

Considerations on Parametric Roll and Dead Ship Conditions for the Development of Second Generation Intact Stability Criteria

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ABSTRACT

Work is in progress at IMO-SLF on the development of so called "Second Generation Intact Stability Criteria". This development is expected to be embedded in a three-plus-one-tiers framework comprising vulnerability criteria of level 1 and 2, direct stability assessment and operational guidance. This paper presents two procedures for addressing parametric roll at a vulnerability level 1 and the dead-ship condition at a vulnerability level 2. In the context of development of suitable models to be implemented in a regulatory framework, proper attention will be given to the concept of "validation", which seems to be sometime misunderstood in the rule making process.

KEYWORDS

Parametric roll; dead ship condition; vulnerability criteria; second generation intact stability criteria; IMO; stability regulations

INTRODUCTION

Work is in progress at IMO-SLF on the development of the so called "Second Generation Intact Stability Criteria". This development is expected to be embedded in a three-plus-one-tiers framework comprising vulnerability criteria of level 1 and 2, direct stability assessment and operational guidance. In this framework, physically sound criteria are requested to be developed, following the specifications reported in the Annex 1 of SLF52/WP.1 (2010). Such specifications basically indicate the level of complexity expected at each level for the criteria. In addition, the envisioned framework requires that different failure modes (pure loss of stability, parametric roll, surf-riding and broaching, dead ship condition and the recently added excessive accelerations (SLF53/WP.4, 2011)) are considered separately. The work presently carried out is the result of the need of a new generation of intact stability criteria based on physically sound mathematical models of the ship dynamic behaviour rather than on statistical approaches, as it is instead the case of the "Criteria regarding righting lever curve properties" in present 2008 IS Code (IMO, 2009).

The development of criteria based on physical models of the ship dynamical behavior in waves is

a significant challenge, due to the complexity of the problem of ship motions at sea. There is moreover the necessity of implementing several assumptions which allow simplifying the criteria to an extent which is manageable from a regulatory point of view, bearing in mind present available technology.

In the process of developing criteria to be implemented in IMO instruments, there is always a request for a proper "validation" of new proposals. However, different actors on the scene often give different interpretations of what actually such "validation" process is. There is indeed no formal definition at IMO level which allows clarifying when a rule can be considered "validated" and how to carry out this "validation" procedure.

This paper considers two methodologies which have been developed for the Level 1 Vulnerability assessment for parametric roll and for the Level 2 Vulnerability assessment for dead ship condition. Some aspects of the two methods are highlighted and sample calculations are shown. Before addressing the two methods, some considerations are given regarding the "validation" process.

VALIDATION OF "RULES" AND "CRITERIA"

Recently, Story et al. (2010) provided an overview of the matter of verification and validation of numerical prediction methods with particular attention to the field of ship motions. In this context they adopted the following definition used by the US Department of Defense (2009):

- "Validation" is *"the process of determining the degree to which a model and its associated data are an accurate representation of the real world from the perspective of the intended uses of the mode"*

It is therefore clear that, according to this definition, two ingredients are necessary in order to proceed with a "validation process": a calculation method predicting a real world quantity, and the actual real world quantity to compare the prediction with.

Going now to the regulatory perspective, according to Annex 2 of SLF51/WP.2 (2008):

- A "criterion" is *"a procedure, an algorithm or a formula used for judgment on likelihood of failure"*;
- A "standard" is *"a boundary separating acceptable and unacceptable likelihood of failure"*.

The combination of a "criterion" and an associated "standard" allows to create a "rule" (or "regulation"). Indeed, according to Annex 2 of SLF51/WP.2 (2008), a "rule/regulation" is *"the specification of a relationship between a standard and a value produced by a criterion"*.

A criterion is therefore expected to provide some measure of the likelihood of failure reflecting the real world. On the other hand, the setting of the standard consistently with the judgment procedure given by the underlying criterion, and therefore the eventual creation of a regulation, is a mainly political decision which is expected to reflect a societal acceptable level of "likelihood of failure".

According to the definition of "validation" adopted by Story et al. (2010), it is clear that a regulation can not be really validated. On the other hand there is some possibility to validate a "criterion". Unfortunately, however, "criteria" are often the result of simplifying assumptions which

are necessary to develop sufficiently simple methodologies for practical application at a regulatory level. On the basis of the expected complexity level required in SLF52/WP.1 (2010) this necessity of simplification seems to be particularly relevant for the expected Level 1 and Level 2 vulnerability assessment methods in the second generation intact stability criteria. A more direct and transparent approach is expectable at the so-called Direct Stability Assessment level, where an explicit direct simulation of ship motions is envisioned (SLF52/WP.1, 2010).

