A proposed new generation of intact stability criteria for assessment of ship stability in longitudinal waves

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Abstract. Intact ship stability assessment to prevent stability failure in heavy weather conditions is of paramount importance on board vessel. The possibility of assessment the causes that can lead to loss of ship’s stability as well as the assessment of intact stability in heavy seas is an important problem and has attracted a huge interest of the national and international regulatory authorities. Despite the regulations in force, referring to intact ship stability, many ships continued to lose the stability and or capsize due to failure modes that presently are not covered by such regulations. Based on this aspect has been identified the necessity of modelling an updated criteria for assessment of ship’s stability taking into consideration actual possible situations for loss of stability in heavy seas as a measure of increasing ship safety of ships. In this respect, the goal of this paper is to illustrate a possible criteria for assessment ship’s stability in heavy seas through a method of determination the possible problems in a form of dynamic stability criteria. A new intact stability criteria is proposed and developed based on separate levels for assessment of vulnerability and susceptibility of ships in situations of parametric rolling and pure loss of stability encountered in extreme sea conditions. Mathematical models correlated with ship’s construction particulars and weather conditions were developed for every separate level in order to assess the ship’s stability. The objective of the proposed criteria is to bring to officers on board ships the possibility of assessment the ship’s intact stability, as a measure of prevention and improvement of safety during the voyage.

1. Actual developments of intact ship stability criteria
Presently, the IMO Intact Stability Code 2008 [1], are the regulations used for of assessment the ships stability. These stability criteria are developed in a two level scenario, General Stability Criteria and Weather Criterion (Severe Wind and Rolling Criterion).

The General Stability Criteria was developed for assessment the intact ship stability in calm sea and the methodology is based on the calculation of righting lever for this condition, at different angles of heel, as illustrated in figure 1.

The Weather Criterion, plans to assess the resistance opposed by of the ship in front of beam wing and rolling effects acting together. The scenario that a ship has to survive according to this criterion is illustrated in figure 2. Considering the area under lever curve as a measure of the amount of potential energy which an inclined ship has, the criterion requires that for the heeled condition the two areas under the curve, area for heeling angle in condition of equilibrium and the area from windward turning point to new position of equilibrium, to be almost equal.
The assumed Weather Criterion is based on a physical modelling but was adjusted in a form of wind speed, based on casualties of capsized ships. In other words, in this criterion, the wind speed does not illustrate the actual sea state and has only an empirical meaning. This model, developed in a simplified way, takes into account only the effect of wind and waves coming from abeam which in fact it reveals only one situation for loss of ship’s stability, thereafter the level of safety is largely unknown.

![Figure 1. Righting lever curve.](image1)

![Figure 2. Weather Criterion.](image2)

Although this criterion considers the dynamics of ship roll motions, this prescriptive scenario is not suitable to assess the intact stability in the situations when the ship endangering longitudinal waves (head and following waves), like parametric rolling or pure loss of stability, and it was never intended to be used for such situations.

The ship’s safety margin, by the compliance with this stability criteria, is however generally unknown and it still remains a concerning matter. This is because this stability criterion reveals the fact that different typology of ships has an unequally distributed safety margin and moreover the safety margin is strongly influenced by the ship’s dimensions. The criterion mixes the good and bad designs in a set of standards which not have a clear physical relation with the phenomena they are trying to avoid. In addition, the present version of Weather Criterion, due to its relatively poor, although physical, modelling spreads unevenly the safety level among ship types [2].

In respect of ship’s safety, the present Weather Criterion cannot be regarded as an optimal solution. This aspect is emphasized by the ship stability loss casualties that continue to occur, despite the fact that actual intact stability criteria are fulfilled prior commencement of the voyage by all ships involved in casualties.

The existing stability criteria may not have applicability to part of the actual types of modern ships designed with different naval architectural features, especially because the original criteria as adopted by Resolution A.167, was developed more than forty years ago, and were based on casualty statistics that included mainly ships under 100 m in length [3]. The existing criteria may not assure the required level of safety as there is no previous experience in relation to safety and stability with the modern ships of today.

