Considerations on the Weather Criterion Applicability for the Stability Assessment of Large Vessels

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ABSTRACT

The applicability of the *IMO's* weather criterion for a large passenger ship is studied. Two very different mathematical models describing the physical scenario behind the weather criterion are employed. The results yielded by the simple model of the International Maritime Organization (abbrev. *IMO*) are compared to the computations conducted using the sophisticated time domain six-degrees-of-freedom non-linear model. Good agreement of the results obtained by the two methods is noted. The study reveals important assumptions behind the weather criterion. The weather criterion is discussed and a modification to it is proposed. The effect of this modification on the dynamic heel of a large ship is discussed.

Keywords: *weather criterion, dynamic heeling, stability*

1. INTRODUCTION

The purpose of this study is to investigate the applicability of the IMO's weather criterion for a large passenger ship. This is done by using a simple mathematical model given by the legislator and by applying a sophisticated time domain six-degrees-of-freedom non-linear model called *LAIDYN* (Matusiak; 2000, 2001, 2002 and 2003) to the physical scenario behind the weather criterion. Application of two quite different models results in similar results in terms of maximum heel angle developed by a steadily rolling ship subjected to the action of gusty side wind.

Sophisticated numerical simulations of ship's behaviour in random waves and in unsteady wind were conducted by Vassalos, Jasionowski and Cichowicz (2003). Their study also deals with the problem of applicability of the weather criterion to a modern passenger ship. In particular they address the important problem of the likelihood of occurrence of the elements making up the criterion.

The present study is mainly concerned with the model of ship dynamics used in the criterion. The environmental conditions used in the criterion are not concerned. They are taken for granted as given by the legislator. This assumption makes it possible to conduct a deterministic analysis of the criterion. Despite these simplifications the study reveals serious assumptions behind the weather criterion. The recent developments of the weather criterion done by the Intact Stability Correspondence Group are aimed, amongst the others, at updating the weather criterion and making it more suitable for large passenger vessels. However, the basic assumptions are not considered yet. These assumptions are discussed in this paper.

2. MAIN DATA OF THE SHIP AND IT'S DISCRETISED REPRESENTATION

The investigation is conducted for a cruise vessel. The main particulars of the ship are given in Table 1 below.

Table1. Main data of the ship

Length b. p.; L_{pp}	250 [m]
Breadth, dwl; B	32.2 [m]
Draft; T	7.9 [m]
Volumetric displacement	40065 [m^3]
Vertical centre of gravity; KG	15.87 [m]
Wetted surface	9280 [m^2]
Metacentric height, GM_0	1.7 [m]
Natural roll period, T_{φ}	23 [s]
Windage area	9598 [m^2]
Vertical distance from the baseline to the centre of the windage area; Z_A	25.67 [m]
Vertical distance of the windage area centre from the centre of the underwater lateral area; Z	21.73 [m]
Radius of the roll moment of gyration, k_{xx}	14.55 [m]

The righting lever curve is shown in Figure 1 below.

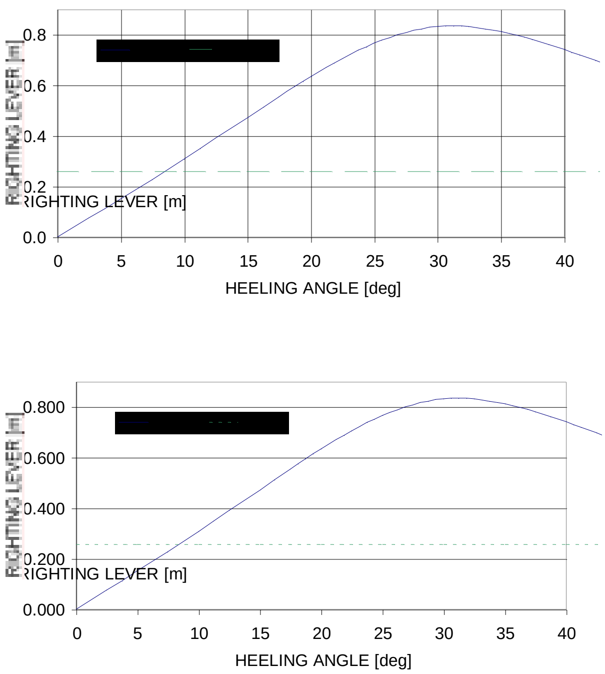

Figure 1 Righting lever curve of the ship.