Accordingly, it is expectable that a proper full "validation" can be, and should be, carried out for methods to be employed at the Direct Stability Assessment level. This would mean a proper comparison between real world data and predictions given from numerical methodologies. For what concerns simplified Level 1 and Level 2 vulnerability criteria, it is expectable that the proposed methodologies could contain simplifying assumptions with the intention of leading to sufficiently simple calculation frameworks. The obtained outcomes from such simplified frameworks are likely to be "vulnerability indices" which are intended to be related to the likelihood of failure, but which are not actually the true likelihood of failure. As a consequence, in this context, a proper validation of the whole method cannot really be carried out. However, working at two different levels could allow developing sufficiently robust methodologies. At the preliminary development stage it is necessary to show that each building block of the proposed method can sufficiently reflect the real world behavior. This would basically mean a "validation" of each basic building block, when feasible, i.e. when the block is not based on arbitrary assumption. The "validation" of the block should show that the block is able to provide a sufficiently good representation of the real world, taking into account a trade-off between simplicity and accuracy. In order to allow a, though partial, validation, it would therefore be extremely beneficial to keep semi-empirical or not well justifiable assumptions to a minimum. At a final level of development, an "overall consistency check" process for the criterion could be, and actually should be, carried out checking the

correlation between the "vulnerability indices" predicted by the simplified criteria and the outcomes from either experiments or validated numerical codes in terms of likelihood of failure. This final "overall consistency check" could represent the basis for the setting of the standards, in terms of "vulnerability indices", starting from a real world quantity (the likelihood of failure) measured by validated more advanced methods.

As a result, it is clear that just the extensive application of a proposal of criterion to a large set of sample ships, judging the outcomes from a purely qualitative perspective, maybe on the basis of the expected outcomes, cannot be considered a proper "validation" process. Such improper way of judging the quality of a criterion proposal should therefore be avoided in the rule making process.

LEVEL 1 VULNERABILITY ASSESSMENT FOR PARAMETRIC ROLL

In (Italy, 2010; Annex 1 of SLF53/INF.10, 2010; SLF53/3/9, 2010; Bulian & Francescutto, 2010) a procedure was proposed for assessing the vulnerability of a ship, in a given loading condition, to parametric roll. The complexity of the procedure was considered to be suitable for a 1st level vulnerability assessment. The procedure can be summarized, for a specified loading condition, as follows:

- A series of 16 regular waves ("wave cases") are considered as reference calculation waves, each with a given weight (see Table 1).
- For each "wave case" the variation of the metacentric height is calculated by means of a standard hydrostatic code for one wave passage, i.e. when the wave crest spans one wave length. Waves are considered to be exactly longitudinal with respect to the ship.
- The dimensionless parametric excitation for the considered wave is determined, as usual, as the ratio between the amplitude of the fluctuation of the metacentric height ($\delta \overline{GM}$) and the average metacentric height (\overline{GM}_{ave}). For simplicity, $\delta \overline{GM}$ is calculated as half the difference between the maximum and the minimum metacentric height during the considered wave passage.

- The dimensionless parametric excitation for the considered "wave case" is compared with a limiting threshold curve (see Appendix 1). In this way it is possible to determine, for a given ship speed, whether this speed is "dangerous" (excitation above threshold) or "not dangerous" (excitation below threshold). A range of speeds in head and following waves is considered up to the ship design speed V_d . Since the average metacentric height in waves is, in general, different from the metacentric height in calm water, the roll natural frequency is corrected for this difference when calculating the threshold curve.
- The vulnerability index VI_i for the considered i-th "wave case" is defined as the fraction of dangerous speeds with respect to the whole ship operational range. In case the average metacentric height, for the considered wave, is non-positive, the vulnerability index is conventionally set to $VI_i = 1$.
- The final vulnerability index is determined as a weighted average of the vulnerability indices VI_i using the weights W_i associated with each wave case.

The procedure above will be referred herein as "complete procedure".

During recent SLF53, an idea for a simplified procedure was also roughly discussed. Drawing from such discussion, a "simplified procedure" could be envisaged which differs from the procedure reported above in the way the vulnerability index is calculated. Instead of calculating the vulnerability index as the "fraction of dangerous speeds", a simplified binary vulnerability index $VI_{S,i}$ could be defined for each generic i-th "wave case" as follows:

$$VI_{S,i} = \begin{cases} \overline{GM}_{ave,i} \leq 0 & \text{or} \\ 1 \left(\frac{\delta \overline{GM}_i}{\overline{GM}_{ave,i}} \geq (h_{0,lim})_{min} \text{ and } |V_{PR,2:1,i}| \leq V_d \right) & \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

In (1), the quantity $(h_{0,\text{lim}})_{\min}$ is the minimum of the threshold curve (see Appendix 1), while $|V_{PR,2\lambda,i}|$ is the minimum speed (in absolute value) at which, in longitudinal waves, the absolute value of the encounter frequency for the i -th wave case is equal to twice the roll natural frequency in waves. As said in Appendix 1, making reference to (A1.5), we can consider an approximation for $(h_{0,\text{lim}})_{\min}$ as given by:

$$(h_{0,\text{lim}})_{\min} \approx 4 \cdot (\nu_R + \nu_T (\Lambda = 2)) \quad (2)$$

when $\nu_R + \nu_T < 1$. Such procedure will be referred herein as "simplified procedure".

