Capsize probability analysis for a small container vessel

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1. INTRODUCTION

In this paper we investigate the long term capsize probability for a small container vessel which is operated in a regular service schedule on the North Sea and the north-east part of the Atlantic Ocean. The numerical simulation techniques involved are a ship route scenario simulation method and a time domain simulation method for large amplitude ship motions.

The scenario simulation tool GULLIVER was developed at MARIN as a product for clients interested in the performance of their ship(s) in service conditions, with respect to safety, economy and reliability. The large amplitude ship motion program FREDYN was developed at MARIN within the framework of the Cooperative Research Navies project. Both methods have been applied successfully in many projects and have proven their value in both a research and a commercial context.

Our primary goal is to find a way to combine these two tools into a method for calculating the long term capsize probability. With GULLIVER we are able to account for the effect of involuntary speed loss due to waves, wind and current and to quantify the encountered weather conditions in terms of (long term) scatter diagrams. This part of the approach is described in Section 2. With FREDYN we are able to identify the conditions in which the ship is prone to capsize. This part of the work is described in Section 3. Combining the two gives an impression of the average short term capsize risk. The final step is to translate this short term capsize risk into a long term capsize risk, which is described in Section 4.

As for the captain's influence on the safety of the ship, Gulliver provides us some means to quantify the effect of the captain's decisions based on the ship behaviour. However, at the time of writing this paper, these measures are restricted to reducing speed whenever a certain criterium is exceeded; they do not (yet) include the possibility to change course during a trip. In Section 5 we will present a method to mimic course-deviations a posteriori, in order to estimate the effect of the captain's decisions on the capsize risk.

2. GULLIVER SIMULATIONS

Figure 1 shows a schematic representation of the scenario simulation procedure followed in GULLIVER. At each time stage the sustained speed is calculated from the balance between the total resistance (i.e. the sum of the calm water resistance, the added wave resistance and the wind resistance) and the available thrust. Voluntary speed loss may occur whenever a certain criterium is exceeded, e.g. roll angle or relative motion. The ship position is updated and this process is repeated until the destination has been reached.

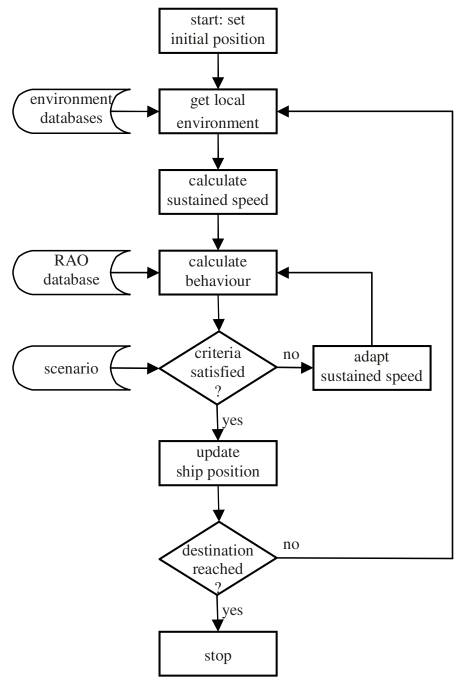

Figure 1: Scenario simulation procedure.

We simulated a weekly container service between The Netherlands, the United Kingdom, the Faroer Islands and Iceland. The routes are shown in Figure 2 and the schedule is presented in Table 1.

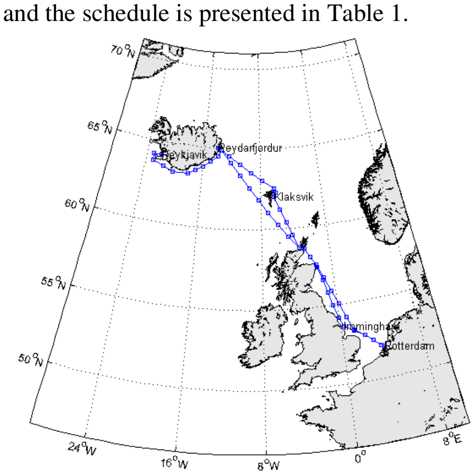

Figure 2: Ship routes.

Port	Day
Reykjavik	Monday
Reydarfjordur	Wednesday
Klaksvík	Thursday
Immingham	Saturday
Rotterdam	Monday
Reydarfjordur	Friday

Table 1: Service schedule.

