Assessment of Intact Stability – Revision and Development of Stability Standards, Criteria and Approaches

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Abstract

Two main draw–backs can be observed with respect to the assessment of the intact stability of ships today:

1. There are no internationally agreed mandatory minimum requirements. IMO's code on intact stability [5] is recommendatory only, though mandatory in many countries. Additionally several national requirements exists.
2. The existing code on intact stability is known to have deficiencies:
   (a) with respect to applicability for modern designs (significance and reliability of the assessment) and
   (b) presents itself rather as a collection of requirements and recommendations than a user-friendly guidance.

These deficiencies are not surprising and originate to some extent from the way the code evolved over the years (as non-mandatory instrument). Also it is not surprising, that the requirements themselves fail to present a reliable basis for assessment of some modern types of ships, as in today's highly competitive environment ship designs change very rapidly. Especially in areas where the design process is supported by advanced design and analysis tools, which are available for application worldwide today, e.g. CFD-optimization or FEM-Analysis used by either the yard themselves or being accessed via subsuppliers. Consequently also the sea keeping characteristics of modern vessels change. Typical problems occuring today are large Container ships being susceptible to parametric rolling and/or pure loss of stability, Ferries and Cruise vessels suffering from very short periods of roll and/or high accelerations and the like.
Consequently a revision of IMO's Code on Intact Stability was started in 2002 with the aim to enhance the applicability of the code:

1. The code is to be restructured and revised to enhance the user-friendliness and update the state of the art in stability assessments based on the existing requirements.
2. It was decided that in a future code criteria should be formulated in a "performance based" way – allowing for both a more transparent physical formulation and the straight forward use of alternative means of evaluations (e.g. model tests) if found more appropriate.

In Germany a national working group with experts from a wide range of backgrounds is working to support the revision process. The work is mainly based on national research projects (e.g. the BMBF funded Roll-S and SinSee).
The paper will present some of the latest developments with respect to the revision process based on ongoing research work as basis for the revision as well as development of future performance based criteria.

Keywords

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

1 Needs and Views from Ship Design and Approval

The intact stability rules were developed to ensure a minimum international standard regarding the safety of intact ships at sea. The interface between ship design and classification on the one hand and operation on the other hand are KG-max (or GM-required) curves. This approach has proven to be very advantageous. It is the task of the naval architect designing the ship to produce KG-max curves so that all current rules and requirements are fulfilled. If the used rules and regulations allow for a well balanced and fair evaluation of the ships performance with respect to intact and damage stability, then those KG-max curves represent the internationally agreed uniform safety level. And it is the operators responsibility to make sure that the actual KG during the entire voyage is always below the approved KG-max curve. While the formulation of KG-max curves has proven to be a functional interface between ship design and operation, the determination of those curves according to the current rules does not assure a uniform level of safety for modern ships. So a revision of the intact stability code needs to reflect all safety related physical phenomena to judge the intact ships stability of modern vessels, so that the safety level within the rules and regulations becomes uniform. Such a newly revised intact stability code should be mandatory for all future vessels.

The intact stability or more general the seaworthiness of a vessel is one important area addressed in ship design. But it is important to note that there are many more performance criteria for a design to be met, e.g. speed power performance and fuel consumption, cargo capacity, etc.. The task of a naval architect designing a ship is to find the most competitive possible compromise to fit the customers needs. The most suitable formulation for criteria and boundary conditions to be met are performance based criteria. Stating clearly which sort of problem or dangerous scenario has to be dealt with. Then the naval architect's task is to solve a physically described problem, and this fits well into the designers world and the design process. The same is valid for the design (and stability) approval – with ships developing very fast, purely empirical formulations will always have problems to sufficiently reflect the latest state of the art. With rules and regulations which clearly define their purpose and belonging criteria in a performance based way, not only the stability assessment itself becomes more transparent but also the appropriateness and reliability of the safety evaluation.

The aim of intact stability criteria is to ensure a minimum international standard regarding the stability of intact ships at sea. In order to avoid dangerous situation there are two possible ways:

1. The ship should be designed in a way, that even when travelling in rough and unfavourable conditions, the danger of a damage or loss of the vessel is sufficiently small (mitigation).

2. Another very effective measure is to make dangerous situations less probable, e.g. by avoiding resonances within the typical operational profile (prevention).

Additionally of course the crew needs to be able to identify and avoid potentially dangerous situations.

