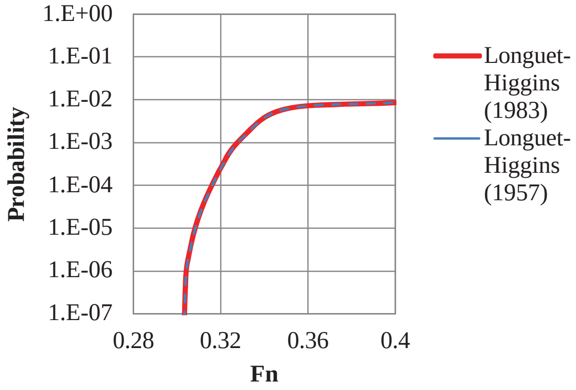

Figure 16 Effect of the wave probability formulae on surf-riding probability of the RoRo ship

It is indispensable for practical application of them to quantify effect of these two different formulae on surf-riding probability. Thus the authors executed comparison studies using the subject ships. The result shown in figure 16 as an example indicates the difference in surf-riding probability is negligibly small. This could be partly because the subject ships are longer so that they do not respond to smaller waves. Thus it can be presumed that at least the use of the formula in Longuet-Higgins (1983) is recommended although a similar study using a smaller ship is desirable.

6. RELATIONSHIPS WITH BROACHING

If a ship does not comply with the draft criterion for surf-riding, it is expected that her safety against capsizing due to surf-riding/broaching is examined with the direct stability assessment, in which failure probability in irregular seaways is directly estimated with a numerical time-domain simulation. This is because surf-riding is only a prerequisite for broaching or capsizing.

For verifying this approach, the authors calculate also probability of capsizing due to broaching in the North Atlantic. The calculation method used here was proposed and validated with the Monte Carlo simulation by Umeda et al. (2007). The failure probability is calculated by integrating the probability density of local wave height and wavelength on the region in which capsizing due to broaching occurs in systematic time domain simulation using a coupled surge-sway-yaw-roll model with an autopilot in periodic waves. Here capsizing is defined as the roll angle of 90 degrees or over and the rudder gain is 1.

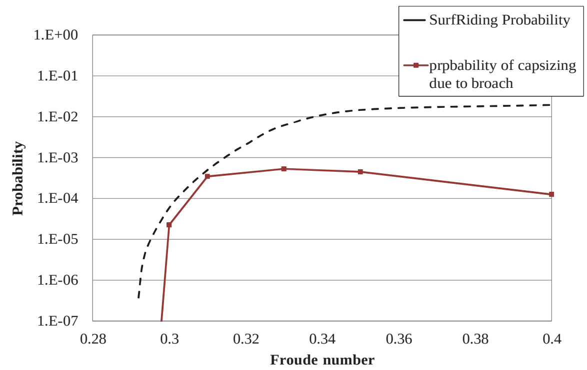

Figure 17 Comparisons between surf-riding probability and probability of capsizing due to broaching for the ONR tumblehome topside vessel.

The results shown in Figure 17 indicate that the probability of capsizing due to broaching is smaller than the surf-riding probability. Thus we can conclude that the draft criterion for surf-riding guarantees safety against capsizing due to broaching. It is noteworthy here that in critical speed range around the Froude number of 0.3 the difference between the two is rather small. This means that the safety margin is not so large.

7. CONCLUSIONS

For reasonably evaluating surf-riding probability to be used for design and operational criteria, diffraction effect on wave- induced surge force is indispensable, calm- water resistance can be modelled with model tests covering the Froude number up to 0.6 or standard speed/power trials and choice of stochastic wave theory is not crucial. The evaluated surf-riding probability is a conservative index for capsizing due to broach.

8. ACKNOWLEDGEMENTS

This work was supported by JSPS (Japan Society for Promotion of Science) KAKENHI Grant Number 24360355 and 15H02327. It was partly carried out as a research activity of Goal-based Stability Criteria Project of Japan Ship Technology Research Association in the fiscal year of 2013, funded by the Nippon Foundation. The authors appreciate Mr. William Peters from United States Coast Guard and Dr. Vadim Belenky from David Taylor Model Basin for their useful discussion.

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