It could be said that, while the "complete procedure" provides a measure of the fraction of dangerous speeds, the "simplified procedure" provides a measure of the fraction of "dangerous waves". While the "complete procedure" provides a smooth and continuous vulnerability index for each wave case, the simplified procedure allows only 0 or 1 for the vulnerability index for each wave case. As a result it is expectable that the simplified procedure will be associated with stronger quantization effects due to the finite number of considered "wave cases".

Both the "complete" and the "simplified" procedures have been applied to a sample of 11 ships. The main characteristics of the tested ships are reported in Appendix 2. In the determination of the threshold curve (see (A1.5)) the dimensionless linear roll damping coefficient has been taken as $\nu_R = 0.03$. For what concerns the coefficient ν_T allowing for a limited divergence (transient effects), the following definition based on the number of roll oscillations has been used:

$$\begin{cases} q_L = 11 \\ p_{OSC} = 4 \end{cases} \Rightarrow \nu_T = 0.0954 \cdot \frac{|\Lambda|}{2} \quad (3)$$

which gives an approximated value for $(h_{0,\text{lim}})_{\min}$, to be used in the "simplified procedure", equal to:

$$(h_{0,\text{lim}})_{\min} \approx 4 \cdot (\nu_R + \nu_T (\Lambda = 2)) = 0.502 \quad (4)$$

It must be noted that, while ν_R can be considered as a reasonable value of dimensionless linear roll damping coefficient for relatively low / moderate forward speeds, the parameters q_L and p_{OSC} have

been set to the reported values only in order to keep quantitative consistency with proposals reported in Annex 2 of SLF53/INF.10 (2010) and SLF53/3/7 (2010) in terms of maximum acceptable dimensionless fluctuation of \overline{GM} . Indeed, the limit value for $\delta \overline{GM} / \overline{GM}$ is proposed as 0.49 in SLF53/3/7 (2010) and as 0.51 in Annex 2 of SLF53/INF.10 (2010). The quantitative closeness of the two values, however, seems to be more a pure coincidence than a true convergence of the two extremely different underlying approaches. Moreover the two proposals are characterized by a quite large level of semi-empiricism. Therefore, additional justifications from the proposes could help in evaluating the appropriateness of the proposals.

Table 1: Reference calculation waves ("wave cases") for parametric roll vulnerability assessment (from Annex 1 in SLF53/INF.10 (2010)).

Wave Case	Wave length λ_w [m]	Wave amplitude a_w [m]	$\frac{\lambda_w}{2a_w}$	Weighting factor W_i [nd]
1	37.901	0.250	75.8	0.000013
2	62.653	0.354	88.6	0.001654
3	93.593	0.612	76.4	0.020912
4	130.721	0.925	70.7	0.092799
5	174.037	1.237	70.3	0.199218
6	223.541	1.575	71.0	0.248788
7	279.233	1.926	72.5	0.208699
8	341.113	2.268	75.2	0.128984
9	409.180	2.589	79.0	0.062446
10	483.436	2.886	83.8	0.024790
11	563.880	3.158	89.3	0.008367
12	650.512	3.407	95.5	0.002473
13	743.331	3.641	102.1	0.000658
14	842.339	3.835	109.8	0.000158
15	947.535	4.015	118.0	0.000034
16	1058.919	4.250	124.6	0.000007

The vulnerability index obtained from the application of the complete and of the simplified procedures to the set of ships reported in Appendix 2 is shown in Fig. 1 as a function of the calm water metacentric height \overline{GM}_{cw} .