What is much more important to be mentioned, is the fact that dynamic instabilities of ships in heavy seas situations are not part of the present stability criteria. Criteria necessary for the assessment ship’s vulnerability in front of such phenomena, from the beginning of the voyage, as a measure of safety has to be developed in a form of stability criteria and to be integrated into the present intact ship stability regulations.

Based on the analysis presented it can be concluded that presently, intact ship stability assessment is based only to the fulfilment of criteria related to the static lever curve for still water condition. The IMO stability criteria are prescriptive rules established many years ago, based on practical experiences. In this respect, it is obvious that new approaches must be implemented in order to issue
valid, simple and trustworthy methodology to provide the Master on board vessel with a possible solution for acting against ship stability failure that can occur in different situations of heavy seas.

The actual preventive guidelines to avoid dangerous situations in heavy seas, are the simple alteration of ship courses and speeds and are chosen based on the guidance provided in the references and on a subjective experience of every Master for how the ship is reacting to forces of the sea in such conditions. The prescribed information to guide the Master how to act when the vessel encounters severe sea condition is poor, whilst a possible method to assess the stability in severe sea conditions is almost absent.

Designs of ships are changed extremely fast, as the market demands, and the current stability criteria (based on the static lever curve for still water condition) are no longer taking into consideration the dynamical characteristics of novel vessels. The designs of new ships are incorporated new geometries of hulls that are almost totally different from old conventional forms. This aspect may lead to a different ship’s dynamic reaction and behaviour.

New appeared dangerous mechanisms, developed in severe sea conditions, as well as other dangerous and unfavourable seakeeping conditions, are not covered by actual intact stability regulations.

The development of an updated stability criteria revealed to be a great challenge in the maritime community. For the first time, such a proposal was made known at IMO session SLF 49/5/2 in 2006 whilst a new approach was discussed one year later at the 50th session of SLF where distinctions had been made between different types of criteria like deterministic, probabilistic and performance-based criteria. Later on, in 2010, the correspondence groups of IMO received as a main task the study of ships vulnerability to dynamic instabilities in extreme sea conditions, which later on, on the agenda of the 52nd session of Safety Committee, become the main concern in respect of the development of a new generation of intact stability criteria. Safety of ship and crew is one of the most important concerns for Master and officers, as well as the naval architects [4, 5]. Due to the importance of stability criteria, many authors presented and discussed new forms during international conferences [6, 7, 8, 9].

Based on the analysis presented, the main purpose of this paper was to cover this goal: to propose a dynamic stability criteria, as a procedure for assessment of intact stability of ships in heavy seas.

2. The scope of the proposed stability criteria
Kluwe in [10], explains the fact that when a ship spend a sufficient period on the wave crest, has the possibility to capsize if the stability is extremely reduced to a certain limit. The value of the righting arm reach the minimum when the wave crest is at about midship and at this moment, the vessel suffers a large heeling. In those successive variations of righting moments, between crest and through, and if the righting and heeling moments achieve critical values and the damping is to reduced, the ship meets the situation of parametric rolling. Therefore, the reduction of metacentric height in crest/trough variations is correlated with large rolling amplitudes and, for that purpose, the new stability limits should be expressed.

The criteria presented in this paper has the aim to ensure that minimum values of stability for actual ship’s loaded condition, is ensuring a level of safety in case of variation of stability in heavy seas.

3. The structure of the proposed stability criteria
Because dangerous phenomena, in which ships are exposed in severe seas, cannot be totally avoided only by design improvements, there is a necessity of development of specific requirements. These specific requirements take the form of criteria, which may result from methodologies, based on direct assessment.

The phenomena that develop large rolling angles in severe seas can be directly assessed by connecting the minimum intact stability requirements in still water with the righting lever variations between wave crests and trough conditions. Having in view that these variations are always in a strong
correlation with the design of the ship, the areas under the curves of righting arms, for crest and through situations, is reflecting the actual energy induced in ship’s hull [10].

