Performance Based Approaches for the Evaluation of Intact Stability Problems

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Abstract
Recent investigations have shown a demand for the introduction of additional criteria to the IMO-intact stability code, accounting for dynamic phenomena related to the behaviour of ships in rough weather. The general need for such kind of criteria arises due to the fact that certain ship designs suffer from specific phenomena in rough weather that were not foreseen at those designs which were relevant when the intact stability code was developed. This paper suggests a structure for these dynamic criteria and within this proposed structure, one set of criteria will account for a minimum stability limit required to ensure that these minimum stability standards will provide the ships with sufficient safety. For the development of this proposed set of criteria, validated tools and procedures are used that have been successfully used to design ships with increased safety margins on one hand and without any competitive disadvantage on the other.

Keywords
Intact stability, parametric excitation, capsizing index, safety assessment, numerical simulations

Proposed Structure of Criteria

Definition of the Problem
When the operation of ships in heavy weather is considered, the following dangerous situations may occur:

- Pure loss of stability, typically on a wave crest
- Parametric rolling
- Excessive roll moments introduced to the ship
- Cargo shift or other heeling moments
- Broaching

These conditions typically happen in a sea state under the influence of arbitrary loads, which might come from wind and waves. The nature of these phenomena is purely dynamic, and therefore, the approach to tackle these phenomena must be a dynamic approach. Following a performance based concept, intact stability should then cover the following issues:

- Sufficient ability of the ship to withstand dynamic heeling moments in a sea state
- Low heeling angles and low accelerations in operating conditions
- Avoidance of critical resonances in operating range (making dangerous situations less probable, which can be achieved either by an appropriate ship design or by specific on board information).
- Sufficient roll damping especially for ships with large mass moments of inertia
- Sufficient course keeping and steering ability for safe operation in heavy weather.

The related stability criteria should then focus on the following:

- Avoidance of large rolling angles
- Avoidance of large accelerations

In this context, a large rolling angle is defined as a rolling angle which may lead either

- to the capsizing of the vessel
- to the submergence of major non weathertight openings
• to the failure of an important system (e.g. propulsion plant failure)
• to a cargo shift which causes an even larger rolling angle (e.g. trailer shift on a RoRo-Deck)

A large rolling angle is therefore an event which may lead to the total loss of the vessel. A large acceleration is defined as any acceleration which causes

• massive cargo loss or damage (e.g. lost deck containers)
• severe damage to machinery or major safety relevant systems
• structural overload of safety relevant members
• severe discomfort or injuries to passengers or crew

A large acceleration is therefore an event which may result in severe damages to the ship or its cargo but not necessarily in a total loss.

It is important to note that large rolling angles are not necessarily accompanied by large accelerations and large accelerations can occur at relatively small rolling angles. Furthermore, depending on the stability values of the ship, the same seastate, course and speed settings may either result in large rolling angles, or large accelerations, or both. Large accelerations typically occur at high values of initial GM, and therefore, criteria are necessary to limit the stability accordingly (maximum GM limits). Large rolling angles can occur either at low values of initial GM or during broaching situations. As broaching problems are related to coursekeeping problems in heavy weather, broaching can hardly be avoided by modifying the GM value of the ship. Broaching is a manoeuvring problem and must be dealt with accordingly. If the roll damping is not sufficient, large rolling angles may also occur in beam seas, zero speed condition (dead ship) if a resonance occurs. The avoidance of large rolling angles coincides with the establishment of minimum GM limits.

Proposed Structure of Dynamic Criteria

From all these findings and related design experience, the dynamic criteria to be developed may have the following structure:

• Criteria to avoid large rolling angles (Minimum Stability requirement)
• Criteria to avoid large accelerations (Maximum Stability limit)
• Criteria to guarantee sufficient roll damping in dead ship condition (Minimum Damping requirement)
• Criteria to avoid broaching (Minimum Course keeping limit)

The following sections deal with the detailed investigations of possible criteria to ensure a minimum intact stability limit based on dynamic evaluation of ships in rough weather.

Introduction to Parametric Rolling and Pure Loss of Stability

Besides broaching which is considered a manoeuvring problem, pure loss of stability and parametric rolling are the relevant phenomena which can be related to large rolling angles, provided the roll damping is sufficient. Both phenomena have their source in large alterations of the righting levers between still water, crest and trough conditions. Although this has been known for more than fifty years, it became a serious problem when the first ships with large barge-type aftbodies and V-shaped frames in the forebody accompanied by large flare were introduced.

Fig. 1 may indicate what happens to such kind of ship in a wavy surface:

• In the crest condition, the aftbody is significantly out of water which means a drastic stability breakdown.
• In the trough condition, the ship has excessive stability due to the high form stability of the forebody.