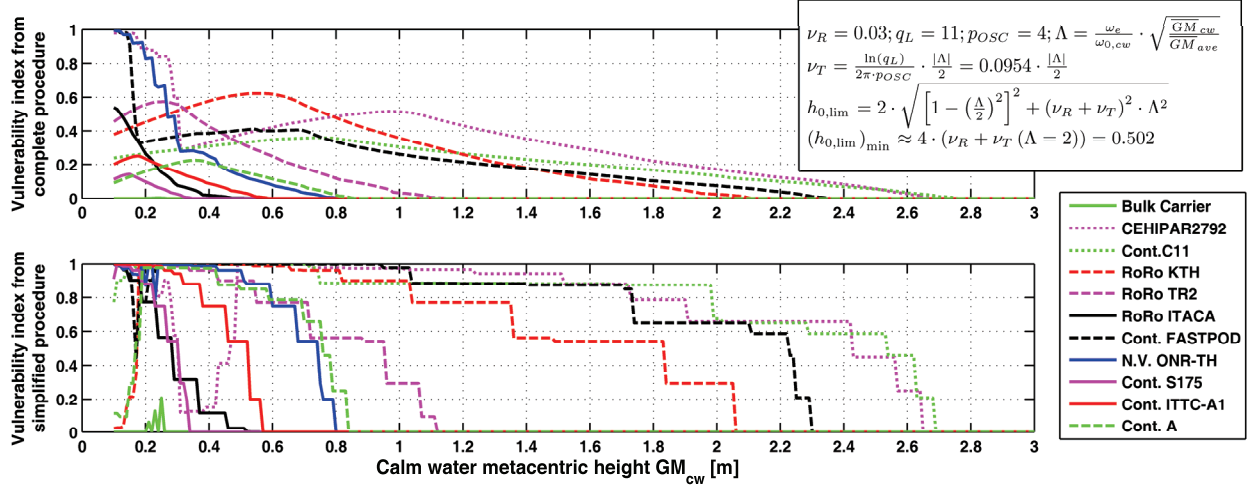


Fig.1: Example application of "complete" and "simplified" procedure to the set of sample ships (see Appendix 2).

From the results in Fig. 1 it can be seen that the "simplified procedure" suffers from an evident general quantization, i.e. the calculated vulnerability index from the simplified procedure changes in steps in the whole range of tested metacentric heights. This is the consequence of the fact that the simplified procedure either "counts" or "not counts" the weight factor W_i for each single wave case: if a "wave case" is determined as "dangerous", the associated weight factor W_i is added to the vulnerability index, otherwise it is not added. At extremely low values of \overline{GM}_{cw} some limited quantization problems appear in the complete procedure too, particularly for CEHIPAR2792, because the average metacentric height in waves \overline{GM}_{ave} becomes negative for some wave case. However such situations are rare in the considered sample of ships. The values of the calm water metacentric height at which the vulnerability indices goes to zero for the two procedures are close each other.

In order to quantify the sensitivity of the methods to the selection of the parameters ν_R and ν_T , some additional calculations of the vulnerability index have been carried out in case of the Containership C11 (Levadou & van't Veer, 2006) using the complete (see Fig. 2) and the simplified (see Fig.3) methodologies. Three curves are reported in Fig. 2 and Fig.3. One reference curve is associated with the same parameters as used in Fig. 1. A second curve

takes into account the roll damping ν_R and neglects the "relaxation" for transient effects ($\nu_T = 0$). Finally, a third conservative curve considers $\nu_R = 0$ and $\nu_T = 0$. It can be seen that the selection of the parameters ν_R and ν_T is quite critical and has significant effects on the obtained results. A similar analysis for the Container C11 is also reported in Annex 11 of SLF53/INF.10 (2010), but in such case different values of ν_R were considered, and transient effects were not taken into account ($\nu_T = 0$). It must however be underlined that what is really important for the finally obtained vulnerability index with both the complete and the simplified procedure is basically the sum $\nu_R + \nu_T (\Lambda = 2)$.

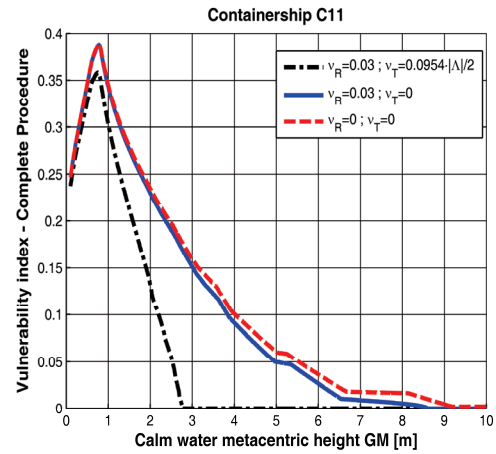


Fig. 2: Containership C11. Vulnerability index according to complete procedure

As a consequence very similar results can be obtained by using different values of the two terms v_R and v_T if the aforementioned sum is kept the same in the complete procedure. At the same time, in the simplified procedure, exactly the same result is obtained when v_R and v_T are changed if $v_R + v_T (\Lambda=2)$ is kept constant, provided the approximation (2) is used