The proposed intact stability criteria, presented in figure 3, is designed to have a multi-level structure, based on empirical approach and it has the basis for the simplified determination of stability parameters that may be judged quantitatively in the end.

![Figure 3. Structure of the proposed stability criteria.](image)

The first levels of has the intention to separate the ships that can be affected or not by the stability failures in severe sea conditions. Thus, the ships that did not pass the first level of criteria, can be assumed as vulnerable to the specified mode of stability failure.

The second levels of criteria are based on physics methods, which take into consideration the dynamics of relevant phenomena and have the target to confirm the assessment made at first level about the vulnerability of the ship according to specific stability failure mode. These levels provide an important indication on which ships shall be considered actually vulnerable.

If the ship fails to comply with second and next levels of criteria, and the actual ship loading condition cannot be reconsidered, in order to improve the results the criteria establish limitations, mainly for ship’s speed, having the target avoidance of dangerous situations of parametric rolling and pure loss of stability.

The development of the criteria and methodology of assessment was based on the factors that are directly influencing the ship’s behaviour in severe sea conditions and in the same time are easily accessible by the officers on board ships, such us loading condition, environmental conditions and operational range of ship speeds.
These parameters are easily accessible to officers on board vessel and thus can make the proposed criteria a very helpful tool for assessment the ship vulnerability to dangerous phenomena in waves since the preliminary calculations of stability.

4. The calculation procedure of the proposed stability criteria

4.1. Modelling of environmental conditions
In order to be assessed the ship’s vulnerability to dangerous phenomena in longitudinal waves it is necessary to be established the parameters of encountered waves.

The conventional standard wave, which was taken into consideration for proposed criteria, has the trochoidal profile because it has the closest profile of the wave, which is encountered in reality, due to wind action (figure 4). The designed wave, for which the proposed criteria is developed, is modelled starting from the condition that wavelength is equal to the ship’s length. This condition causes dynamic stability events, like maximising the stability changes, because is the most unfavourable situation. In this respect, the connection between wave height and wind speed is illustrated in figure 5.

![Figure 4. Connection between wave height and average wind speed.](image)

4.2. Proposed stability criterion for parametric rolling

4.2.1. Level 1 – Threshold value of GM variation. This level is based on the fulfilment of one of the main condition for parametric rolling to be generated, taking into consideration the relation between frequency of ship’s rolling and frequency of encountered wave.

The development of this level started from the situations presented in Annex 2 of SLF 53/INF.10 [11] and more detailed in [12] and can be considered as a new modelled version, based on the fact that the positions of the waterlines where used in more appropriate position as in a real situation.

The necessary value for parametric rolling to be developed, was deducted from the equation (1):

\[
2 \cdot \frac{1}{2} \left( \frac{\omega_E}{\omega} \right)^2 < \frac{\delta GM}{GM_0} < \frac{1}{2} \left( \frac{\omega_E}{\omega} \right)^2 - 2
\]

which illustrates a threshold value, from where can be deducted the necessary stability variation for development of parametric roll, as expressed in equation [2]:

\[
\text{(1)}
\]
The possibility for occurring a parametric roll situation is considered when the above ratio is large. In this respect, the threshold value can be considered as the lowest value of this ratio, as illustrated in equation [4]:

\[
\frac{\delta GM}{GM_0} = \frac{4\eta}{\omega \phi} \geq 4
\]

4.2. Level 2 – The minimum areas under righting moment curves for parametric rolling response. The minimum areas under the righting lever curves for the wave crest and wave trough condition may be calculated by using the equations (4) and (5):

\[
A_{\text{crest}} = \int_0^{\phi} GZ_{\text{crest}}(\phi)d\phi
\]

\[
A_{\text{trough}} = \int_0^{\phi} GZ_{\text{trough}}(\phi)d\phi
\]