The selected ship is a small size container vessel. Table 2 lists the key characteristics. The selected loading conditions are shown in Table 3. We applied a distribution of 25%, 50% and 25% for the conditions 100%, 80% and 50% loaded respectively.

Length between perpendiculars	93.80 m
Maximum breadth	15.85m
Draught	6.40 m
Speed	15.5 knots
Container capacity	364 TEU
Deadweight	4,820 tons
Main engine	3,960 kW

Table 2: Ship key characteristics.

Loading Cond.	displ. (tons)	Mean Draft [m]	Trim [m]	KG [m]	GM [m]
100%	5567	4.87	1.00	6.13	0.85
80%	4826	4.29	1.50	6.36	0.71
50%	3715	3.40	2.00	6.06	1.48

Table 3: Loading conditions.

The vessel's calm water resistance and effective thrust were calculated for the 3 loading conditions using MARIN's program DESP. The results are presented in Figure 3. Not surprisingly, the resistance increases with increasing draft. The effective thrust is plotted for the 80% loaded condition only, since it hardly depends on the draft.

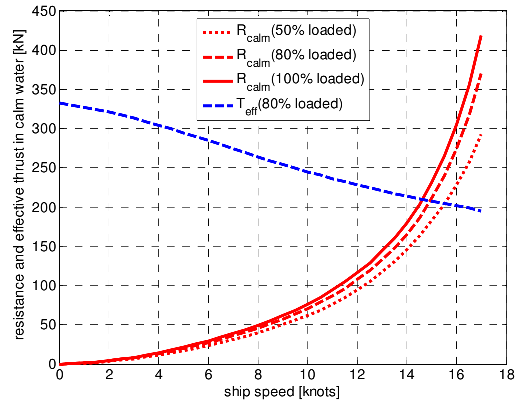

Figure 3: Calm water resistance and effective thrust.

The vessel's added resistance in waves was calculated in terms of quadratic transfer functions for the 3 loading conditions listed in Table 3. For each loading condition, the added resistance in head waves was calculated at service speed (15.5 knots) using our frequency domain strip theory program SHIPMO. With this result, the added wave resistance in all other speed-heading combinations was calculated using the Jinkine-Ferdinande formulation [2].

Figure 4 shows the added wave resistance for the 80% loaded condition at 10 and 15 knots. The added resistance is shown in the form of polar diagrams with the wave frequency along the radial axis and with the wave direction in the angular direction. From these diagrams, we observe that the added wave resistance reaches its maximum in bow quartering to head seas conditions, it increases with speed.

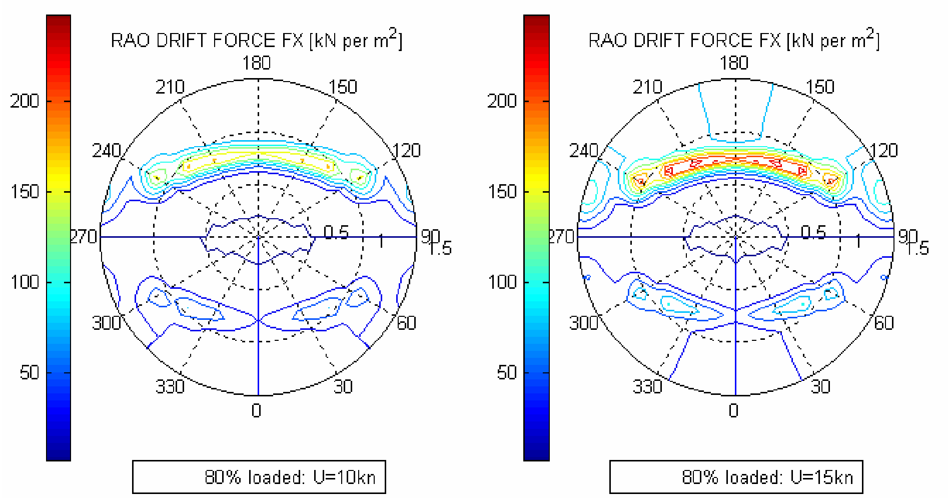

Figure 4: Added wave resistance as function of wave frequency and wave direction.

The resistance due to wind is calculated from the frontal area and the relative wind speed which includes the ship's forward speed. Figure 5 shows the wind resistance coefficient as a function of the relative wind direction.