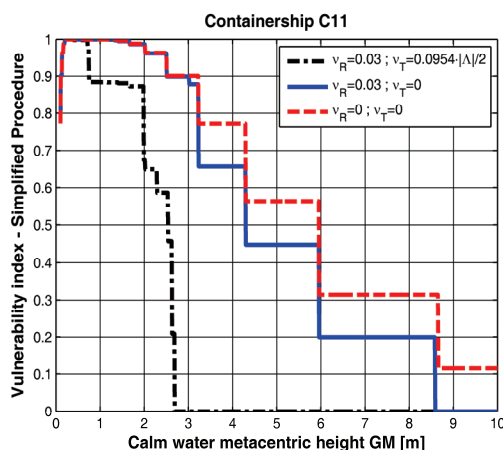
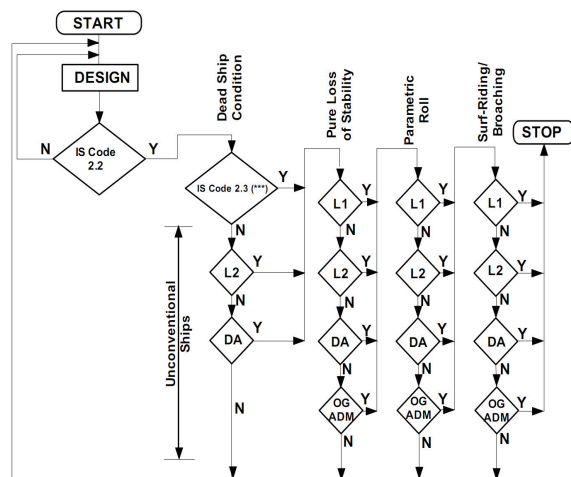


Fig.3: Containership C11. Vulnerability index according to simplified procedure.

LEVEL 2 VULNERABILITY ASSESSMENT FOR DEAD SHIP CONDITION

One of the most important discussions regarding intact stability at IMO-SLF in recent years has been that of the partial inadequacy of the Weather Criterion for certain types of ships (Francescutto, 2004). Waiting for a new agreed updated Weather Criterion (see §6.2 in SLF47/17 (2004), interim alternative experimental means of compliance have been developed (MSC.1/Circ.1200, 2006; MSC.1/Circ.1227, 2007). The possibility of applying alternative experimental means of assessment is now an integral part of the Weather Criterion in the 2008 IS Code (IMO, 2009). It seems that the present Weather Criterion in the 2008 IS Code plays an important technical, and maybe also psychological, role in the intact stability rules framework as a sort of "(perceived) safety level keeper". Perhaps this could be associated with the fact that the severe wind and rolling criterion (weather criterion) is the only one criterion based on a simplified physical model of the ship dynamic behavior

(apart from the simple turning and crowding criteria for passenger vessels) in the 2008 IS Code. It is actually a fact that, on the basis of Japanese and Italian proposals, the only agreed level one vulnerability criterion at the moment is that regarding dead ship condition, where it has been decided to keep the Weather Criterion framework, with possible modification of the wave steepness table in accordance with that in MSC.1/Circ.1200 (see Annex 1 in SLF53/WP.4 (2011)). This situation seems to confirm the general tendency in the IMO rule making framework, where significant rule changes occur quite slowly and with a not negligible delay with respect to the advances in scientific knowledge. This extremely prudent behavior is reflected in the final results of the discussion which took place at the Working Group on Intact Stability at SLF53. Looking indeed at Annex 3 in SLF53/WP.4 (2011) it can be seen that a possible structure of the Second Generation Intact Stability Criteria was clarified, as shown in Fig. 4, but such structure is expected to be implemented only "after gaining sufficient experience in the application of second generation stability criteria". It can be seen from Fig. 4 that a modified Weather Criterion in the 2008 IS Code is envisaged, with the possibility of not complying with it if compliance is shown at the 2nd level of vulnerability or at the direct assessment level for the dead ship condition.



*** = WeC possibly amended with steepness table from MSC.1/Circ.1200

Fig. 4: Possible final situation after gaining sufficient experience in the application of second generation stability criteria (Annex 3 in SLF53/WP.4, 2011).

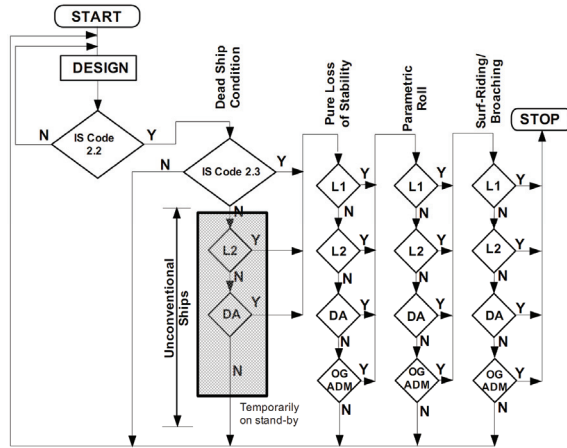


Fig.5: Possible situation in the interim period (Annex 3 in SLF53/WP.4, 2011).

However, at SLF53, the prudent behaviour suggested, in the interim period, not to abandon or modify the Weather Criterion in the 2008 IS Code. As a consequence, the structure in the interim period has been envisaged as that reported in Fig. 5. It is very interesting to see that the whole "dead ship branch" has been put in stand-by in order to avoid possible interim regulatory inconsistencies with the present 2008 IS Code. This situation is, to some extent, paradoxical, when considering the fact that a large part of the discussion on Second Generation Intact Stability Criteria originated from the need of updating the present Weather Criterion (see SLF45/6/3 (2002) and SLF45/6/5 (2002)) and that, on this basis, the Working Group on the Revision of the Intact Stability Code at SLF45 was instructed by the Sub-Committee to *"prepare a work methodology and scope for the revision exercise...possibly including the interim deletion of some criteria"* (see §6.4.1 in SLF45/14 (2002)).

