EVALUATION OF THE IMO WEATHER-CRITERION FOR PASSENGER SHIPS BY DIRECT CALCULATION OF CAPSIZING FREQUENCIES

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1 SUMMARY

In the past, the damage stability requirements have been the governing criteria for the limiting KG-curves of passenger ships. Now the situation has changed so that for improved subdivisions the intact criteria, namely the IMO- weather criterion, becomes the governing stability limit, also due to large windage areas. Therefore, intensive studies have been carried out at TUHH, simulating capsizing scenarios and large rolling angles by direct, nonlinear computational methods. Using this approach, capsizing frequencies or probabilities of reaching large rolling angles can be calculated so that it is possible to analyze the applicability of the weather criterion in a rational way. This paper will describe the main results and conclusions for the application of the weather criterion to passenger vessels.

2 INTRODUCTION TO THE PROBLEM

When safety of ships like RoPax or RoRo- vessels is addressed, it comes automatically into our mind that damage stability is the major safety relevant problem. Consequently, many actual research projects in the EU deal with damage stability issues, e.g. harmonization of the rules or alternative, mainly first principle based procedures. Due to these developments, which were strongly influenced by the loss of ships (ESTONIA etc.) because of the public reaction, intact stability code development has not taken place for many years, although ships are operated in intact condition. And they should be designed to do so as good as possible.

Intact stability problems are, according to my opinion, much more complex to deal with seriously than damage stability problems, which may be illustrated by the following example: The required index of a 200m ship according to the probabilistic regulations (SURCAP) amounts to 0.567. This means, that the ship will not survive 43.3% of all possible damages. If we now consider, that 70% to 80 % of the attained index are mainly gained on the partial draft, the survivability of the ship at the design load case (or close to it) is then some 15%. If we also consider

- that the minimum requirements of a specific damage case are quite low, (a damage case of 1 degree range and 1 cm righting lever still gives positive contributions)
- that the existing damage probability distributions state much higher values in the forward part of the ship,
- that no bottom damages are included,

we come to the conclusion that the ship will most probably sink if she is hit (and most probably survive if she hits another ship). As a matter of fact, the survivability of ships is quite high due to the fact that the probability of getting a damage is very low.

On the other hand, when dealing with intact stability problems, we find that situations that expose danger to a ship occur quite often (e.g. wave heights of 8 m or more can occur more than 10% per year in certain areas) on one hand and we expect much higher survivabilities in these situations than in damaged conditions. If we would, for example, consider a ship’s life of 20 years and a safety margin of e.g. 10, then we could conclude that a tolerable capsizing frequency of 0.005 (1 capsize in 200 years) could be acceptable. On the other hand, if the world fleet would consist of 20000 ships, then we would have 100 capsize accidents each year which is totally unacceptable. This clearly shows that the absolute safety values of intact ships have to be considerably higher which makes the investigations more complicated.

As mentioned above, intact stability code development was out of the focus for many years and the question is whether the existing stability rules for intact conditions do meet the requirements of today’s fleet. Because we have to face the situation that most of the ships, and this especially holds for RoRo and RoPax- Ships, are operated at a GM- required (or KG- max) curve that is dominated by the damage stability requirements. When a clever designer is able to optimize his subdivision and/or the damage stability rules will change, ships could be designed where the limiting criteria are governed by intact stability requirements. The question then arises wether the intact criteria represent a safety limit that we consider as sufficient.

In this context, we have to face the fact that ship designs changed drastically compared to the ships that were relevant when the intact criteria were developed. A general trend is the trend to much more deck cargo, which leads to higher ZCGs and to higher stability demands. The development of container vessels makes this obvious, and the same holds for
RoPax- Ferries and Cruise liners. In the pure RoRo market, the development has already started. On the other hand, we have the trend for higher speeds and better fuel economy, which has lead to completely different hull forms. To check the safety level of a specific ship design, we have to analyze the behaviour of the ship in waves (because they represent dangerous situations for ships) with appropriate methods. This paper gives an example of such method, demonstrates how safety levels can be accessed and shows that especially RoRo and RoPax ships are critical in rough weather.