4.2.3. The threshold value of ship’s forward speed for susceptibility to parametric rolling. Starting from the main condition for occurring the parametric rolling, as reflected in the equation (7):

\[
T_\phi \approx (1.8 \div 2.1)T_E
\]

and if it is considered that the wavelength is almost equal to the ship’s length, then the ship’s speed in longitudinal waves (head or following waves) become:

\[
V_{pr} = \frac{g}{2\pi} \left( \frac{2 \cdot LBP \sqrt{GM}}{C \cdot B} - \frac{2\pi \cdot LBP}{g} \right)
\]

In order to avoid parametric rolling, the actual ship’s speed must be \( V_s > V_{pr} \), where \( V_s \) is the maximum speed of the ship that can be developed in extreme seas.

4.3. Proposed stability criterion for pure loss of stability
The method of assessment the pure loss of stability differs from the way of assessment the parametric rolling as in this situation the ship encounters only a single large longitudinal wave [8]. Apart from this aspect, another influencing factor for occurrence of pure loss of stability is the ship’s speed which has to be almost equal or similar with wave celerity.
Whilst on the wave crest, the restoring moment become negative and produce a sudden large heeling to ship from upright position. If the ship spends a considerable period on the wave crest to develop large angles of heel, before passing in a wave trough where positive restoring moments starts, then the capsizing cannot be avoided [8].

4.3.1. Level 1 - Assessment of the minimum metacentric height on wave crest. At this level, ship dynamic stability is assessed for the situation when the wave crest is at midship position, being considered the most reliable situation that leads to the evaluation of minimum metacentric height.

Assessment of the minimum metacentric height on wave crest, is based on the same mode of assessment as used for parametric rolling, considering that midship section of the vessel is on the crest and the waterline considered for the minimum draught at a vertical distance equal to half of the mean draught. Hence, the minimum metacentric height may be calculated with the relation from equation (9):

\[
GM_{crest} = BM_L - KG + VCB_L
\]

(9)

Having in view the factors from equation (9), which reveal that the metacentric height depends on the influence of submerged area and submerged volume, it is quite clear that its value for the wave crest amidships will be smaller than the value in still water. Moreover, from the equation (9) it can be pointed out that an important factor for loss of ship stability on wave crest is the vertical position of ship’s centre of gravity (KG), which represents the actual loading condition of the ship. Thereafter, the correct vertical distribution of weights and cargoes on board ship is of great importance.

The value of \( GM_{crest} \) is the minimum value that the ship can encounter in longitudinal waves. Thus, the first level of stability criterion, for pure loss of stability, is given by the fact that GM on the wave crest to be positive, \( GM_{crest} > 0 \). A negative value will reveal the fact that vessel is vulnerable to pure loss of stability.

4.3.2. Level 2 - Assessment of maximum righting lever in longitudinal waves. In this respect, the vulnerability of ship to pure loss of stability will be more clearly indicated by the calculation of righting lever, as the in waves the right levers suffers considerable variations.

In the methodology of development the criterion, the ship is considered “stopped” on the wave crest. This situation can be considered similar to a static and then the righting lever may be modelled in a similar manner as was modelled the righting lever curve in calm water, as per equation (10):

\[
GZ_{crest}(\phi) = GZ_0(\phi) - (GM_0 - GM_{crest}) \sin(\phi)
\]

(10)

For this level, the righting lever is calculated to have largest value for the situation when crest is amidships and when length of the wave is almost equal to ship’s length. The value of the calculated maximum righting lever needs to be positive as a condition for the ship against vulnerability to pure loss of stability. For the situation when the calculated maximum righting lever is negative, then the criterion supports the conclusion of the previous criterion, of minimum metacentric height, and ship fails to comply, being possible to be developed a pure loss of stability situation if the time spend by the ship on the wave crest is longer.

