A PROCEDURE FOR DETERMINING A GM LIMIT CURVE BASED ON AN ALTERNATIVE MODEL TEST AND NUMERICAL SIMULATIONS

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ABSTRACT

This paper presents an alternative approach of the Weather Criterion (IMO Res. A.749(18) Chapter 3.2) and the Alternative Assessment of the Weather Criterion (MSC.1/Circ.1200 & MSC.1/Circ.1227). A short study of first principle model tests performed in irregular waves for a very large passenger cruise ship design is carried out. Following this study, a calculation procedure for determining a Weather Criterion GM limit curve is based on the results from the model tests in combination with numerical simulations. The applicability of the Weather Criterion is discussed for the cruise ship design based on the new model tests and the results from the numerical simulations, confirming that the criterion is not the limiting requirement for the examined ship design. Proposals for instructions are presented in order to improve accuracy of model test results and facilitate the possibility to derive limiting GM values based on model tests.

Keywords: *weather criterion, metacentric height, limit curve, roll, damping, irregular wave, sea state*

1. INTRODUCTION

The IMO Weather Criterion, resolution A.749(18) Chapter 3.2 (today superseded by resolution MSC.267(85) Part A Chapter 2.3), describes the ability of a ship to withstand the combined effects of beam wind and roll motions under a specified weather condition. The basic idea of the criterion is to determine the minimum metacentric height for which a ship still is able to withstand a prescribed sudden wind gust, while rolling under the action of beam waves and constant wind.

Following ship design development the criterion has nowadays limited applicability for some ship types (especially for ships having larger dimensional ranges than what the criterion originally was designed for). It has consequently become interesting to consider the potential of alternative approaches that better deal with dynamic effects. Another reason for why alternative methods are being investigated is that the Weather Criterion requirements are often more stringent and quite frequently restraining design dimensions when other stability criteria indicate a satisfactory safety margin. As a result, IMO allows the use of model tests (wind tunnel and towing tank tests) to substitute the empirical estimations for the wind heeling lever arm and the angle of roll in the Weather Criterion and suggests test procedures for this purpose as described in the Interim Guidelines for Alternative Assessment of the Weather Criterion, and its Explanatory Notes to the Interim Guidelines for Alternative Assessment of the Weather Criterion, ref. MSC.1/Circ.1200 and MSC.1/Circ.1227.

The purpose of this paper is to continue the development of alternative test procedures and present an alternative calculation method to both the standard IMO Weather Criterion and the Alternative Assessment, based on a first principle model test for a very large passenger cruise ship. The first principle method implies that model tests are carried out in an irregular environment defined by a sea state and that the number of assumptions and possible sources of error are reduced as much as possible. Hence, the actual ship condition and its motion responses are by this procedure better represented with a more close correlation to actual environmental conditions since first principle model tests uses sea states defined by statistical data. The first principle approach is already familiar to the maritime industry, for instance being applied in the design phase of new offshore constructions. Therefore, it is believed that the existing know-how also can be applied to carry out tests with ships.

Subsequent to the model tests, numerical simulations are carried out by utilizing the model test results with the aim to derive more realistic minimum allowable metacentric heights compared to that obtained by the Weather Criterion and the Alternative Assessment. The above mentioned practice is believed to be advantageous considering that model tests are costly and time consuming, meaning that the current alternative procedures become unattractive as they require several model tests to cover the entire range of a ship's loading conditions. This fact has raised the question whether numerical simulations for prediction of ship motions shall be allowed by regulatory bodies or not.

2. WEATHER CRITERION

The Weather Criterion is based on several assumptions and empirical formulas. The principle is to measure the restoring capability of a vessel to its equilibrium angle and it is expressed as an energy balance, illustrated in Figure 1. It is initially supposed that a ship is being exposed to 26 m/s steady side wind represented by the wind heeling lever arm, l_{w1}, resulting in an angle of heel, θ_0. In addition to the resultant angle of equilibrium θ_0, a wave that triggers resonant roll motion is assumed to affect the ship which is supposed to reach its most vulnerable condition at the maximum roll-back angle θ_1 on the weather side. This angle is given by equation (1) which is composed by a number of coefficients related to different ship characteristics such as the block coefficient, beam, draught and the influence of bilge keels.