3 GENERAL APPROACH

Collecting situations that are dangerous for a ship in real operation, we find the following:

- Pure loss of stability, typically on a wave crest
- Parametric rolling
- Cargo shift or other heeling moments
- Broaching

Figure 1: Two examples of a capsize. Left: Broaching of a multi-purpose vessel due to poor course-keeping ability in quartering waves. Right: Capsize of a RoRo-Carrier due to Parametric Rolling/Pure Loss.

These conditions typically happen in a sea state under the influence of arbitrary loads, which might come from wind and waves. The examples show that the nature of these phenomena is purely dynamic, and therefore, the approach to tackle these phenomena must be a dynamic approach. Therefore, we should come to a new definition of intact stability, which from the designer’s point of view should 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
- Critical resonances not in operating range (making dangerous situations less probable).
- Sufficient course keeping and steering ability for safe operation in heavy weather.

Looking at these criteria, we find that none of them is covered by existing stability criteria, simply because they disregard dynamics as well as a wavy surface in general. Therefore, a proper ship design should focus on the improvement of these criteria and treat the existing stability rules as a necessary boundary condition. To do so, we have developed appropriate design philosophies.

To simplify the problem, the maneuvering influence is separated from the pure seakeeping effects. Then, we can not deal with broaching, but we can approach parametric rolling, pure loss of stability and combinations of these two.

4 INTRODUCTION TO PARAMETRIC ROLLING AND PURE LOSS

As mentioned above, modern ships are characterized by a substantial portion of stability coming from the aft body. If we separate the ship into a fore and an aftbody, we find the following basic different behaviour of these two parts:

- The forebody alone has a low metacentric height, but high form stability and high range of positive righting lever.
- The aftbody has high initial stability but no form stability and a poor range of positive righting lever.

Combining these two bodies, we get a still water characteristic that can fulfill all stability rules although the righting lever curve is completly below the $GM_\phi$ line. Fig. 4 shows what happens to the ship in a wavy surface, wave length equals $L_bP$, which is roughly equivalent to regular head or following seas.

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

March 2003: The Royal Institution of Naval Architects
If the correct frequency is met, the ship is heavily uprighted at maximum heel (due to the fact that the righting lever is excessively high) and is heavily heeled in the upright position (due to the fact the the crest lever is extremely diminished). A rolling motion is observed that can lead to a capsize also in regular waves, if heeling/righting moments take a critical value and/or damping is too low. This effect becomes most pronounced for all ships that gain a substantial portion of stability out of the aft body, as the following example shows.

On the other hand, the right picture of fig. 5 shows that it is possible to design ships with good rolling characteristics also within the existing regulations, if sufficient care is taken and sophisticated tools are used.

Figure 5: Example of a capsize after parametric exitation. $\lambda_{1/3} = LbP$, ship speed 8 knots, $H_{1/3} = 5.5m$.

Therefore, it is important to understand the physical phenomena related to a specific design that lead to severe rolling. This is demonstrated in fig. 5, where some results of a numerical seakeeping simulation for a 25 knot, 200 m RoPax-Ferry are shown. The left picture shows the time function of the rolling angle (red) vs. wave amplitude at main frame (blue). It can clearly be seen that for a long time, the response of the ship is moderate. Suddenly, if two or three significant wave packets strike the ship in the right manner, it dramatically starts to roll and rapidly reaches the angle of no return, which then leads to a capsize. Significant wave length is chosen equal to $LbP$, significant wave height 5.5m, and the encounter frequency (determined by wave period and ship speed) is selected to get close to the resonance. This case is extremely dangerous, because the crew can not foresee that the vessel will capsize in a few minutes (right picture of fig. 5).

To achieve favourable seakeeping behaviour, two main steps have to be performed:

- Making dangerous situations less probable by shifting critical resonances to situations that hardly occur.

- Optimizing the ship for better survivability in critical situations.