5. Demonstration of the proposed stability criteria

For demonstration of reliability of the proposed stability criteria, a series of calculations, for a number of 28 different ships, were carried out following the methodology described in this paper. The results, presented in tables 1 and 2, revealed the ships that comply or failed to comply with the proposed stability criteria.
Based on the results presented, it can be noted that the criteria made a distinction between the ships, used for calculations, in two distinctive groups. In the first group are ships like tankers and bulk carriers that comply with both levels of criteria and can be considered conventional ships, not at risk for failures related to stability changes in waves. This group of ships passed the criteria mainly due to the geometry of hull, as these types of ships have only small flares or almost wall-sided bow and the result is large values of metacentric height with small variations of restoring moment.

In the second group are ships like Containerships, Ro-Ro ships or Pure Carrier Ships, which not pass the levels of criteria and can be considered with high risk for stability failures related to righting lever variations in waves. The results are highly influenced by the geometry of hull, as these ships are designed with large flared forms at fore and aft part. This type of geometry has a negative influence over ship’s stability because at reduced draughts the immersed underwater hull volume is also considerably reduced in fore and aft part, leading to an increased vulnerability to dynamic instabilities in waves, like parametric rolling.

Apart from this aspect, a hull with large flares fore and aft presents lower values of damping, as the bilge keel is fitted only on a vertical part of the hull and in this case is considerably reduced in length. Such ships are more vulnerable to dynamic instabilities in waves, due to large variations in restoring moments, and most of them not comply with the criteria. The fact that most of the containerships from the new generation lost their intact stability in severe sea conditions is revealed by the sample calculation and consolidates the affirmation already expressed in this respect (e.g. France [15]).

| Failure mode | Parametric rolling | Comply | Level 2 | A_crest/A_rough | η | Risk zone |
|--------------|--------------------|--------|---------|----------------|---|-----------|
| Ship Type    | δGM/δGM_0 | 4η/ω_η | δGM/δGM_0 | 4η/ω_η | GM | Trough | |
| Container Ship 1 | 1.83 | 1.45 | Yes | Failed | 0.392 | 0.016 | Yes |
| C2           | 2.01 | 1.51 | Yes | Failed | 0.369 | 0.017 | Yes |
| C3           | 2.28 | 1.37 | Yes | Failed | 0.399 | 0.018 | Yes |
| C4           | 2.43 | 1.73 | Yes | Failed | 0.393 | 0.019 | Yes |
| C5           | 2.67 | 1.79 | Yes | Failed | 0.193 | 0.019 | Yes |
| C6           | 2.85 | 1.69 | Yes | Failed | 0.201 | 0.021 | Yes |
| C7           | 2.92 | 2.17 | Yes | Failed | 0.238 | 0.024 | Yes |
| C8           | 3.12 | 2.26 | Yes | Failed | 0.241 | 0.026 | Yes |
| C9           | 3.38 | 2.41 | Yes | Failed | 0.262 | 0.026 | Yes |
| C10          | 3.51 | 3.76 | No | Yes    | 0.438 | 0.035 | Yes |
| Ro-Ro Ship 1 | 1.84 | 1.30 | Yes | Failed | 0.381 | 0.021 | Yes |
| R2           | 1.71 | 1.36 | Yes | Failed | 0.385 | 0.022 | Yes |
| R3           | 1.98 | 1.81 | Yes | Failed | 0.413 | 0.026 | Yes |
| R4           | 2.14 | 1.92 | Yes | Failed | 0.421 | 0.027 | Yes |
| R5           | 2.38 | 2.04 | Yes | Failed | 0.418 | 0.031 | Yes |
| R6           | 2.24 | 2.17 | Yes | Failed | 0.347 | 0.031 | Yes |
| Pure Car Carrier Ship 1 | 0.58 | 2.95 | No | Yes    | 0.215 | 0.031 | Yes |
| PCC2         | 0.67 | 3.03 | No | Yes    | 0.256 | 0.035 | Yes |
| PCC3         | 0.78 | 3.21 | No | Yes    | 0.274 | 0.037 | Yes |
| Tanker Ship T1 | 0.24 | 2.54 | No | Yes    | 0.798 | 0.041 | No |
| T2           | 0.27 | 2.84 | No | Yes    | 0.801 | 0.043 | No |
| T3           | 0.21 | 3.27 | No | Yes    | 0.823 | 0.046 | No |
| T4           | 0.23 | 3.98 | No | Yes    | 0.846 | 0.051 | No |
| T5           | 0.16 | 4.28 | No | Yes    | 0.875 | 0.052 | No |
| Bulk Carrier Ship 1 | 0.27 | 2.72 | No | Yes    | 0.788 | 0.038 | No |
| B2           | 0.26 | 2.83 | No | Yes    | 0.791 | 0.041 | No |
| B3           | 0.28 | 2.92 | No | Yes    | 0.791 | 0.046 | No |
| B4           | 0.31 | 3.01 | No | Yes    | 0.800 | 0.051 | No |
### Table 2. Results for pure loss of stability criteria, Level 1 & Level 2