Despite the temporarily "stand-by" of the dead-ship branch, proposals for higher levels of assessment for the dead ship condition are on the table. In particular, a proposal by Italy for Level 2 Vulnerability assessment (Annex 3 in SLF52/INF.2, 2009) and a proposal from Japan for the direct assessment level (Annex 4 in SLF52/INF.2, 2009; Annex 7 in SLF53/INF.10, 2010), despite being intended by the respective Delegations to be applied at different levels, share basically the same underlying mathematical model, while they differ in the

proposed way of solving it. The considered mathematical model has the following form:

$$\ddot{\phi} + 2\mu \cdot \dot{\phi} + \beta \cdot \phi |\dot{\phi}| + \delta \cdot \phi^3 + \omega_0^2 \cdot c(\phi) = \omega_0^2 \cdot (\overline{m}_{wind,tot} + m(t)) \quad (5)$$

The model (5) takes into account the mean heeling moment due to wind $\overline{m}_{wind,tot}$ (comprising drift reaction), while the time dependent term $m(t)$ is the forcing due to waves and wind gustiness. The modeling (5) is based on an absolute roll angle approach, which has been shown to have some drawbacks (Italy, 2009; Bulian & Francescutto, 2009). In both the proposals from Italy and Japan based on a modeling of the type (5), the intention is to obtain a measure of the probability of "capsizing". In this context "capsizing" is intended in broad terms as the exceedance of too large heeling angles. The methodology for obtaining the estimation of such probability differs among the two proposals: equivalent area method for Italy and piecewise-linear approximation for Japan. However, the results in terms of probability as a function of the metacentric height are qualitatively in line.

The particular aspect which is noteworthy is that in both methods the finally obtained "capsize/failure probability" (or "capsize/failure index") is not a monotonically decreasing function of the ship metacentric height as the usual static approach would suggest. This is shown in Fig. 6, where the failure index has been calculated for an exposure time of 1 hour for three ships (LPS242 is a large passenger ship). "Full WSD" in Fig. 6 means that the full wave scatter diagram for North Atlantic according to IACS Rec. 34 (2001) has been used. Similar results are shown also in Annex 2 and Annex 3 of SLF52/INF.2 (2009).

The fact that the calculated capsize index in Fig. 6 shows a minimum as a function of the metacentric height clearly indicates that the "axiom" of static stability, i.e. "the larger \overline{GM} the better it is" is likely to be no longer valid in the framework of Second Generation Intact Stability Criteria, where dynamic aspects are accounted for. This is particularly true also taking into account the introduction, in

SLF53/WP.4 (2011), of "Excessive accelerations" as an additional failure mode to be taken into account (see also SLF53/3/2 (2002)).

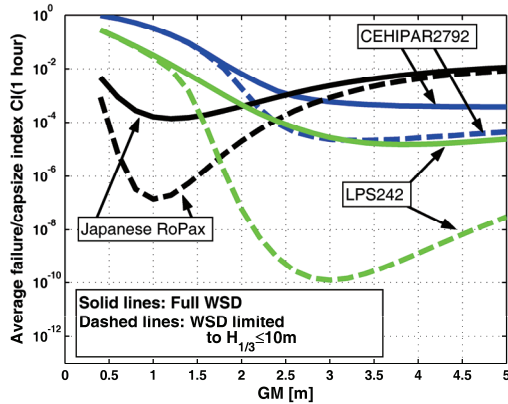


Fig. 6: Capsize index from a sample of ships from Bulian et al. (2009).

CONCLUSIONS

In order to promote discussion during the Workshop, this paper has presented three topics relevant to the development of Second Generation Intact Stability Criteria.

First of all the problem of "validation of criteria" has been addressed showing that this wording has inherent weaknesses and should be better clarified.

Then, a proposal for a first level vulnerability assessment criterion for parametric roll has been reported in two forms: a "complete" and a "simplified" procedure. Sample calculations have been carried out showing that the simplified procedure can suffer of quantization problems and that the quantitative outcomes from the methodology, either in complete or simplified form, are significantly dependent on some assumed parameters. Particularly, parameters associated with "transient effects" can have a significant impact, while their setting can be subject to significant arbitrariness.

Finally the development of a level 2 criterion for the dead ship condition has been addressed. This matter has been discussed also in view of the recent results from the discussion at the SLF53 Working Group on Intact Stability regarding the possible structure of the Second

Generation Intact Stability Criteria. The reported example calculations show that, when dynamics aspects are taken into account, as it is expected to occur for Second Generation Intact Stability Criteria, the "axiom" of static stability, i.e. "the larger GM the better it is" will likely to be no longer valid.