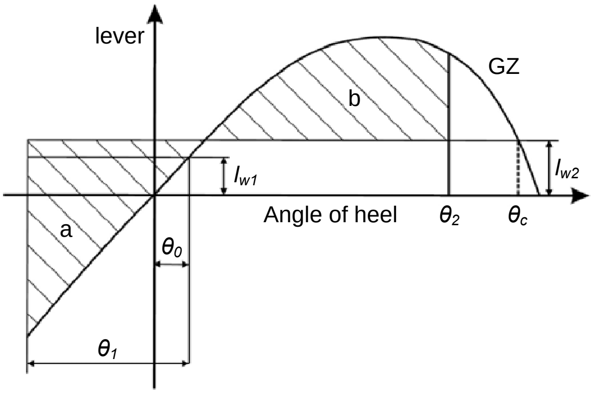

Figure 1. Weather Criterion energy balance.

$$\theta_1 = 109 \cdot k \cdot X_1 \cdot X_2 \cdot \sqrt{rs} \qquad (1)$$

Furthermore, to illustrate a worst case scenario the ship is assumed subjected to a wind gust when rolling from θ_1 towards lee side. The wind gust is represented by a wind gust heeling lever arm, l_{w2}, being 50% larger than the magnitude of l_{w1}. Consequently, in an energy balance point of view, the work done by the wind excitation as the ship rolls from windward to leeward should not exceed the potential energy at the limiting angle, θ_2. Hence, the requirement is that area *b* should be equal to or greater than area *a*.

3. GM LIMIT CURVE DETERMINATION

As indicated in chapter 1, IMO also allows the use of alternative model test procedures to replace the outlined procedures of the interim guidelines, if approved by the maritime administration. Recent publications show that there is still room for development of the interim guidelines. Ishida, Taguchi and Sawada (2006) point out that experience still has to be acquired in order to rely on the current procedures. Yoon et. al. (2006) performed tests based on the guidelines for a Ro-Ro model and encountered some shortcomings when carrying out tests in regular waves.

Consequently, the wanted outcome of this study is to derive a GM limit curve by using a single loading condition from first principle model test results combined with numerical simulations to cover the Weather Criterion. The interim guidelines provides a good illustration of how weather criterion model tests should be carried out but there are at the moment no recognised distinguished guidelines describing how to derive a GM limit curve based on model tests. Furthermore, it is the intention to formulate recommendations and suggestions for improvements, thus creating a basis for more extensive and accurate model tests which in turn facilitates the appliance of numerical simulations.

3.1 Passenger Cruise Ship

The main particulars and some important stability related information of the examined passenger cruise ship are presented in Table 1. It can be observed that the dimensional ratios of this ship clearly fall outside the associated ranges of what is suggested by the Weather Criterion, ref. Table 2.

Table 1. Cruise ship characteristics.

Designation	Size	Unit
Length over all, L_{oa}	360.5	m
Length perpendiculars, *Lpp*	330.0	m
Breadth, *B*	47.00	m
Design draught, *d*	9.15	m
Breadth to draught ratio, *B/d*	5.14	-
Length - breadth ratio, *Lpp/B*	7.02	-
Length - draught ratio, *Lpp/d*	36.06	-
Natural roll period, *T*	22.00	s
OG	15.93	m

Table 2. Ship characteristics used in the Weather Criterion, dimensional ranges.

$2.4 \leq B/d \leq 3.5$
$-0.3 \leq OG/d \leq 0.5$
$6 \leq T \leq 20$

The coefficient OG in the above tables represents the distance between the vertical centre of gravity and the waterline.

3.2 Model Tests

The first principle methodology of the model tests for determining the wind heeling lever arm and the roll-back angle are to a large extent similar to those described in the interim guidelines. There are however some important differences of which the most significant are the following items:

- Measurements of the roll-back angle are performed in an irregular sea state. The actual ship condition and its motion responses are represented with a more close correlation to actual environ-mental conditions since sea states defined by statistical data are utilized. This approach excludes the correction of the roll angle when going from regular waves to an irregular sea state.
- The first principle model tests avoid the split-up in drift and wave tests, hence staying closer to a realistic condition. Wave tests are performed combining free drift due to beam waves and with a constant wind load applied. The wind load is generated by a mechanical constant tension winch, pulling the ship model in the wave propagation direction. The combination of wave and wind loads triggers a mean roll angle, assumed as the equilibrium angle θ_0.
- The wind load is obtained from wind tunnel model tests, performed using a turbulent atmospheric boundary layer while the proposal in the interim guide-lines is to generate a uniform wind profile. The turbulent boundary layer is more realistic

when modelled properly and is for that reason considered to be advantageous to use for investigating the weather criterion effects.