This is calculated using the panel representation of the hull. The entire ship is represented by 25960 triangular panels. The ad hoc constructed panel model extends on the ship sides to a height of 25.43 [m]. Moreover, there is no weather deck in the discretized model. However, these shortcomings of the panel model do not affect the results because the maximum values of the heel angle do not exceed 35^0. The control points of the panels are shown in Figure 2.

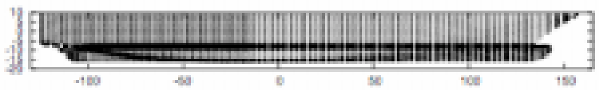

Figure 2 Side view of the discretized hull. Origin of the co-ordinate system is located at the centre of gravity. Control points of the panels are marked.

The dashed line of Figure 1 represents the static wind loading of the weather criterion.

3. SIMULATION OF THE ROLL DECAY TEST

The roll decay test was simulated first. The purpose of the simulation was to evaluate viscous roll damping to be used in the simulations so that the total damping would correspond to the result of the model test. Moreover, simulation yields the roll moment of gyration resulting in the observed value of the natural roll period of the ship (T_{φ}=23[s]). The result of the simulation is presented in Figure 3, below.

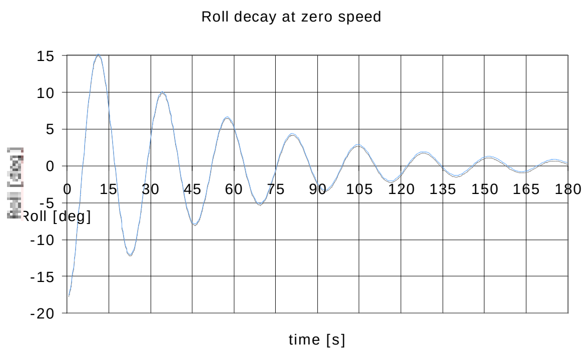

Figure 3 Simulated roll decay test. The initial heel is as in the model test. Total critical damping ratio ζ=0.07.

The total critical damping ratio compares well to the corresponding value obtained in the model tests at large roll amplitudes. This agreement was achieved adjusting the viscous part of roll damping to 0.025. The desired natural roll period was obtained with the radius of the roll moment of gyration in air being k_{xx}=14.55 [m].

The linearity assumption of the roll damping is believed to be sufficient in this case because of several reasons. Firstly roll damping and wave excitation roughly cancel each other at the resonance. Secondly the peak value of a transient response does not depend much on damping. Thirdly there is no scrupolous non-linear model of roll damping available that can be used in the time domain simulations.

4. ROLL AMPLITUDE AT RESONANCE FOR THE SHIP IN BEAM WAVES

4.1 Critical wave length

The natural roll period rules the length of the critical regular wave. For a deep sea condition and for the beam waves the relation between the wave length λ and the wave period T_w is

$$\lambda = \frac{gT_W^2}{2\pi} \tag{1}$$

yielding the critical wave length λ=826 [m]. The height of this wave can be evaluated using the so-called steepness factor as proposed in SLF 45/14 of 2nd of August 2002 (see also SLF 48/4/3). Thus the wave height to be used in the weather criterion check is H=0.026•826=21.5 [m].

4.2 Roll amplitude at resonance

Computed roll and heave of the ship in the beam critical regular waves are presented in Figure 4.

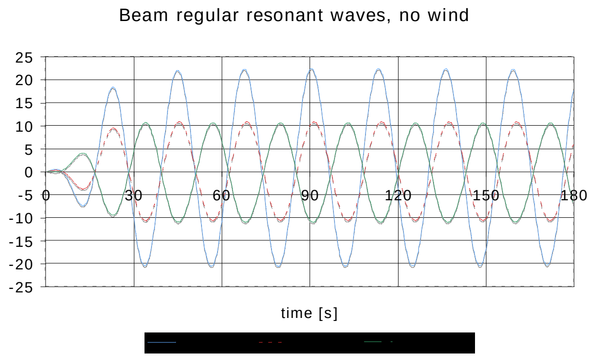

Figure 4 Steady motion of the ship in the critical beam waves.

The amplitude of roll is φ_A=21⁰. This can be identified as the steady roll amplitude θ_r of the ANNEX of the document SLF 47/6/19. The following sign definition is used:

Roll is positive when ship is heeled to the starboard.

Wave elevation means positive values.

Heave is positive for the downward motion of the ship's COG.