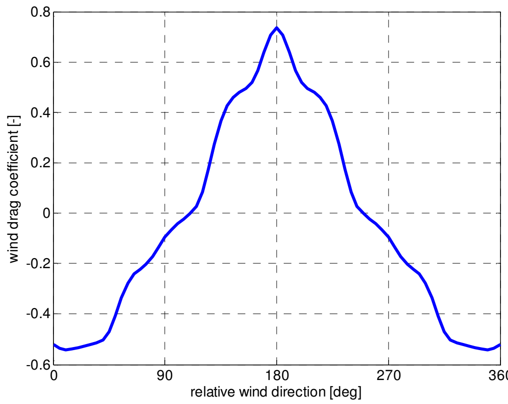

Figure 5: Wind drag coefficients.

Wave and wind data are obtained from ECMWF and are available for the North Atlantic, specifically between (60N, 90W) and (30N, 3E). The wave and wind parameters comprise:

- Significant wave height, mean wave direction and mean wave period for both wind sea and swell;
- Wind speed at 10m above mean sea level and wind direction.

The parameters are given on a 1.5 deg by 1.5 deg grid with a time step of 6 hours, i.e. 4 samples per day.

The current consists of a global (ocean-scale) current field and a local (tidal) current field. These components are superimposed and the resulting current is accounted for in the calculation of the sustained speed over ground.

The results represent the encountered weather conditions and the ship behaviour during 5 years of operation in service.

Figure 6 shows the distribution of the vessel's sustained speed. The top figure shows the *probability of* occurrence in histogram form: For instance, in about 47% of the operational time the sustained speed is about 15 knots. The bottom figure shows the *probability of exceedance*: For instance, starting at 15 knots on the horizontal (sustained speed) axis, the vertical grid line intersects the graph at about 1.5×10^{-1}, which is the corresponding probability of exceedance. This means that in 15% of the time the sustained speed is 15 knots or higher or, equivalently, in 85% of the time the sustained speed is 15 knots or lower.

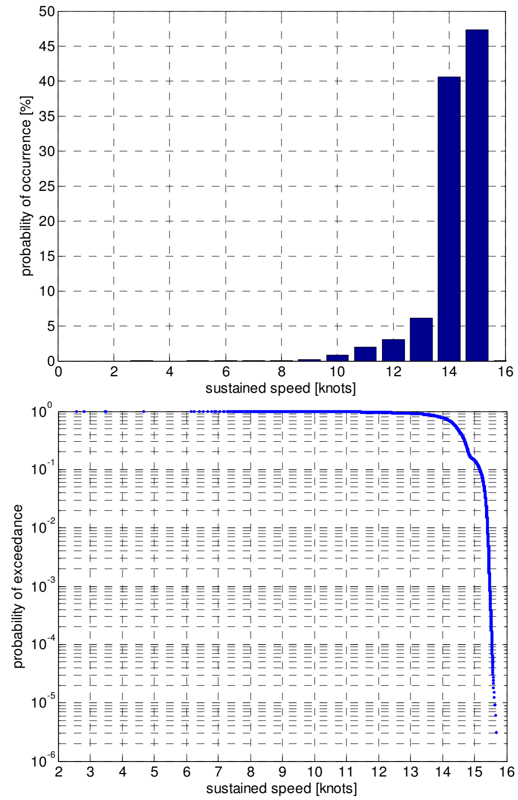

Figure 6: Distribution of sustained speed.

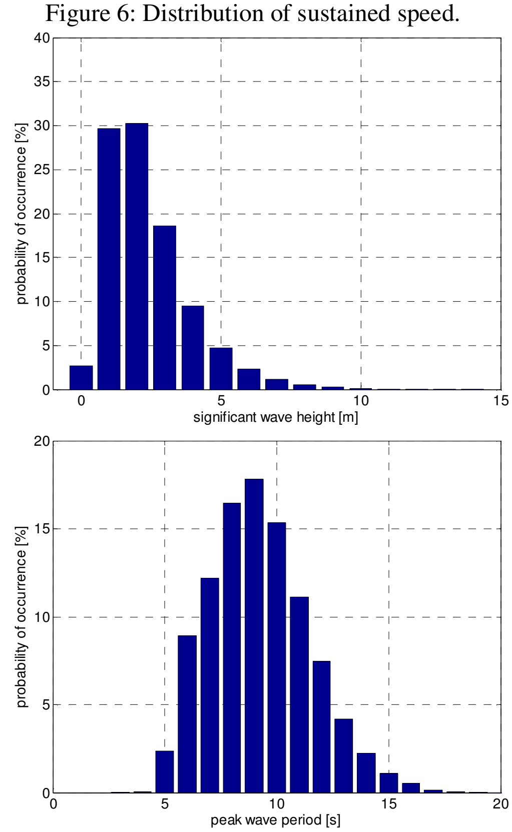

Figure 7: Distributions of significant wave height (top) and peak wave direction (bottom).