The above mentioned items clearly show the main contradictions to that of the outlined procedures in the interim guidelines, i.e. the suggestion to perform drift tests in calm water and wave tests in a regular environment.

Model test sea states were selected from the World Wide trade scatter diagram for the 1-year return period contour and the 20-year return period contour. By doing so, the selected sea states cover a range ensuring that a severe roll motion is accounted for. Irregular sea state conditions were specified in terms of Pierson-Moskowitz wave spectrum. The selected reference test condition and the results from both the wind tunnel and towing tank tests are presented in Table 3 and Table 4.

Table 3. Input data for the reference loading condition.

Test No.	Test conditions			
	Return period contour	PM spectra		Wind speed [m/s]
		H_s [m]	T_p [s]	
4	20 year	11.4	19	26

Table 4. Results for the reference loading condition.

Test No.	Test results	
	Wind load [kN]	Mean roll angle, θ_0 [deg]
4	7256	4.13

The ship model produced for towing tank tests has a scale of 1:46. A large model size is justified to avoid scale effects. The skeg and bilge keels are included on the model for hydrodynamic purposes since both actively contribute to the roll damping.

3.3 Stepwise Methodology

Numerical simulations are performed using the software package HydroD, developed by DNV Software, being a hydrostatic and hydrodynamic analysis tool that can be used for computing wave loads and motion responses in a six degree of freedom coordinate system of a ship model. The wave motion analysis is done by a linear three-dimensional potential flow diffraction code with zero forward speed. The proposed calculation procedure is hereafter briefly presented followed by detailed descriptions of all steps in chapter 3.4.

- Define the sea state and wave spectrum corresponding to that of the model test.
- Set input parameters for the loading condition corresponding to that of the model test, for example draught, mass distribution and radius of gyration.
- Ship characteristics adjusted to reflect the model test condition with respect to motion responses by tuning of the roll damping.
- Variation of the vertical centre of gravity and calculation of the weather criterion energy balance, until the area ratio *b/a* equals to one.
- The previous step, including a variation of the damping, is performed for the whole operational draught range to obtain the complete limit curve.

Loading condition input parameters are selected to cover the operational range of the cruise ship with respect to draught and centre of gravity. Information from the model test reports for a ballast loading condition, ref. details presented in Table 5, constitutes the basis for tuning of the ship’s characteristics. Adjustments were made so that the metacentric height, displacement, roll damping, equilibrium angle and natural roll period matched that of the experimental model. The ballast loading condition is assumed to be the most relevant condition for weather criterion investigation purposes due to its large windage area and limited restoring capability.

Table 5. Input parameters for the ballast draught condition.

Designation	Size	Unit
Draught, *d*	8.60	m
Centre of gravity, *KG*	24.53	m
Radius of gyration, r_{gyr}	20.02	m

3.4 Process Description

The process to derive a GM limit curve for a particular selected sea state is illustrated by the flowchart in Figure 2 and followed by a stepwise description. The procedure basically consists of calculations and simulations in HydroD.

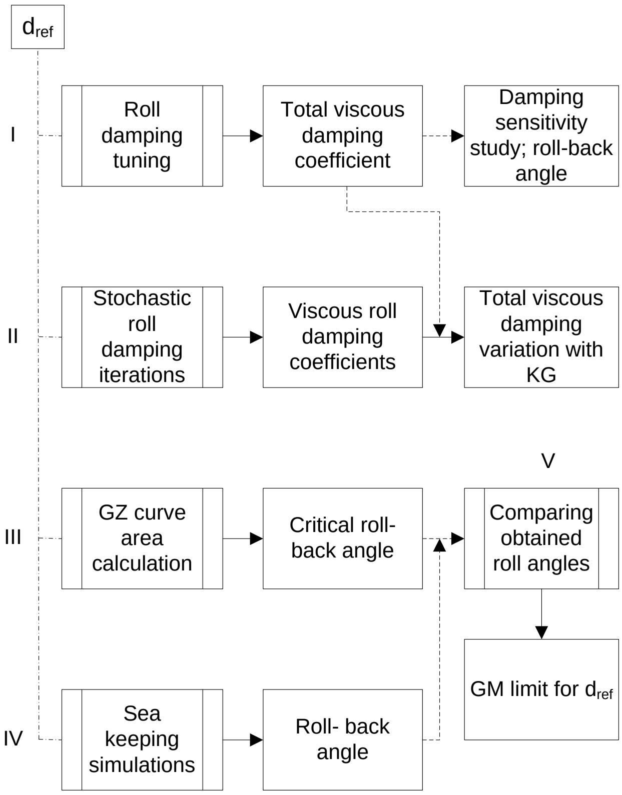

Figure 2. Simulation and calculation process.