2 Proposed Structure of Criteria

2.1 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
- Resonances including parametric rolling
- Excessive roll moments introduced to the ship
- Cargo shift or other heeling moments
- Broaching

The conditions in which such phenomena typically happen are sea states under the influence of arbitrary loads 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 angles of roll
- Avoidance of large accelerations

In this context, a large angle of roll is defined as an angle of roll which may lead to either

- the capsizing of the vessel
- the submergence of major non weathertight openings

- the failure of an important system (e.g. propulsion plant failure)
- a cargo shift which causes an even larger angle of roll (e.g. trailer shift on a RoRo-Deck)

A large angle of roll 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 angles of roll are not necessarily accompanied by large accelerations and large accelerations can occur at relatively small angles of roll. Furthermore, depending on the stability values of the ship, the same seastate, course and speed settings may either result in large angles of roll, 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 angles of roll typically occur either at low values of initial GM or during broaching situations. As broaching problems are related to course keeping problems in heavy weather, broaching can hardly be avoided by modifiing 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 angles of roll may also occur in beam seas, zero speed condition (dead ship) if a resonance occurs. But in general the avoidance of large angles of roll coincides with the establishment of minimum GM limits.

2.2 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 angles of roll (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 identify a minimum intact stability limit based on dynamic evaluation of ships in rough weather.

3 Basic observations with respect to minimum intact stability requirements

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 stillwater, crest and trough conditions. Although this has been known for more than fifty years, it became a serious problem only recently when the first ships with large barge-type aftbodies and V-shaped frames in the forebody accompanied by large bow flare were introduced.
In general these phenomena significantly effect all ships that gain a substantial portion of static stability out of the aftbody. Therefore, it can be concluded that the most important phenomena leading to large angles of roll can be directly accessed by linking the righting lever changes between crest and trough condition to the minimum calm water stability requirements. Many investigations carried out during ship designs and related research projects indicated, that whenever large angles of roll 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. Based on such numerical investigations a procedure for the calculation of a capsizing index was developed, with the aim to compare different individual designs. Until today numerious ships where evaluated according to this methodology and the resulting capsizing indices were compared in order to identify interrelations between seaworthiness and hull shape and propose possible dynamic stability criteria.

4 Capsizing Index as basis for developments

The development of the capsizing index was presented in detail in [1], thus in this paper only a short summary will be given.

4.1 Numerical simulation method

Ship motion simulations are currently carried out using the program 'Rolls' originally developed by Kroeger [6] and Petey [7] 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 [8], [9] and others.

Results from model tests are frequently used for validation purposes. A preliminary comparison of simulation and model test results is presented at this conference in the paper by Clauss [3].

4.2 The Failure-Criterion

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 [2] 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. 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 $\bar{E}_R - 3s > 0$.

This criterion has been found very appropriate in many investigations, see for example [4]. However, when ships have large angles of incidence, the a.m. Blume-criterion might prevent the ship from capsizing but the vessel may fail due to the damages of major systems. Thus the maximum roll angle was limited additionally to 50 degrees for such vessels.

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 criteria. All these limiting significant wave heights can be plotted in a polar diagram, an example is shown in Fig. 1.

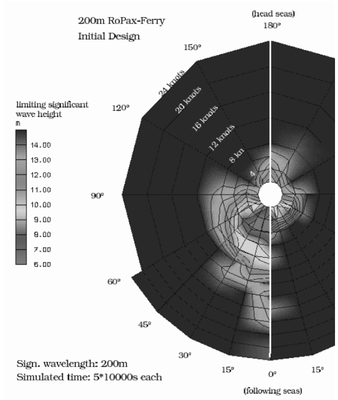

Figure 1: Polar diagram for limiting significant wave height, comparison of two different designs

4.3 Definition of the capsizing index

Based on such diagrams it is possible 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 in order to compare ships on a more rational basis, and thus use a capsizing index defined as follows:
The contribution to the capsizing index P_c of a single situation represented by one polar diagram is given by the formula:

$$P_c = P_B \cdot P_{Sea} \cdot P_{Course} \cdot P_{speed} \tag{1}$$

where P_B means the probability of a capsize in that specific seastate, P_{sea} means the probability that this seastate, represented by significant wave length and height, will occur. P_{Course} and P_{speed} are the probabilities that a specific course and speed are sailed. The total sum of all P_c represents the probability of a capsize in a seastate represented by the significant wave length of the polar plot. The total capsizing index is then calculated as the sum of several significant wave lengths, which are selected according to the class representation of the sea state.