In case the stability loss on the crest exceeds a certain limit, the vessel may have no stability left and capsizes if it rests in this crest condition for a certain time (pure loss of stability). In cases where some stability is left and the correct frequency is met, the ship is righted up at maximum heel which coincides with the trough condition (due to the fact that
the righting lever is excessively high) and is heavily heeled in the upright position where the crest is at about LbP/2 (due to the fact the crest lever is extremely reduced). A rolling motion is observed that can lead to a capsize, if heeling/righting moments take a critical value and/or damping is too low (Parametric Rolling).

This general effect becomes most pronounced for all ships that gain a substantial portion of stability out of the aftbody. Therefore, it can be concluded that the most important phenomena leading to large rolling angles can be directly accessed by linking the righting lever changes between crest and trough condition to the minimum stillwater stability requirements. All investigations carried out during ship designs and related research projects indicated that whenever large rolling angles had to be avoided, it was found important to minimize the crest- trough alterations or to attain the stability values according to these alterations. This was investigated by a numerical simulation method validated by sufficient model experiments. The numerical simulations will allow to determine a capsizing index for each individual design, and from the required capsizing index, a proposal for dynamic criteria is formulated.

The Present Simulation Method

Ship motion simulations are currently carried out using the program 'Rolls' originally developed by Kroeger (1987) and Petey (1988) at the Institut fuer Schiffbau, University of Hamburg. 'Rolls' simulates the motion of intact and damaged ships in time domain in all six degrees of freedom in regular waves and irregular long or short crested sea ways. For four motions, namely heave, pitch, sway and yaw, response amplitude operators (RAO) are used, calculated linearly by means of strip theory. The surge motion is simulated assuming a hydrostatic pressure distribution under the water surface for the determination of the surge-inducing wave forces. Further details are published in Soeding (1987) and others.

The Capsizing Index

The Failure-Criterion

![Figure 2: Principle of the failure criterion used by Blume during his model tests](image)

In both model testing and evaluating the results of numerical simulations it is necessary to find a way to judge whether a ship is safe in the investigated situation or not. To overcome this problem Blume (1987) established the following criterion for model tests: Whenever the ship did not capsize in the respective run (or here simulation) the area $E_R$ under the calm water curve of righting arms between the maximum roll angle encountered in the run and the vanishing point is calculated (illustrated in figure 2). Whenever the ship did capsize $E_R$ is set equal to zero for the particular run. Then the mean $\bar{E}_R$ of all runs (or simulations) in the same condition and the standard deviation $s$ of the $E_R$’s are determined. A ship is regarded as safe when $\bar{E}_R - 3s > 0$.

When ships have large angles of incidence, the a.m. FAILURE- criterion might prevent the ship from capsizing but the vessel may fail due to the damages of major systems. In such cases, either 50 Degree Roll angle or the a.m. FAILURE- Criterion, whichever is more critical, is used. For a given situation represented by ship parameters, speed, course and significant wave length a limiting significant wave height can be calculated where the ship just fulfills the a.m. limiting criterion. All these limiting significant wave heights can be plotted in a polar diagram, ref. Fig. 3.

![Figure 3: Polar diagram for limiting significant wave height, comparison of two different designs](image)

**Estimating the Capsizing Index in Heavy Weather**

The a.m. approach gives the possibility to design and compare ships on the basis of equivalent designs. Furthermore, the designer is able to follow procedures that lead to improved behaviour of the ships in heavy weather. Although this is a useful tool or procedure, we like to go one step forward to compare ships on a more rational basis, which should be a capsizing probability. As absolute probabilities can not be determined at the moment due to lack of some basic probability distributions, we call our capsizing probability a capsizing index. This also gives the opportunity to check whether the existing rules give a sufficient and unique safety level by comparing the capsizing index of different designs all ful-
Modelling the Seastate – Statistical Data

To determine the probability of the different seastate scenarios, we make use of the Global Seaway Statistics by Prof. Soeding (TU- Hamburg Harburg, Schriftenreihe Schiffbau, Report Nr. 610, 2001). Soeding gives the probability distributions of significant period and wave height for 126 different areas in a tabular form. Area Nr. 125 represents the North Atlantic, which we use as reference area in all our calculations. In principle, it is also possible to calculate the capsizing index for other areas, but to compare the ships we have restricted ourselves to the reference area NA. This is important to note, because in other areas with different probability distributions, other conclusions could be drawn. At present, it is the aim of our work to compare ships on a rational basis and to identify safety targets (or deficits).