The model test draught, d_{ref}, is initially used for the following steps I to V.

Step I:

To ensure that damping characteristics of the computerized model correspond to the full scale ship, the viscous roll damping was tuned so that the roll response was in accordance with the model test results. Explicitly, the most probable extreme roll angle was calculated and compared to the experimental result. The calculation procedure for this roll angle is presented in step IV. The potential damping contribution (damping from surface wave radiation) is automatically included in the calculations. A study of the damping influence on the roll-back angle is initiated based on the roll damping tuning.

Step II:

The potential damping contribution is assumed to be calculated accurately by the software and this is the situation for all loading conditions, i.e. independently of draught or centre of gravity. The viscous damping calculation is performed by a stochastic iteration process, where non-linear damping contributions from the GZ curve are included in a linearised manner according to the maximum expected roll angle. The obtained roll damping coefficient, $B_{visc,stoch}$, is not assumed as the definite value but the iteration results are used to analyze how the viscous damping changes with varying loading conditions (KG and draught). This is performed by calculating ratios between the different conditions. When a ratio has been determined, this is applied to the tuned viscous damping in step I and the result is the total viscous damping for the loading condition of interest. This is illustrated by equation (2).

$$B_{visc}(KG_i) = B_{visc}(KG_{ref}) \cdot \frac{B_{visc,stoch}(KG_i)}{B_{visc,stoch}(KG_{ref})} \qquad (2)$$

where $B_{visc}(KG_i)$ is the total viscous damping for the examined vertical centre of gravity, KG_i, and $B_{visc}(KG_{ref})$ is consequently the tuned total viscous damping for the model test condition, KG_{ref}. The last part of the equation shows the ratio between the stochastically iterated viscous damping contributions for the examined loading condition and the reference loading condition.

Step III:

GZ curves are generated for the examined loading condition and the critical roll-back angle is calculated. The critical roll-back angle, θ_{crit}, is determined when the Weather Criterion area ratio *b/a* equals to one. For the examined passenger cruise ship all critical openings are located above 40 degrees heeling angle and this limit is used for the cases where it becomes relevant.

Step IV:

The most probable extreme roll-back angle, $X_{\max}$, is derived by using equation (3) - (6). This is the worst roll response the ship will experience for the specified loading condition and sea state. The mean of one third of the largest responses in the response spectrum is defined by equation (3).

$$X_{1/3} = \frac{4\sigma}{H_s} \tag{3}$$

where σ is the standard deviation (zero moment of the response spectrum) and 4σ represents the significant response. H_s is the significant wave height. The most probable extreme response for a narrow banded response spectrum is calculated by using equation (4).

$$X_{\max} = \sigma \cdot \sqrt{2\ln(N)} \tag{4}$$

where *N* represents the number of oscillations, i.e. the number of wave cycles passing in total or the number of zero up-crossings in the short term sea state, and defined in accordance to equation (5).

$$N = \frac{t}{T_z} \tag{5}$$

where t is the time duration of the short term sea state and T_z is the mean zero up-crossing wave period. Equation (6) is then reformulated as presented below.

$$X_{\max} = \frac{H_s \cdot X_{1/3}}{4} \cdot \frac{180}{\pi} \cdot \sqrt{2\ln\left(\frac{t}{T_z}\right)} \tag{6}$$

The PM spectrum characteristics presented in Table 3 are used in the calculations and a 3-hour storm has been considered, thus making it possible to tune the roll damping against model test results.

Step V:

The KG limit for draught d_{ref} is found when the critical roll-back angle equals the windward roll angle. This limit is determined by plotting the critical and windward roll angles as functions of the examined KG values.

Following step V, other draughts within the operational range are examined and step I to V are performed all over again with the addition that the total viscous damping also is corrected with respect to the change in draught. The complete KG (GM) limit curve is obtained when the whole operational draught range has been examined.

4. RESULTS AND DISCUSSION

A total number of 20 examined loading conditions were considered within the operational draught range, where the range is defined from 8.0 to 9.0 metres. The simulation and calculation results for the reference loading condition are presented in Table 6 and the GZ curve is shown in Figure 3.