4.4 Modelling P_B – the Capsizing Probability

The polar diagrams state significant wave heights where the ship just fulfills the a.m. failure-criterion (Blume-criterion or 50 Degree, whichever is less). As the aim of present studies is focussed on the comparison of ships on a rational basis rather than to present absolute capsizing probabilities, we make the following conservative assumption: 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 angle of roll 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.

4.5 Modelling P_{Sea} – based on Seastate Statistical Data

To determine the probability of the different seastate scenarios, we use the Global Seaway Statistics as developed by Prof. Soeding [10]. Soeding gives the probability distributions of significant period and wave height for 126 different areas of the world in a tabular form. Area Nr. 125 represents the North Atlantic, and is used 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 restriced ourselves to the reference area NA. This is important to note, because in other areas with different probability distributions effect the results. At present, it is the aim of our work to compare ships on a rational basis and to identify safety targets (or deficits).

4.6 Modelling P_{Course} and P_{speed} – the Speed and Course Probability

In real life, the capsizing probability strongly depends on the way the ship is operated, which again strongly depends on the knowledge and skills of the crew. It is our aim to compare ships and not the skills of the crew, thus 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.

5 Results - Capsizing index for different ships

This procedure was applied to a large number of different ships, where for most of the ships several loading conditions have been analyzed. All ships were first of all examined at design draft, at the limiting GM-value according to the IMO intact criteria. This means intact stability criteria only, which is important to note with respect to the results and the belonging conclusions, if it is mentioned 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 damage stability or operational requirements is not regarded here, because the task is to suggest minimum stability requirements for dynamic criteria for intact ships.

For many vessels further load cases were investigated, all these have 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 up 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.

Ship type	Ships	Cases
RoRo	20	57
RoPax	24	86
Pax	12	32
Container	6	23
Bulker	8	25
Tanker	3	8
Multi-Purp	9	22

Fig. 2 shows a total overview about the results. Each marker represents one capsizing index calculation for a ship, if a curve is connecting several markers they all belong to one ship and several load cases were examined. The marker with the lowest GM always represents the intact criteria limit, which may result from any of the criteria. The x-axis represents the GM-value of the ship, and the y-axis the calculated capsizing index.

In general, the following conclusions can be drawn:

- The current code on intact stability 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 increases 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 modern designs for ferries, RoRos or container ships have significant problems due to large righting lever alterations.

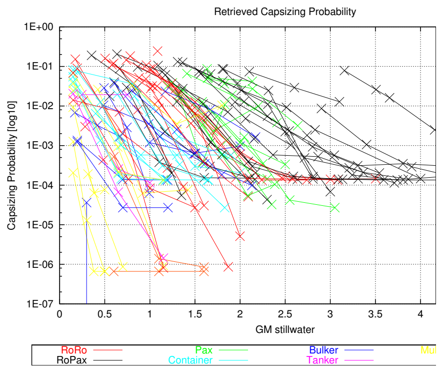

Figure 2: Capsizing index as function of GM for different ships

6 Experiences and Observations with respect to the Development of Minimum Stability Requirements

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.

Thus it seems worthwhile to investigate possible dependencies between lever arm curve variations and results regarding the capsizing index.

6.1 Reference Waves for Hydrostatical Calculations

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. For criteria based on crest and trough righting levers, reference waves are needed. For this investigation Soeding's Global Seaway Statistics [10] were used once more, as it was found useful to select an approriate wave height as function of the wave length. The 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 belonging seastates: 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:

Period s	Length m	Height m	L/H -
2.50	9.76	.49	19.86
3.50	19.13	.73	26.17
4.50	31.62	1.44	22.00
5.50	47.23	1.98	23.91
6.50	65.97	2.72	24.27
7.50	87.83	3.70	23.72
8.50	112.81	4.36	25.88
9.50	140.91	5.43	25.96
10.50	172.14	6.53	26.38
11.50	206.49	7.43	27.80
12.50	243.96	8.44	28.90
13.50	284.56	9.37	30.38
14.50	328.28	10.30	31.88
15.50	375.12	10.95	34.27
16.50	425.08	12.06	35.24
17.50	478.17	13.10	36.50
18.50	534.37	14.30	37.37
19.50	593.71	15.28	38.86
20.50	656.16	16.35	40.13

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.