The effective roll-back angle is obtained by reducing the amplitude of roll at resonance as defined in the 'Guidelines for alternative assessment of weather criterion' of SLF 48/4/3. A reduction factor 0.7 accounts for the difference between resonant roll amplitudes in regular waves and irregular seas.

The summary of roll amplitudes evaluated by different approaches is presented in Table 2 below.

Table 2. Summary of the critical roll amplitudes.

ϕ_1, DnV, rules for Ships, January 2004	Roll amplitude obtained by simulations; ϕ_A	The "effective" roll-back angle $\phi_1 = 0.7\phi_A$
15^0	21^0	15^0

5. SIMULTANEOUS ACTION OF REGULAR WAVES AND GUSTY WIND

According to the weather criterion the ship is subjected to a steady wind heeling the ship with a moment

$$M_{w1} = PAZ = \Delta l_{w1} \qquad (2)$$

where P=504 [N/m^2] (wind speed of 26 [m/s]), A projected lateral area of the portion of the ship above the waterline, Z vertical distance from the centre of A to the centre of the underwater lateral area. The static wind loading heels the ship by 8.5^0 (see Figure 1). In addition to the static wind loading, the ship is steadily rolling in the critical i.e. resonant condition. There are two possibilities to implement in the numerical simulations the scenario behind the weather criterion. The first one is as follows. The ship rolls in critical regular waves of maximum height. When the instantaneous roll angle is 70% of the amplitude value (the “effective” roll-back angle is achieved) and the ship is heeled towards the wind, the heeling moment due to wind is increased by 50%. A sudden increase of the wind moment is meant to simulate a wind gust that starts to affect the ship when she is heeled by approximately -15^0+8.5^0=6.5^0. The action of waves continues. The result of the motion simulation for this situation is presented in Figure 5 below.

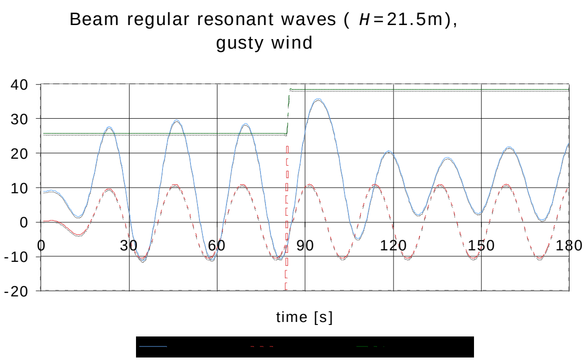

Figure 5. Steadily rolling in critical waves ship is subjected to gusty wind when roll angle is 70% of the minimum roll angle.

In this situation the ultimate value of roll as peak-to-peak value is 32^0. A clear increase of heel up to 35^0 is noted. The ship withstands the combined action of waves and gusty wind. It is interesting to note that static heel decreases roll amplitude at the developed resonance. This may be caused by a small shift in a natural frequency or by a decrease of wave loading for a statically heeled ship. In Figure 5 gust started to act when ship was returning to the up-right position. If gust is activated for the same roll angle but with increasing heel towards the wind, the transient maximum roll reaches the value of 30^0 only.

Another situation, which is closer to the assumptions of the weather criterion but assumes the linearity of the roll response, is considered below. The wave height is only 70% of the previously considered value, that is it is 15 [m], but the action of a wind gust starts at the instant the vessel is heeled at the maximum towards the wind. In other words there is no kinetic energy of the roll motion at the instant of wind loading increase. The result of the simulation is presented in Figure 6, below. In this case the ultimate value of roll as peak-to-peak value is 25^0.

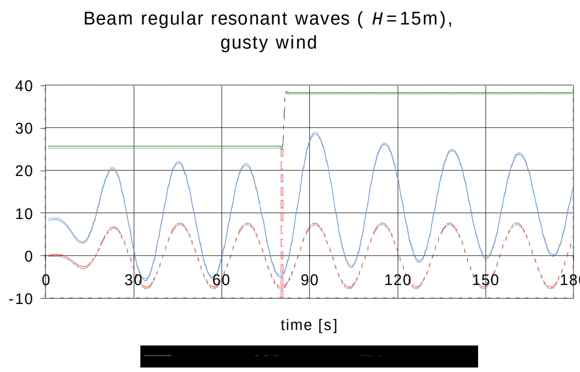

Figure 6. Steadily rolling in critical waves ship is subjected to gusty wind at the maximum roll angle towards the wind.