| Ship Type               | Failure mode | $GM_{crest}$ | Comply | $GZ_{crest}$ | Comply |
|-------------------------|--------------|--------------|--------|--------------|--------|
| Container Ship 1        |              | -0.53        | Failed | 0.738        | Yes    |
| C2                      |              | -0.85        | Failed | 1.025        | Yes    |
| C3                      |              | -1.29        | Failed | 1.121        | Yes    |
| C4                      |              | -1.31        | Failed | 1.136        | Yes    |
| C5                      |              | -1.56        | Failed | 1.143        | Yes    |
| C6                      |              | -1.48        | Failed | 1.136        | Yes    |
| C7                      |              | -1.28        | Failed | 1.238        | Yes    |
| C8                      |              | 0.18         | Yes    | 1.571        | Yes    |
| C9                      |              | 0.18         | Yes    | 1.858        | Yes    |
| Ro-Ro Ship 1            |              | -0.88        | Failed | 0.251        | Yes    |
| R2                      |              | -0.79        | Failed | 0.232        | Yes    |
| R3                      |              | -0.73        | Failed | 0.243        | Yes    |
| R4                      |              | -0.72        | Failed | 0.264        | Yes    |
| R5                      |              | -0.67        | Failed | 0.387        | Yes    |
| R6                      |              | -0.71        | Failed | 0.331        | Yes    |
| Pure Car Carrier Ship1  |              | -0.38        | Failed | 0.523        | Yes    |
| PCC2                    |              | -0.21        | Failed | 0.711        | Yes    |
| PCC3                    |              | -0.27        | Failed | 0.697        | Yes    |
| Tanker Ship 1           |              | 1.08         | Yes    | 2.916        | Yes    |
| T2                      |              | 1.24         | Yes    | 3.654        | Yes    |
| T3                      |              | 1.57         | Yes    | 3.898        | Yes    |
| T4                      |              | 1.81         | Yes    | 4.418        | Yes    |
| T5                      |              | 2.13         | Yes    | 4.537        | Yes    |
| Bulk Carrier Ship 1     |              | 1.28         | Yes    | 3.436        | Yes    |
| B2                      |              | 1.61         | Yes    | 3.561        | Yes    |
| B3                      |              | 2.54         | Yes    | 3.875        | Yes    |
| B4                      |              | 2.32         | Yes    | 3.936        | Yes    |

### 6. Conclusions

In the present paper was presented a possible way of practical calculation of ship dynamic stability in heavy seas, especially in situations of longitudinal waves.

Because the occurrence of these situations is generated by a series of conditions to be met, the methodology is developed in a multi-level criterion. Every level was developed in order to assess the vulnerability of ship in such situations as well as the corrective measures to be taken in order to avoid, situations that can be dangerous.

The criteria presented in this paper can be considered suitable to be incorporated in a new generation of stability criteria under development of IMO, because it allows the assessment of the dynamic behaviour of the ship under certain types of stability failure modes in longitudinal waves presently not covered by any regulations in force. Moreover, it can be used as guidelines on board ships with enough reliability that the intact stability is assessed at least at a level that can offer a clear picture for ship’s officers for the voyage that stay to commence.

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