Reference Waves for Hydrostatical Calculations

The table is also useful to answer another problem. When hydrostatic calculations of righting levers in waves are performed, the question arises which wave height is to be chosen relative to the wave length. In most cases, the steepness ratio is kept constant, e.g. L/20 or L/30. As the proposed criteria shall be based on crest and trough righting levers, reference waves are needed. Therefore, it is useful to select an appropriate wave height as function of the wave length. This wave height is determined from the probability distribution in such a way that a limiting significant wave height is calculated as 90% quantil of the seastate: 90% of all possible waves of a given peak modal period are below this 90% limit. The following table states this wave height for the NA area:

<table>
<thead>
<tr>
<th>Period</th>
<th>Length</th>
<th>Height</th>
<th>L/H</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.50</td>
<td>9.76</td>
<td>.49</td>
<td>19.86</td>
</tr>
<tr>
<td>3.50</td>
<td>19.13</td>
<td>.73</td>
<td>26.17</td>
</tr>
<tr>
<td>4.50</td>
<td>31.62</td>
<td>1.44</td>
<td>22.00</td>
</tr>
<tr>
<td>5.50</td>
<td>47.23</td>
<td>1.98</td>
<td>23.91</td>
</tr>
<tr>
<td>6.50</td>
<td>65.97</td>
<td>2.72</td>
<td>24.27</td>
</tr>
<tr>
<td>7.50</td>
<td>87.83</td>
<td>3.70</td>
<td>23.72</td>
</tr>
<tr>
<td>8.50</td>
<td>112.81</td>
<td>4.36</td>
<td>25.88</td>
</tr>
<tr>
<td>9.50</td>
<td>140.91</td>
<td>5.43</td>
<td>25.96</td>
</tr>
<tr>
<td>10.50</td>
<td>172.14</td>
<td>6.53</td>
<td>26.38</td>
</tr>
<tr>
<td>11.50</td>
<td>206.49</td>
<td>7.43</td>
<td>27.80</td>
</tr>
<tr>
<td>12.50</td>
<td>243.96</td>
<td>8.44</td>
<td>28.90</td>
</tr>
<tr>
<td>13.50</td>
<td>284.56</td>
<td>9.37</td>
<td>30.38</td>
</tr>
<tr>
<td>14.50</td>
<td>328.28</td>
<td>10.30</td>
<td>31.88</td>
</tr>
<tr>
<td>15.50</td>
<td>375.12</td>
<td>10.95</td>
<td>34.27</td>
</tr>
<tr>
<td>16.50</td>
<td>425.08</td>
<td>12.06</td>
<td>35.24</td>
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<td>17.50</td>
<td>478.17</td>
<td>13.10</td>
<td>36.50</td>
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<td>18.50</td>
<td>534.37</td>
<td>14.30</td>
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</tr>
<tr>
<td>19.50</td>
<td>593.71</td>
<td>15.28</td>
<td>38.86</td>
</tr>
<tr>
<td>20.50</td>
<td>656.16</td>
<td>16.35</td>
<td>40.13</td>
</tr>
</tbody>
</table>

The results show that shorter waves are in general steeper. This is important to note when the results of the simulations are quantified. If a ship has problems in shorter waves (e.g. a resonance problem), then waves with a remarkable relative height can occur. All righting levers are determined for the wave parameters stated above. The vessel trims freely, wave crest is always fixed to LbP/2, wave trough position is wave crest position +wavelength/2. It was proven that this simplified procedure can compensate the lack of pitching phase in the best way without making the criteria unnecessarily complicated.

Modelling the Capsizing Probability

The polar diagrams state significant wave heights where the ship just fulfills the FAILURE- Criterion (or 50 Degree, whichever is less). As the aim of present studies is more to compare ships on a rational basis than to present absolute capsizing probabilities, we make the following assumption, which is definitively on the conservative side: For all wave heights above the limiting wave height according to the FAILURE- Criterion, we assume that the ship will capsize or be exposed to a large rolling angle that leads to a loss. Consequently, the capsizing probability \( P_B \) is set to 1. For all waves below this limiting wave height, we assume that the ship is safe and the probability is set to 0. For the moment, this seems to be sufficient.

Modelling the Speed and Course Probability

In real life, the capsizing probability strongly depends on the way how the ship is operated, which strongly depends on the knowledge and skills of the crew. As it is our aim to compare ships and not the skills of the crew, we assume that all speeds that
can be achieved are sailed with the same probability, which is also assumed for courses. If in a later stage more detailed speed or course distributions of ships will be available, the capsizing index needs to be recalculated.