As we can see, the maximum roll angle is significantly lower in this case. This can be mainly attributed to the decreased wave amplitude and to the fact that there is no kinetic energy in roll motion at the instant of gust loading. Although both considered situations include two important elements of the criterion, i.e. resonant rolling and gusty wind, the simulated situations are somewhat artificial and they may be in disagreement with the weather criterion. In the weather criterion, ship resonant roll motion is used to evaluate the initial condition for the dynamic heel analysis. The wave loading, as such, is not concerned at all. Although, as it was stated before, it may be argued that the wave loading and the roll damping compensate themselves at the resonance. This means that if we want to simulate in the time domain situation covered by the weather criterion, we can calculate or measure in model scale the ship response caused by the gusty wind loading only for the initial condition set by the resonant roll motion. This is analysed in the following with an aid of numerical simulations.

6. TRANSIENT ROLL RESPONSE COMPLYING WITH THE WEATHER CRITERION

In this Chapter the dynamic response of the ship due to gusty wind and with the initial condition set by the steady wind component and the resonant roll motion in beam waves is considered. The considered model complies with the weather criterion.

The result of the transient roll response caused by a suddenly applied wind load for the ship initially heeled to -5^0 by the combined action of a steady wind and resonant waves is shown in Figure 7, below. The initial heel of -5^0 is taken from the Figure 6.

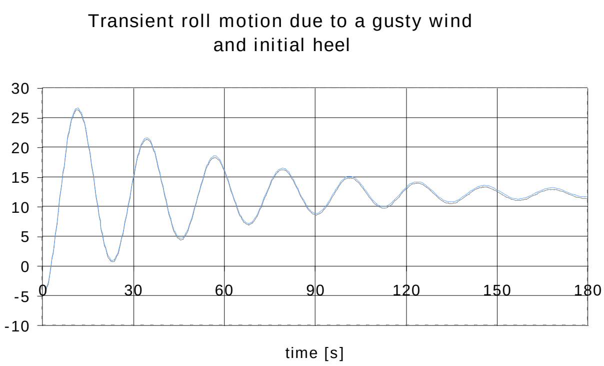

Figure 7. Ship transient rolling caused by the gusty wind and initial heel due to steady wave and resonant roll. Gust loading is taken according to the weather criterion.

The maximum heel angle of Figure 7 is very close to the maximum heel obtained with action of beam waves being included (Fig. 6). A small, approximately 1^0, difference may be attributed to the damping which decreases the maximum roll angle of the transient response. In Figure 8, the dynamical levers are used to evaluate the maximum heel of ship subjected to the action of gusty wind. The continuous line (e-curve) is the integral over the *GZ*-curve while the dashed line l_d corresponds to the heeling work done by the wind.

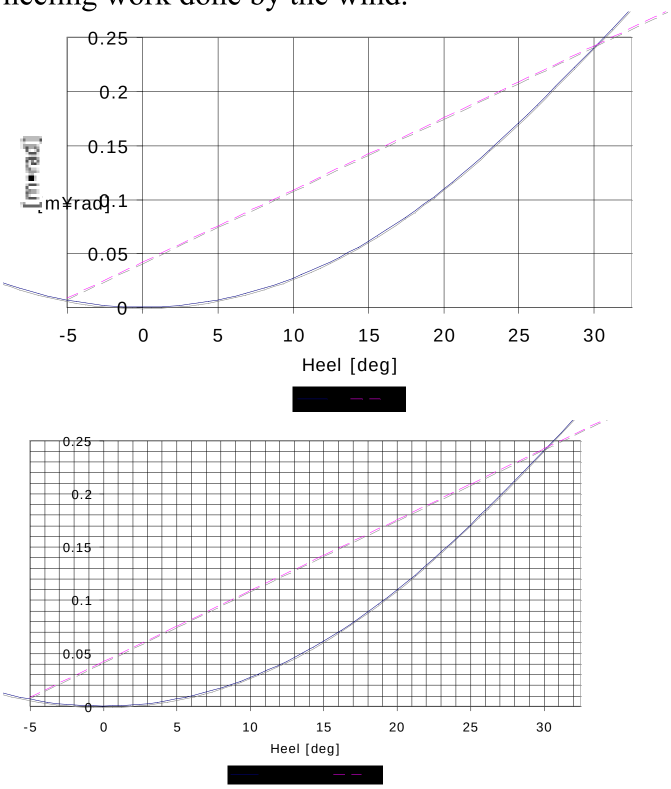

Figure 8. Ship dynamic heeling according to the weather criterion.