Figure 7 shows the distributions of the significant wave height and the peak wave period. The range 1-5m covers about 90% of the waves. The range 8-10s covers about 50% of the waves.
Figure 8 shows the distribution of the peak wave direction relative to the vessel's course. This is a more or less uniform distribution.
Figure 9 shows the distribution of the wind force. The most frequent range is 3-5 Beaufort, in about 2% of the time the wind force of Beaufort 8 or higher.

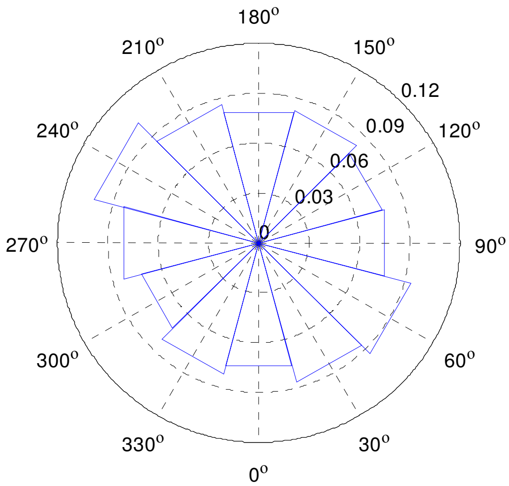

Figure 8: Distribution of relative wave direction.

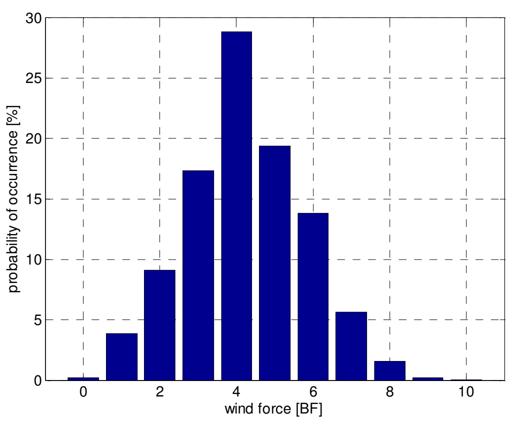

Figure 9: Distribution of wind force.

Figure 10 shows the scatter diagram of waves encountered during 5 years of service. This scatter diagram was compared with other available scatter diagrams (NOAA, GWS) and the overall impression was good.

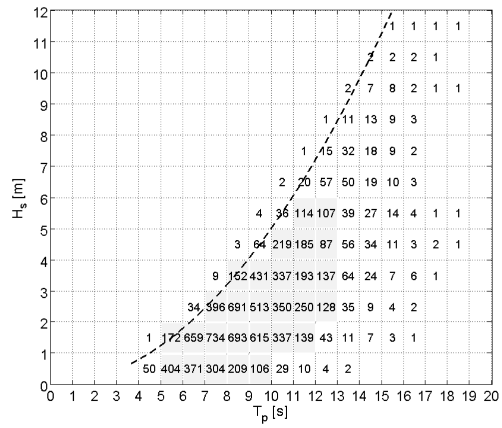

Figure 10: Encountered wave scatter diagram.

3. FREDYN SIMULATIONS

The purpose of the FREDYN simulations is to quantify the capsize probability for each combination of (1) loading condition, (2) speed, (3) wave direction, (4) peak wave period and (5) significant wave height, as encountered by the ship during the GULLIVER simulations. To this end, we distribute the encountered combinations (or states, see Section 5) into 5-dimensional bins and for each bin we calculate the corresponding capsize probability.
The capsize probability calculation procedure is as follows: for each state bin we perform a number (say, 10) of time domain simulations, each with a different seed for the random phase distribution of the irregular wave system. In case of a high capsize risk, the number of simulations (seeds) is extended to 30. The capsize probability is then based on the number of capsizes.