Fortunately, these two issues can be separated from each other which simplifies our design problem. Because critical resonances mainly depend on the vessels main dimensions, whereas the behaviour in critical situations is influenced mainly by hullform details.
5 COMPARING HULLS BY NUMERICAL MOTION SIMULATIONS

5.1 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. While the roll motion is simulated non-linearly using the following equation:

\[
\ddot{\phi} = \frac{M_{\text{wind}} + M_{\text{sy}} + M_{\text{wave}} + M_{\text{tank}} - M_d - \dot{m}(g - \ddot{\zeta})h_s - I_{xx} - I_{xz} \left(\dot{\psi} + \dot{\psi}\dot{\varphi}^2\right)\sin\varphi - \left(\dot{\psi} + \dot{\psi}\dot{\varphi}^2\right)\cos\varphi}{I_{xx} - I_{xz} (\psi \sin \varphi + \dot{\varphi} \cos \varphi)}
\]

where \(M_{\text{wind}}, M_{\text{sy}}, M_{\text{wave}} \) and \(M_{\text{tank}}\) are the roll moments due to wind, sway and yaw, waves and fluid in tanks and flooded compartments, respectively. \(M_d\) is the non-linear damping moment using damping coefficients following Blume (1979). \(\varphi, \dot{\varphi}\) and \(\psi\) are the roll, pitch and yaw angles, respectively, while \(m\) is the mass of the ship and \(g\) the gravitational acceleration. The righting arm in the seaway \(h_s\) is determined for every time step using Grim’s effective wave as modified by Soeding (1987). \(I_{xx}\) and \(I_{xz}\) are the moment of inertia about the longitudinal axis and the product of inertia, respectively, calculated for the actual mass distribution (light ship and cargo). As mentioned above, broaching can not be treated at the moment.

5.2 THE EQUIVALENT SAFETY CONCEPT

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. Simply distinguishing between the ship did capsize or did not is not an adequate criteria, as results would depend on the number of tests or the duration of the simulation. 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 \(\Phi_{\text{max}}\) encountered in the run and the vanishing point is calculated (illustrated in figure 6). 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 save when

\[
\bar{E_R} - 3s > 0
\]

For the evaluation of an equivalent safety the following approach is adopted: As ship of comparison a vessel is chosen which does not only full fill the current rules but also has approximately the same length as the ship to be evaluated. So it is not necessary to scale the seaways in length and height. The maximum KG for the ship of comparison is estimated following the rules. Now several simulations are performed for the ship to be evaluated (with the anticipated maximum KG) and the ship of comparison according to the rules, covering a range of speeds, encounter angles and wave lengths. For each combination of speed, encounter angle and wave length the wave heights are increased until the limiting significant wave height is found. The results are then compared (ref. fig. 6). As the Blume-Criterion was used when establishing the c-factor of the revised IMO 749 stability code, we found that the safety level represented by the Blume-criterion seemed to be of acceptable value.
6 ESTIMATING CAPSIZING PROBABILITIES IN HEAVY WEATHER

6.1 GENERAL

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. On the other hand, one simple number would not be enough, because the designer needs to understand how this number is generated and by which means he can influence it in a positive way at a minimum effort. Therefore, we have to establish a calculation procedure as well as a design philosophy. This also gives the opportunity to check whether the existing rules give a sufficient safety level.

The contribution to the capsizing probability \( P_c \) of a single point in one polar diagram is given by the formula:

\[
P_c = P_B \cdot P_{Sea} \cdot P_{Course} \cdot P_{speed}
\]

where \( P_B \) means the probability of a capsize in that specific seastate, \( P_{Sea} \) means the probability that this seastate, represented by significant period and wave height, will occur. \( P_{Course} \) and \( P_{speed} \) are the probabilities that a specific course and speed are sailed. Each polar diagram is then calculated for a given significant wave length (or period), and the sum of all \( P_c \) is calculated. The total capsizing probability \( P_{total} \) is then calculated as the sum of several polar diagrams, where the wave lengths have been selected according to the class representation of the sea state.