The lack of damping and disregarding other modes of ship motions yield a still somewhat higher maximum roll angle evaluated with the aid of dynamical levers.

7. THE PROPOSED MODIFICATION TO THE WEATHER CRITERION

7.1 Justification

A single heeling moment is a very rough approximation to a complex gusty wind loading. In the following it is shown that it is an appropriate approximation for a steady wind loading, only. A single force vector seems to be a better representation of the loading caused by wind gust for a more sophisticated model of ship dynamics. The first approximation is a force acing at the centre of gravity of the lateral area *A* and fixed in the body, i.e. moving with the ship, co-ordinate system. In the following we discuss this matter using a simple representation of the ship subjected to wind loading. In Figure 9 a steady wind load $F_{W,y}$ and hydrodynamic steady reaction $F_{H,y}$ are presented.

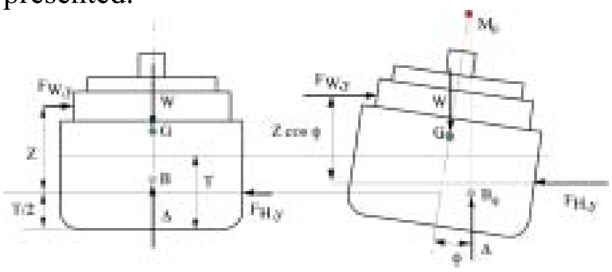

Figure 9. Steady wind loading.

For a stationary vessel or a vessel moving with a constant speed, these forces are the only ones acting athwartships and thus obviously they form a couple heeling the ship with a moment

$$M_W = F_{W,y} Z \cos\phi \qquad (3)$$

For small heel angles formula (3) reduces to the expression (2), which is the wind moment of the weather criterion. The hydrodynamic steady reaction $F_{H,y}$ can be interpreted as the hull resistance opposing the steady sway motion.

In Figure 10 the forces acting on a ship subjected to the additional gust loading $dF_{W,y}$ are presented.

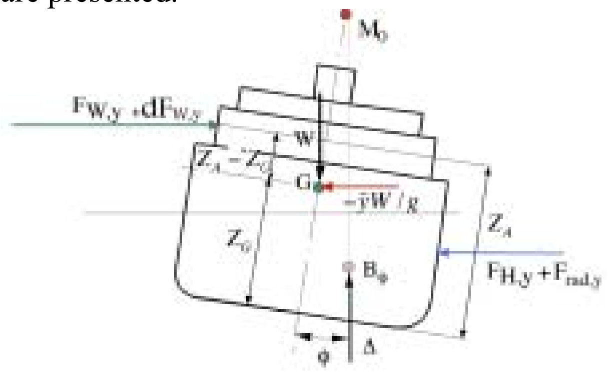

Figure 10. Ship dynamic heeling according to the weather criterion.

The steady balance of ship is perturbed by the action of wind gust. With the assumption of 50% increase of air pressure due to the wind gust the force corresponding to the gust can be evaluated as

$$dF_{W,y} = 0.5 \bullet PA, \qquad (4)$$

which results in the heeling moment external loading

$$dM_{w1} = dF_{W,y}(Z_A - Z_G) \qquad (5)$$

where Z_A is the vertical distance from the baseline to the centre of the lateral area *A*. The term $\cos\phi$ was disregarded using the small heel angles assumption.

During the transient heeling, the vector depicting the inertia force of the ship's mass appears. This vector acts at the ship's centre of gravity G and thus it does not contribute to the ship's heeling. Moreover, an unsteady component of the hydrodynamic reaction appears. This is a radiation force component $F_{rad,y}$ that primarily depends on the sway acceleration. These forces are disregarded by the weather criterion. In principle both new force components can be evaluated by a method like *LAIDYN*. Already from what was discussed above the following can be concluded:

- The weather criterion seems to model properly a steady wind action if the concerned heel angles are not too big. For high heel angles, the assumption of constant valued lever Z can be questioned (see Fig. 9).
- The action of wind gust is to heel the ship dynamically. In general, the effective lever of the heeling moment is smaller than in the steady case because the inertia force of the sway motion component compensates a part of the external loading. Thus it is obvious that the weather criterion in its present form may overestimate the dynamic heel values for the considered scenario.