Evaluating Intact Criteria

The procedure above was applied to a large number of different ships, where for most of the ships several loading conditions have been analyzed. All ships were examined at design draft, at the limiting value according to the IMO intact criteria. It is important to note that all the ships are investigated with minimum stability according to A749 intact criteria. If it will be mentioned later that some ships might have problems, this means that they would have problems if operated at the intact stability limit. The fact that some ships never operate at the intact limit due to the fact that damage stability or operational requirements do not permit to do so is not regarded here, because the task is to suggest minimum stability requirements for dynamic criteria. Then, additional load cases were defined for some ships having higher GM-values. So in all curves the point with the lowest GM-value represents the actual stability limit according to the intact code. For each loading condition, at least six significant wave lengths were examined, and for each significant wave length 7 courses. Speed was varied in steps of 2 knots close to design speed, if achievable. The following table gives an overview about the ship types that have been analyzed. All ships represent recently built vessels, 80% of the ships are younger than 3 years.

<table>
<thead>
<tr>
<th>Ship type</th>
<th>Ships</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>RoRo</td>
<td>20</td>
<td>57</td>
</tr>
<tr>
<td>RoPax</td>
<td>24</td>
<td>86</td>
</tr>
<tr>
<td>Pax</td>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>Container</td>
<td>6</td>
<td>23</td>
</tr>
<tr>
<td>Bulker</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>Tanker</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Multi-Purp</td>
<td>9</td>
<td>22</td>
</tr>
</tbody>
</table>

In general, the following conclusions can be drawn:

- The current code does not represent a unique safety level, because low GM can lead to high safety and vice versa.
- The ships characterized by pure loss of stability failures show a large improvement in safety if GM is slightly increased.
- The ships characterized by parametric roll and/or excessive heeling moments need larger increase in GM to achieve the same safety level.
- Some ships can not go beyond a certain safety level even if GM is significantly increased.
- Most of the ship types which represent more traditional designs such as bulkers, tankers or some multi-purpose vessels, seem to be very safe, whereas more sophisticated designs such as ferries, RoRos or container ships have significant problems due to large righting lever alterations.

Proposal for Dynamic Criteria – Minimum Stability Requirement

From both systematical ship design work as well as from many numerical simulations, the following major principles have been found to improve the safety of the ship:

- The safety of the ship was always improved if the alterations between wave crest and trough had been reduced.
- Most efficient was to improve the stability in the wave crest situation.
- As the alterations of the righting levers are a function of the hull form only (secondary effects on trim disregarded), it was found that some hulls could never go beyond a certain safety limit, whereas other hulls were very safe.
It was found that the limiting GM-values could be smaller if the alterations were smaller, and needed to be larger when the alterations were larger.

Most important parameters seem to be the maximum righting lever at the three conditions and the area below the righting lever curve, if all negative areas were included in the calculation.

This coincides with the investigation of Soeding: He suggested that the stability values to be attained should follow Froude’s law of similitude due to the fact that seakeeping problems do also follow this law. According to Söding’s proposal, larger ships should require larger stability values, where the GM should be a linear function of the size of the vessel. As the crest-through alterations follow this principle, Soeding’s proposal is automatically fulfilled if the stability values are attained as a function of crest-through alteration. As these alterations do also depend on other hullform details, larger ships may have smaller alterations if properly designed than smaller ships and may require less stability, consequently. Therefore, the following figures show the calculated capsizing index as a function of maximum righting lever alteration for all ships investigated

Therefore, the following additional criteria are suggested to ensure a sufficient intact stability in heavy weather:

\[ h_{\text{max,still}} = k_H (h_{\text{max,through}} - h_{\text{max,crest}}) \]  

where \( h_{\text{max}} \) is the maximum righting lever at still water condition up to the angle of incidence. The indices trough or crest denote the maximum righting lever at trough or crest condition.

\[ a_{50,\text{max,still}} = k_{50} (h_{\text{max,through}} - h_{\text{max,crest}}) \]

where \( a_{50} \) is the integral under the righting lever curve up to 50 degree (including all negative contributions).

The righting levers shall be computed in a wave equal to the wetted length of the ship, wave height according to the 90\% quantil (see above) with the vessel trimming freely. The crest shall be located at the half of the wetted length for the crest condition and at A.P. for throught condition. The factors and are constants or functions that are subject to further development.

**Determination of the Proportional Factors or Functions**

These factors (or functions) can be derived if a specific target for the capsizing index is defined, provided some of the deficiencies of the capsizing index could be improved and a reasonable required index could be defined. Based on a given capsizing index, then the required values of the factors could be determined. The stability values would then represent a unique safety level. To do so, further research work is required, especially more ships need to be analyzed to have a more evenly distribution on the ship types. Furthermore, the proposed capsizing index should be improved by introducing more realistic distributions of speed and course.
References