6.2 MODELLING THE SEASTATE

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 points in a tabular form. Point Nr. 125 represents the North Atlantic, which we use as reference area in all our calculations. In principle, it is also possible to calculate capsizing probabilities 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). The table given in the appendix states the probability distribution of our reference area NA. Using this probability distribution, the probabilities \( P_{Sea} \) can be determined. The table is also useful to answer another problem. When hydrostatic calculations of righting levers in waves are performed (e.g. BV1033), the question arises which wave height is to be chosen in dependency of the wave length. In most cases, the steepness ratio is kept constant, e.g. L/20 or L/30. In parallel to the simulations, also static righting levers need to be examined, because they are the basis for the existing regulations. 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 wave height is calculated as 90% quantil of the seastate: 90% of all possible waves of a given 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>2.75</td>
<td>9.76</td>
<td>0.49</td>
<td>19.86</td>
</tr>
<tr>
<td>3.50</td>
<td>19.13</td>
<td>0.73</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>
</tbody>
</table>

The Tables state waves with height probability of 90% within the class of waves given by the period.
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 this context, it should be kept in mind that these results are valid for our area of reference. These data are used for the comparison of righting levers in waves.

6.3 MODELLING THE CAPSIZING PROBABILITY

The polar diagrams state significant wave heights that fulfill the Blume-Criterion. Later, it will be shown that the Blume-Criterion has some deficiencies that have to be overcome in the near future. 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 Blume-Criterion, we assume that the ship will capsize or be exposed to a large rolling angle that leads to a loss (e.g., due to cargo shift or system failure). 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, but in the near future, better criteria with better probabilities have to be defined. This is also due to the fact that ships can capsize also due to other failures, such as excessive accelerations, cargo shift, broaching, external moments etc.

6.4 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. If they are aware of dangerous situations, they will avoid them. For example, a good crew will avoid travelling in following seas when the situation becomes dangerous. The other hand, not all crews are well trained and our opinion is that we should try to design much safety actively into the ship as reasonably possible. And for comparing ship designs, the skills of the crew should not be taken into account. Therefore, at present, we assume that all courses and speeds have the same probability. For the comparison of ships and for the relative safety level, this is sufficient. In the near future, more realistic course / speed distributions should be introduced. Furthermore, if other criteria besides the Blume-Criterion will be introduced (e.g., excessive accelerations), then automatically speed/course restrictions will result. So, the calculation procedure is as follows: The polar diagram is calculated close to the design speed of the ship. For each point that gives a positive contribution to the capsizing probability, it is checked whether this point can actually be reached on the basis of the installed power. If not, the capsizing probability of this point is set to zero.

7 PRACTICAL APPLICATIONS TO SHIP DESIGN

The procedure can be used for both evaluating safety levels of ships as well as evaluating designs or design measures. Both will be demonstrated by the following example.

![Figure 8: Analysis of two hull form variations in different wave lengths](image)

As general strategies to optimize hulls for good safety against capsizing, it was found beneficial

- to shift LCB as far aft as possible to decouple rolling and pitching motion on one hand and to gain more stability out of the aftbody in the critical crest situation
- to select a large bilge radius to force a higher immersion on the crest that the aftbody contributes more to stability.

To demonstrate the usefulness of the first measure, we have made a numerical experiment that demonstrates this design feature as well as the fact that the safety level of the current rules seems to be insufficient. Fig. 8, top, shows the body plan of the UND- vessels designed by FSG in the 3-Deck version. The body plan shows that the ship has a very long forebody, the frame having maximum area is about frame 6.5. The limiting criterion regarding the stability in total
is in fact the damage stability requirement. During the model tests carried out during the German BMBF-funded project ROLLS according to a design load case (GM approx. 1.60m), the general seakeeping behaviour was excellent.

As it is our aim to analyze the intact criteria, we now disregard the damage stability influence. Then, the governing criterion becomes the IMO-weather criterion leading to an initial GM-value of 0.88m with a maximum righting lever of 360mm. For this loading situation, extended simulations have been carried out in wave lengths of 121-360m. The three polar diagrams on top show that at this condition, which would be a legal condition if the subdivision would be designed for this target, the vessel seems to have significant problems caused to the dynamics.