In general, the application of criteria taking explicitly into account the ship dynamics is likely to provide "ranges of allowable metacentric heights" instead of providing the usual minimum allowed \overline{GM} curve. This aspect is likely to have not negligible consequences in the way the problem of determination of allowable loading conditions is addressed at design stage.

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APPENDIX 1: PARAMETRIC ROLL THRESHOLD CURVE WITH TRANSIENT EFFECTS TAKEN INTO ACCOUNT

The determination the threshold for parametric excitation taking into account transient effects, as proposed in SLF53/3/9 (2011), has been thoroughly described in (Italy, 2010). Herein we provide an outline of the derivation of such threshold curve. The development is based on the theoretical background given by Hayashi (1964). The same background was used also by Spyrou (2005) to determine an approximate limiting parametric excitation when the frequency of the parametric excitation is exactly twice the roll natural frequency and considering a particular couple of initial conditions, namely a specified initial roll angle and zero initial roll velocity.

The roll motion equation is written as:

$$\ddot{\phi} + 2 \cdot \nu_R \cdot \omega_0 \cdot \dot{\phi} + \omega_0^2 \cdot (1 + h_0 \cdot \cos(\omega_e \cdot t)) \cdot \phi = 0 \quad (A1.1)$$

where it is assumed that the oscillation frequency ω_e of the parametric forcing is close, but not necessarily equal, to $2\omega_0$ and, without loss of generality, it is assumed $h_0 \geq 0$. By a change of variable $\phi(t) = e^{-\nu_R \omega_0 t} \cdot x(t)$ it is possible to write for $x(t)$ an undamped Mathieu equation to which the results given by Hayashi (1964) are directly applicable. Accordingly, in terms of the original roll angle ϕ , if we assume small damping, i.e. $\nu_R \ll 1$, it is possible to write the generic approximate solution for (A1.1) as:

$$\begin{aligned} \phi(t) \approx & c_1 \cdot e^{-(\nu_R + \nu_p) \omega_0 t} \cdot \sin\left(\frac{\omega_e}{2} \cdot t - \sigma\right) + \\ & -c_2 \cdot e^{(\nu_p - \nu_R) \omega_0 t} \cdot \sin\left(\frac{\omega_e}{2} \cdot t + \sigma\right) \end{aligned} \quad (A1.2)$$

To be precise the form of the solution (A1.2) is to be considered valid when $x(t)$ is inside the instability region, but, for the purpose of this appendix, this is the case. In (A1.2) the constants c_1 and c_2 depend on the initial conditions, while the coefficient ν_p and the phase σ depend on the frequency ratio $\Lambda = \omega_e / \omega_0$ and on the amplitude h_0 of the parametric excitation. In the context of this paper the actual value of the phase σ is not important, what is instead important is the value of the coefficient ν_p which can be determined approximately as:

$$\begin{aligned} \nu_p = & \frac{1}{\Lambda} \sqrt{\left(\frac{h_0}{2}\right)^2 - \left[1 - \left(\frac{\Lambda}{2}\right)^2\right]^2} \\ \text{with } h_0 \geq & 2 \cdot \left|1 - \left(\frac{\Lambda}{2}\right)^2\right| \end{aligned} \quad (A1.3)$$

Actually, the condition on the minimum value for h_0 in (A1.3) represents the approximate condition for the instability of $x(t)$.

Coming back now to the roll motion $\phi(t)$ as approximated in (A1.2) for $\nu_R \ll 1$, we can see that, in general, it is possible to determine a couple of initial conditions $(\phi(t=0), \dot{\phi}(t=0))$ such that $c_1 = 0$. The actual value of such initial conditions is irrelevant, what is important is that it is possible to find a couple of initial conditions for which the first exponentially decaying term vanishes. What remains is only the second term. If $\nu_p > \nu_R$ the second term in (A1.2) is an exponentially diverging term. The considered couple of initial conditions lead to a "worst case scenario", i.e. a case where the divergence of the roll envelope is fastest. In such case the roll envelope $C(t)$ behaves as:

$$\begin{aligned} C(t) \approx & |c_2| \cdot e^{\nu_T \omega_0 t} \\ \nu_T = & \nu_p - \nu_R \end{aligned} \quad (A1.4)$$

The dimensionless coefficient ν_T in (A1.4) governs the rate of exponential divergence. Note that $\nu_p > \nu_R \Rightarrow \nu_T > 0$. Let us now assume that a specified value for the coefficient ν_T is set as a

limit acceptable value. It is then possible to determine the associated threshold value of required parametric excitation h_0 by combining the definition of ν_T in (A1.4) with (A1.3):

$$h_{0,\lim} = 2 \cdot \sqrt{\left[1 - \left(\frac{\Lambda}{2}\right)^2\right]^2 + (\nu_R + \nu_T)^2 \cdot \Lambda^2} \quad (\text{A1.5})$$