In the following all crest and trough righting levers are determined for the wave parameters stated above. The vessel trims freely, wave crest/trough position is always $L_{pp}/2$ the wave length equals the wetted length of the vessel of interest. It was proven that this simplified procedure can compensate the lack of pitching phase in the best way without making criteria unnecessarily complicated.

6.2 Results – Capsizing index versus lever arm curve alterations

The following figures show the capsizing indices once more, but this time plotted versus different lever arm curve (alteration) characteristics. Fig. 3 shows the capsizing index versus the maximum righting lever in still water divided by its difference between crest and trough condition. A clear trend can be identified, which suggests, that for increased intact safety, stability values to be attained should be somehow dependend on their variations in waves.

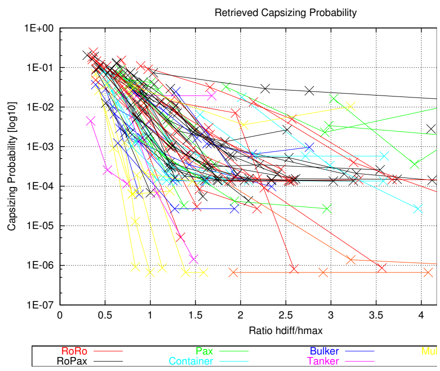

Figure 3: Capsizing index as function of maximum righting lever alteration for all ships investigated

Fig. 4 shows the capsizing index versus the area below the righting lever curve up to 50 degrees of heel in still water divided by its difference between crest and trough condition. These areas were calculated including negative contributions also.

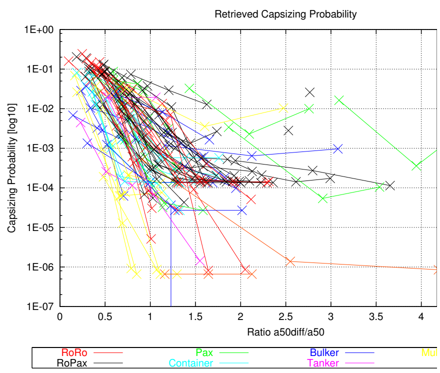

Figure 4: Capsizing index as function of the Area50 alteration for all ships investigated

These results show in general the same trend as found for the maximum lever and its alterations. This becomes even clearer when using the same approach but the areas up to 15 degrees of heel as shown in the following Fig. 5.

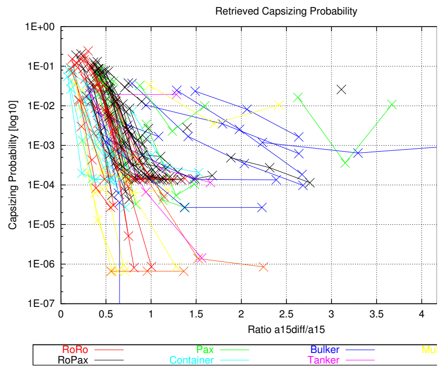

Figure 5: Capsizing index as function of the Area15 alteration for all ships investigated

7 Conclusions

The described evaluation of a capsizing index proves to be a valuable methodology for the comparison of ships with respect to the danger of extreme angles of roll. Due to the underlying assumptions (e.g. speed, encounter angle, load case distribution) the capsizing index can not be interpreted as an absolut probability of capsizing. Thus a comparison to other means of failure (e.g. damage stability, fire safety, etc.) is not possible. Nevertheless when focussing on the necessary revision of the rules and regulations with respect to intact stability, and when targeting intact safety in the design process it is found to be a very useful tool.

When investigating the safety level provided by the current IMO Code on Intact Stability, it was found, that the results spread over a wide range. This supports findings from ship design and other studies suggesting that the current rules and regulation with respect to intact stability can not guarantee a uniform level of safety, especially for modern ship types. For many ships the intact stability requirements are overruled by other rules and regulations, e.g. damage stability, thus stability values exceed the requirements from the code on intact stability. Nevertheless, with ships being optimized and designed to the limits, we are in a need for transparent and appropriately defined limits for intact ships.

Several ships have so far been included in the study and results are being investigated with different approaches. Regarding the revision of intact criteria, the results suggest that stability values to be attained should be a function of their variations in waves. Further details in this respect are being investigated. Additionally further ships are being included in the study to reach a more evenly distribution of ship types. And last but not least the proposed capsizing index should be improved by introducing more realistic distributions for ship speeds and courses.

Acknowledgements

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