To demonstrate the usefulness of having the LCB far aft, an alternative hullform was generated with the main frame at Lbp/2 (lower bodyplan). The displacement was nearly the same as for the original version, so the draft was kept the same. Due to the increased aftbody length, the GM value is now 1.60m with a maximum righting lever of 655mm. These values hold when the ZCG of the initial hullform was kept constant. For this alternative hullform, the same simulations were performed (see polar diagrams below). The results show that the general behaviour has changed drastically: The ship now becomes exposed to head sea problems at shorter waves and in following waves at low speeds, the tolerable wave heights are smaller. In longer waves, the ship is better because the original design has significantly less righting lever and is endangered due to pure loss or large rolling moments. To quantify which design is better, the capsizing probability was determined according to the procedure as stated above for the reference area NA.

The results are plotted in Fig. 9 as function of the wave length. The results show in a quantitative way what was observed before: The original design (named UND3DECK) is better than the modified design (named UND@Lbp/2) at shorter waves and it is inferior at longer waves. The final values show that for the original design, a capsise is calculated each 15.2 years (under the a.m assumptions) and for the modified design each 14.3 years, which is roughly equivalent. It is extremely important to note that the modified design has twice the initial GM and roughly two times the maximum righting lever of the original design, which does not result in any improvement of the survivability. This is due to the fact that the behaviour of the ship in a seastate does strongly depend on critical resonances on one hand and on alterations of the righting levers between crest and through. In this respect, the modified design is worse. This leads to the conclusion that the stability requirements of a ship strongly depend on the alterations in waves and should consequently be a function of them.

As a matter of fact, the comparison has been a little unfair up to now because we have kept the ZCG constant for both designs. A better comparison would be based on the same initial GM value, which should be 0.88m also for the modified design. This alternative was also considered, but when checking the stability criteria, it was found that the design would not fulfill the weather criterion at the corresponding ZCG. Therefore, ZCG was adjusted to meet the weather criterion which finally resulted in a GM-value of 1.10 m (corresponding to ZCG=13.13m). Again, if the subdivision would meet damage stability requirements, this would be a legal load case. For this load case, the same simulations have been made (the polar diagrams are omitted here) and the results are also plotted in fig. 9. The survivability is now drastically smaller (4.1 Years) compared to the original design although the GM value is still larger and the maximum righting lever with 401mm, too. This clearly demonstrates the benefit of hullform optimization strategy on one hand and the fact that at least in this case, the safety level of the existing rules seems to allow to design extremely unsafe ships.

And again, we find that the stability requirements need to be dependent of the alterations in waves.

This is underlined by the next example: The orininal design was later modified and a fourth trailer deck (top deck) was fitted. Due to the increased lateral area, the original hullform (top bodyplan in fig. 8) now requires an initial GM of 1.03 m) at the same draft according to the weather criterion. The results of the survivability determination are also plotted in fig. 9, named UND4DECK. It can clearly be seen that the safety level is drastically improved (capsizing frequency is now calculated by 41.3 Years). In this case, the GM increase of 20cm roughly gives a three times higher safety level, although the total level is still rather low.

This leads to the next example: The ships are equipped with a Flume Tank for roll damping. According to the stability regulation, the free surface effects of this tank (although designed for roll damping) have to be taken into account. This leads to a GM reduction (or ZCG increase) of approx. 40cm. If the vessel sails at 1.03m GM, then the solid GM amounts to 1.43 m. If righting levers are calculated taking into account the fluid shifting moments correctly, we find that the total area under the righting lever curve takes roughly twice the value than according to the solid correction method (not taking into account the damping effect of the flume tank). For this condition, also survivability calculations have been
performed leading to a capsizing frequency of 2780 years, which seems to represent a sufficient value based on the conservative assumptions and the selected area. Calculations with solid GM of 1.43m disregarding the fluid shifting moment (which is more correct, because it is a roll damping device) lead to even higher survivabilities.