The equation (A1.5) represents a threshold curve taking into account the global rate of exponential divergence of the roll motion in the considered "worst case scenario", and, in general, for large values of the time t , i.e. when the first term in (A1.2) becomes negligible in any case. If we assume that ν_T is fixed as a limit value, as said, equation (A1.5) provides an approximate limiting value for the parametric excitation which, in the limit of the approximation, guarantees that the exponential divergence of the resulting roll envelope is not larger than that associated with ν_T . Similarly to what was done by Spyrou (2005), the value of ν_T could be set in terms of a limiting ratio of increase of the envelope in a given time T . Let us define q_L as:

$$q_L = \frac{C(t+T)}{C(t)} \approx e^{\nu_T \cdot \omega_0 \cdot T} \quad (\text{A1.6})$$

Conversely:

$$\nu_T = \frac{\ln q_L}{\omega_0 \cdot T} \quad (\text{A1.7})$$

Depending on whether the reference time T is given in terms of number of roll oscillations p_{OSC} or in terms of natural roll periods p_{NR} , the definition of ν_T becomes, respectively:

$$\begin{aligned} \nu_T &= \frac{\ln q_L}{2\pi p_{NR}} \\ \nu_T &= \frac{\ln q_L}{2\pi \cdot p_{OSC}} \cdot \frac{|\Lambda|}{2} \end{aligned} \quad (\text{A1.8})$$

In determining the second definition in (A1.8) use has been made of the fact that, in accordance

also with (A1.2), the oscillation frequency of the parametrically excited roll in the first parametric resonance region is half the encounter frequency (in absolute value).

In practice, by specifying the limit value for q_L in the reference number of roll oscillations p_{OSC} (or roll periods, p_{NR}) the value of ν_T can be calculated from (A1.8) and the associated limit parametric excitation can be obtained from (A1.5).

It is worth underlining that the minimum of the threshold curve in (A1.5), say $(h_{0,\lim})_{\min}$, for sufficiently small values of the sum $\nu_R + \nu_T$ can be considered to occur approximately at $\Lambda = 2$ with a value close to $4 \cdot (\nu_R + \nu_T)$, where, in this latter sum, ν_T shall be determined at $\Lambda = 2$ in case ν_T is assumed to be dependent on Λ as in the second definition in (A1.8). In addition, when transient effects are not taken into account, i.e. when it is considered $\nu_T = 0$, the threshold curve in (A1.5) reduces to the usual approximation of the threshold excitation in the first parametric resonance region.

APPENDIX 2: SAMPLE SHIPS FOR PARAMETRIC ROLL VULNERABILITY ASSESSMENT

A set of sample ships has been used for checking both the "complete" and the "simplified" first level vulnerability assessment procedures for parametric roll. Main data of the tested ships are reported in Table A2.1. The reported data are: the reference ship length L , the ship beam B , the checked draught T , the depth D of the used offset, the maximum speed V_d used in the calculations, the dimensionless wet roll radius of inertia k'_{xx}/B for the calculation of the roll natural frequency, the block coefficient C_b and the prismatic coefficient C_p (both based on the reported reference ship length, beam and draught). All calculations have been carried out with zero trim.

Table A2.1: Main data of sample ships used for example calculations of the first level vulnerability assessment procedures for parametric roll.

Ship #:	1	2	3	4	5	6	7	8	9	10	11
L [m]	225	205.7	262	135	132.22	53.4	275	154	175	150	201
B [m]	32.24	29.9	40	24.2	19	10	30.0	18.8	25.4	27.2	32.2
T [m]	14.0	6.6	11.5	5.5	5.875	2.1	10.3	5.5	9.5	8.5	11.5
D [m]	19.70	20.20	24.45	18.00	11.4	6.18	26.0	14.5	19.5	18.0	23.1
V_d [knots]	15	22	24	21	22	16	35	30	23	23	21
$\frac{k'_{xx}}{B}$ [nd]	0.328	0.421	0.445	0.417	0.385	0.470	0.438	0.459	0.400	0.368	0.400
C_B [nd]	0.808	0.591	0.560	0.628	0.521	0.506	0.567	0.538	0.572	0.669	0.648
C_P [nd]	0.814	0.607	0.577	0.636	0.548	0.579	0.582	0.638	0.589	0.674	0.673
Description of used ships - #1: Bulk Carrier (Bulian & Francescutto, 2010); #2: CEHIPAR2792 (Bulian & Francescutto, 2010); #3: Container C11 (Levadou & van't Veer, 2006); #4: RoRo KTH (Garme, 1997); #5: RoRo TR2 (Bulian, 2006); #6: RoRo ITACA (Bulian, 2006); #7: Container FASTPOD (Turan et al., 2008); #8: Naval Vessel ONR Tumblehome (Sadat-Hosseini et al, 2010); #9: Container S175; #10: Container ITTC A1 (Spanos & Papanikolaou, 2009); #11: Container A.											