7.2 Transient roll response according to the proposed modification of the weather criterion

The transient roll response of this modified sea weather model (called in the following the Y-force model) is shown in Figure 11.

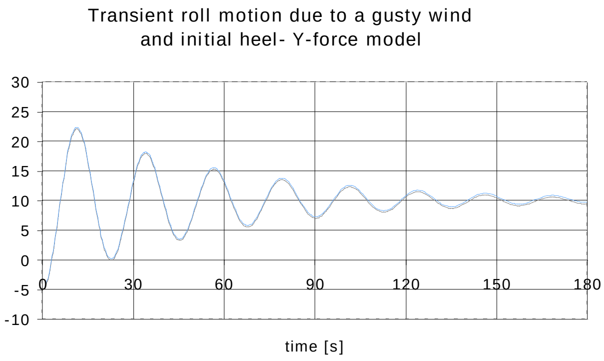

Figure 11. Ship dynamic heeling according to the modified weather criterion.

Comparing the transient roll responses given by two variations of the weather criterion (Figs. 7&11), a decrease of maximum roll angle of 4^0 is noted when using the proposed modification. The maximum heel angle given by considering the dynamic levers in the context of the weather criterion (refer to Figure 8) is approximately 8 degrees higher than the one obtained by the numerical simulations using the Y-force model. The drawback of the Y-force model is the fact that it cannot be used as easily as the original weather criterion. It requires either the numerical model of ship dynamics, which allows for sway motion, or the model tests. The model tests would be similar to the roll decay tests with the model free to roll and sway. The new elements in these tests would be an a priori evaluated initial roll angle and an application of the gusty wind loading as given by formulas (3) and (5).

Finally the result of roll simulation using both the weather criterion loading represented by the Y-force model and by the action of the resonant beam waves is presented in Figure 12, below. A reasonable agreement of maximum heel angle for this case when compared to a pure transient response (given in Figure 11) is noted. Again the maximum heel angle is about 4^0 smaller than the one obtained with the pure heeling moment (refer to Fig. 6 for the comparison) and it is approximately 5^0 smaller than the one obtained by the weather criterion.

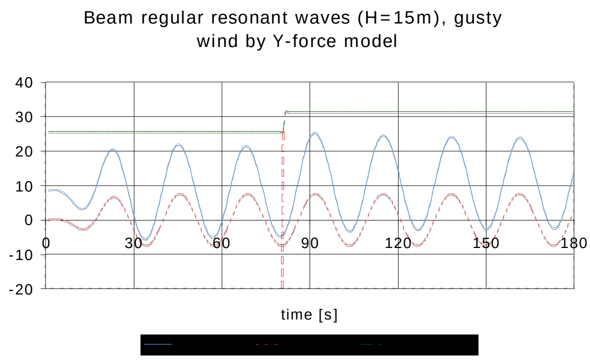

Figure 12. Steadily rolling in critical waves ship is subjected to gusty wind at the maximum roll angle towards the wind. The wind loading is represented by the Y-force model.

8. CONCLUSIONS AND RECOMMENDATIONS

The weather criterion, which is a simple check of the ship's intact stability, describes qualitatively well the transient behaviour of a ship subjected to the combined loads of gusty wind and waves. However, the criterion's simplicity may result in higher values of the maximum heel angles than the ones produced by the more sophisticated numerical tools. The assumed scenario is simplified by disregarding the sway motion. Thus the criterion can be too conservative, especially for large passenger vessels, (as well as other ship types with dimensions beyond the statistical base of the criterion).

In the current proposal for a revised Intact Stability Code, a procedure for alternative assessment, based on model testing is included, but a numerical simulation is not accounted for. Numerical methods usually offer advantages in schedule and cost.

For this reason, we recommend that the Intersessional Correspondence Group on Intact Stability (ISCG) recommends to the Sub-Committee On Stability And Load Lines And On Fishing Vessels Safety (SLF) of IMO to make an allowance for a numerical simulation of ship transient motion as subjected by the loading of the weather criterion. The validated and benchmark tested numerical methods should at least include, in addition to a non-linear roll model also, a proper modelling of sway motion.

Moreover, a possibility for conducting dedicated model tests simulating physically the transient heel behaviour of the ship should be investigated further with an aim of allowing for it in the Intact Stability Rules. This would be in agreement with the latest suggestions of the ISCG making an allowance for the model tests when evaluating the roll-back angle.

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