Table 6. Data and results for the reference loading condition.

d [m]	*KG* [m]	*GM* [m]	θ_0 [deg]	$X_{\max}$ [deg]	θ_w [deg]	θ_l [deg]
8.6	24.53	4.27	4.28	9.16	4.88	13.44

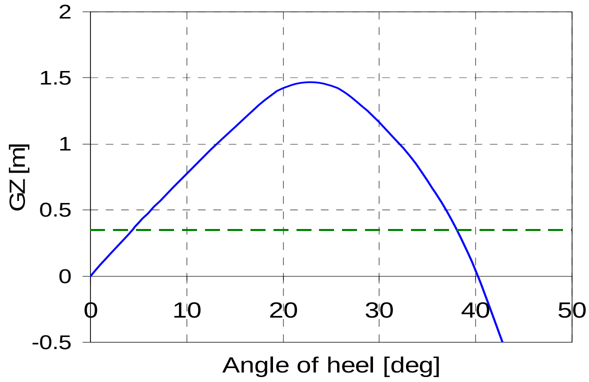

Figure 3. GZ curve for the reference condition, including the wind heeling lever l_{w1}

It should be noted that the calculated most probable response $X_{\max}$ corresponds to the roll-back angle θ_1, thus being defined from θ_0. The angle θ_w is the windward roll angle and θ_l is the leeward angle from the vertical axis. As a comparison it is observed that θ_1 when calculated by the standard equation (1) becomes approximately 20 degrees, meaning that the standard Weather Criterion heavily overestimates the roll-back angle for this ship.

In this connection it should be noted that because of the linearization in the software, there is likely to be a slight deviation in the calculation of the restoring moment. Nevertheless, the calculated roll angles are not significantly large and it has been seen that the GZ curves can be considered linear up to the calculated roll angles. Therefore, even though a linearization perhaps could be considered as a rough approximation, it is assumed that a linear approach is reasonable and that the initial GM could be used for small roll angles

The largest responses are as expected found in loading conditions with shallow draught and a low vertical centre of gravity. It is therefore believed that the capsizing possibility due to pure roll motion is low since this would imply a very large GM, which results in an increase of area *b*. Nevertheless, this is most often not the situation for a passenger ship, having a high and constant KG, but could be relevant for other cargo ships. On the other hand, the examined cruise ship is quite unique in that respect that it has large GM values, thus being very stiff compared to more conventional large passenger ships, and the calculation results indicate that for a ship constructed like this it is not relevant to have a minimum GM curve but rather a maximum GM limit curve. It can be observed in Table 6 that the leeward angle is considerably larger than the windward angle, and it has been observed that the leeward angle increases with increasing GM. This relation between large GM values and considerable responses indicate the relevance to investigate maximum GM limits.

The maximum acceptable responses for each loading condition were calculated and the result for the reference loading condition is presented in Table 7. The critical windward roll angle is obtained from the area principle of the Weather Criterion, based on the actual GZ curve and the wind heeling lever arms.

Table 7. Critical windward roll angle.

d [m]	KG [m]	θ_{crit} [deg]
8.60	24.53	16.80

Finally, limiting KG values are determined by plotting θ_w against θ_{crit} as a function of KG for each draught. For the ballast condition the result of this process is presented in Figure 4.

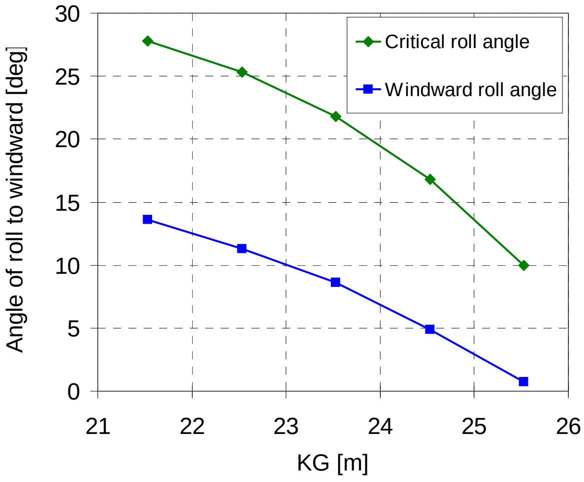

Figure 4. Deriving limiting KG for the ballast condition draught of 8.60 m ($KM = 28.80\,\mathrm{m}$).

It can for this case easily be observed that there is no intersection between the curves. Similar plots were created for the whole operational range and the results were the same for all examined cases, i.e. no intersections were found.