This clearly shows that there are hidden safety reserves in the existing rules which can hardly be detected. But the result seems obvious: If an operator decides to drain the Flume Tank and utilizes more solid cargo instead (which would be legal if he sails below the KGMAX- Curve), then the safety level is drastically reduced (roughly by factor 65). Using the prescribed probability approach, this now can be quantified.

8 EVALUATING SAFETY REGULATIONS, HERE: WEATHER CRITERION

The procedure was applied to analyze the safety level of the IMO weather criterion. This criterion is the dominating criterion for RoRo and RoPax vessels, and if the inner subdivision is optimized, the vessels can in principle be operated with a KGmax- curve according to the weather criterion. Furthermore, this criterion is the only stability criterion that claims to include dynamic effects. The criterion bases on the balancing of the area below heeling and righting levers with solid GM of 1.43m disregarding the fluid shifting moment (which is more correct, because it is a roll damping device) lead to even higher survivabilities.

The criterion bases on the balancing of the area below heeling and righting levers within any requirement for the area itself. Consequently, the weather criterion can be fulfilled by more or less any area below the righting lever curve. We analyzed a couple of recently build RoRo, RoPax and Pax ships as well as older ships and Stockholm conversions according the a.m. procedure and determined the capsizing probabilities. Furthermore, we identified the dominating phenomena that lead to a capsizing. Fig. 11 shows the results for all ships analyzed. The required area to fulfill the weather criterion is plotted against the calculated capsizing frequency. As capsizing criterion, 50 Degree heel was used instead of the Blume criterion. Although the picture seems quite unclear, some general trends can be observed when specific details of the ships are taken into account. First, it is to be noticed that both the area requirement as well as the capsizing probability varies drastically. The same area level can lead to drastically different capsizing frequencies which indicates that the criterion does not represent a unique safety level. Furthermore, the ships seem to cluster into three groups:

- low capsizing probabilities at low areas
- low capsizing probabilities at high areas
- high capsizing probabilities at low areas

Figure 11: Typical righting levers of the three different groups identified

The ships MV120-2 and PS163-2 are Stockholm conversions. The first category of ships are vessels characterized by moderate or low GM- values, such as older RoRo-Ships without damage stability requirements or SOLAS 90 compliant RoPax. They are characterized by low initial stability and high additional form stability. These ships have low risk of parametric excitation due to the fact that critical resonances hardly occur, but suffer from pure loss of stability problems in mainly in quartering waves.

The second group represents mainly Pax and RoPax vessels without lower hold characterized by higher GM- Values and moderate form stability. Roughly up to 30 Degree the righting lever curve follows the straight line represented by $GM \phi$. These ships have problems with parametric excitation at lower speeds mainly in quartering waves and pure loss problems if the wave height is sufficiently high.

The third group is represented by lower hold RoPax vessels having high to extremely high initial GM values and low or no additional form stability. These ships suffer from parametric excitation at wider speed range as well as from excessive roll moments in longer waves that lead to a capsize. For these type of ships, the damage stability requirement influences the intact behaviour via the height of the weather-tight superstructure which is included in the fulfillment of the IMO weather criterion. All ships of this type have large alterations of righting levers at through or crest conditions. As general conclusion, it can be stated that the safety level of the IMO weather criterion is neither constant nor sufficient, because many ships seem to be unsafe. Therefore, new criteria need to be developed that can better deal with the dynamic effects.
9 CONCLUSIONS

Simulation of dynamic effects in seastates are a worthwhile tool to design ships that have better seakeeping characteristics, which means increased safety on board. Based on these methods, design principles can be found that lead to improved ships. The examination of the existing intact stability rules show that most ships gain sufficient safety levels only due to the fact that damage stability requirements overrule intact criteria. In this respect, especially RoRo and RoPax ships seem to become critical, if they can be operated at the intact criteria limit. In this context, the weather criterion is the limiting criterion which does not represent a reasonable safety level for these type of ships and allows to design ships with insufficient safety in rough weather. At present, further ships are analyzed to go into further details.

10 ACKNOWLEDGEMENTS

The authors wish to thank the German BMBF for the funding of the projects ROLLS and SinSee. Without the support of BMBF, the research work would have not been possible.

11 REFERENCES