The results indicate that the specified wind and sea state are not severe enough for the examined passenger cruise ship. The ship would indeed reach higher responses if subjected to a more severe sea state, e.g. if the wind speed or wave height was increased. It could therefore be of interest to investigate what sea state that would become critical for the ship, i.e. performing simulations with an environmental condition that provokes a situation where intersections between the windward roll angle curve and the critical roll angle curve are obtained.

Although KG and corresponding GM limit curves were not found within the examined range, the procedure is believed to be accurate and the simulations indicate reasonable results. It is revealed that the ship is stable for high values of KG (most probable extreme roll angles are quite small) and even though when GM is low there is a large amount of restoring capacity left in the GZ curve. The calculated responses (angle of roll to windward) are small if compared to the critical windward roll angles, meaning that the area ratio b/a in all cases will meet the requirement.

Taking into consideration other ships with different characteristics (e.g. breadth, centre of gravity and radius of gyration), results as presented in Figure 4 would become somewhat different and it is therefore expected to find an intersection point between the two curves. It is for instance believed that for ships with less restoring capabilities it is very likely to find an intersection and thereby be capable of deriving limiting values.

Consequently, to summarize this chapter, results show that the requirements of the Weather Criterion set a very high limitation and it is clear that the examined passenger cruise ship will never obtain roll angles of the magnitude that the Weather Criterion specifies. In other words, the dynamic stability of the ship is very good with respect to pure roll motions and it is in this case not rational to follow the suggested Weather Criterion requirement stipulated by IMO.

5. CONCLUSIONS

It is concluded that the first principle approach based on alternative model tests is practicable and that the presented calculation procedure seem to predict reasonable results. Investigations indicate that the proposed methodology could be used as a platform for determining a limit curve for ships in the design stage. The procedure is also believed to be advantageous considering fewer expenses for model testing and lower time consumption.

It has been shown that the combination of severe wind and rolling is not a safety issue for the examined passenger cruise ship and that the Weather Criterion is not the limiting stability criteria. Bearing in mind that the 2008 International Code on Intact Stability became mandatory through the adoption of IMO Resolution MSC.267(85) in December 2008, it is therefore important to be aware of the inapplicability of the Weather Criterion for large passenger cruise ships (and other ships with similar dimensions) and to encourage the use of alternative methods.

6. RECOMMENDATIONS

It is suggested that further investigations are carried out with respect to the precision of the methodology. It is recommended that different solution methods are investigated where applicable. In addition it is sensible to perform further validation of different parameters and to carry out a sensitivity analysis before new calculation procedures become subject for various ship types and dimensions.

A factor of safety should be considered as well as an analysis to determine the accuracy of the results. For this purpose, it is rational to perform additional model tests for a selection of draughts and metacentric heights to be able to distinguish tendencies and appropriate values that could be used for input data in the numerical simulations as well as for extrapolation of results. For instance, it would be interesting to trace how damping characteristics vary with draught and centre of gravity in order to reach higher accuracy and adequate results.

The risk for capsize due to excessive GM values should be investigated, ref. discussion in chapter 4 of this paper.

The influence of non-linear simulations should be investigated in order to reach higher degree of accuracy and better representation of actual conditions in a nonlinear stochastic environment.

It is important to stress that the sea state used for the model tests should be chosen carefully with respect to its probability of occurrence. It is recommended that the World Wide trade scatter diagram should be used for ships with unrestricted operations. Considering that the probability of occurrence to have a damaged ship in extreme weather conditions is low, the definition of a sea state with one occurrence in 20 years may be too conservative. For that reason it could be appropriate to use the 1-year return period contour for ships with for instance redundant propulsion and steering systems. It is suggested that further investigations are carried out on this subject. As for the sea state, the wind speed shall either be chosen in a similar way (i.e. related to the wave spectrum) or follow the recommendation stipulated by IMO.

The selection of a wave spectrum should be realistic, thus corresponding to a fully developed sea (e.g. the Pierson-Moskowitz and JONSWAP spectra). The peak period of the selected spectrum should be close to the ship's natural roll period to trigger roll at resonance. It is recommended that a screening of different periods is made to find the worst roll response to be used for the simulations.

Finally it is recommended that the current stability code allows for alternative methods as described in this paper. First principle model tests enable a more accurate representation of actual environmental conditions and ship responses and should be utilized as far as practicable, independently if followed by numerical simulations or not.

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