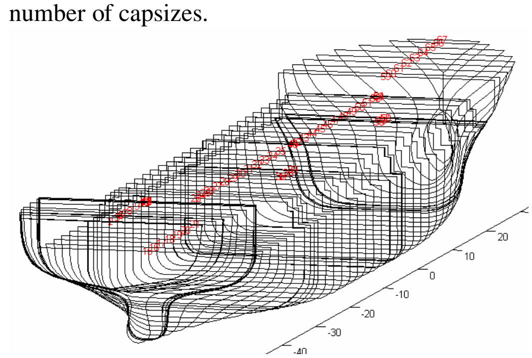

Figure 11: Ship geometry.

Figure 11 shows the vessel geometry as used in the FREDYN simulations. The hull description includes the fore castle, the coamings and the poop deck, which is needed for the calculation of the nonlinear Froude-Krylov (wave excitation) forces.

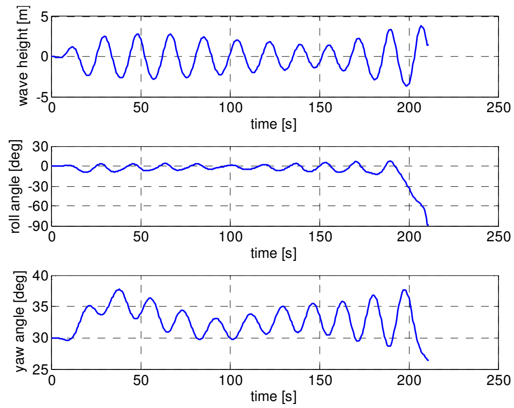

Figure 12: Sample of FREDYN output.

Figure 12 shows an example of a simulation where the ship sails in stern quartering seas at design speed. Course deviations up to 8 degrees occur and the ship rolls at angles up to 10 degrees. Finally, the ship capsizes due to a combination of large yaw motions and loss of roll stability.

Figure 13 shows a combination of results from GULLIVER, FREDYN and model tests. From GULLIVER the scatter diagram of the encountered waves is shown; the area representing 90% of the most occurring waves is boxed. From FREDYN the capsize probability is shown in color, ranging from 0% (blue) to 100% (red). Note that the capsize risk is not calculated for sea states which do not occur in the GULLIVER simulations, since their contribution to the overall capsize probability will be zero anyway. The dashed line represents the $H_s / T_p^2 = 0.05$ wave steepness limit. On top of all this, the model test results are plotted as “S” (save, or no capsize) and “C” (capsize). There is a good correlation between the numerically predicted capsize probabilities and the model test results.

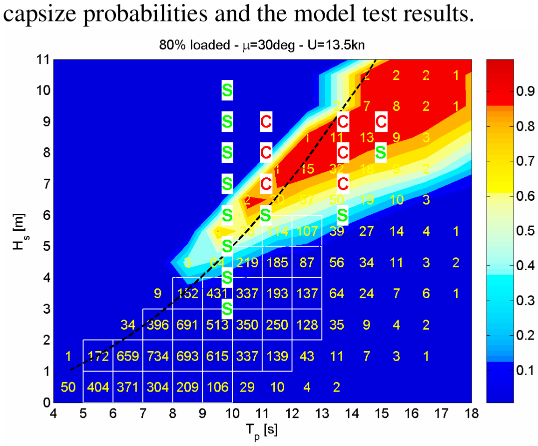

Figure 13: Wave and capsize probability scatter diagram, results from simulations and model tests.

4. CAPSIZE PROBABILITY CALCULATION

The long term capsize probability is defined as the probability of capsizing during a long period (say, 5 years) of operation under a certain scenario in a specified area or on a specified route. The long term capsize risk depends on many factors:

- the average loading condition and the loading condition variation;
- the encountered wave, wind and current conditions;
- the captain’s decisions.

The long term probability that the ship will capsize is, mathematically speaking, equal to the probability that the ship will capsize at least once during a long time. If we consider a long time range (say, 1 year) as a concatenation of a large number N of short time ranges (say, 1 hour), then we are able to express the long term capsize probability in terms of the short term capsize probability:

$$P_{LT}^{cap} = 1 - \left(1 - P_{ST}^{cap}\right)^N$$

As we have seen in Section 2, a GULLIVER simulation represents a continuous service of 5 years in which the ship makes about 130 round trips, i.e. about 780 single trips in total. Each single trip yields a registration of the ship behaviour and of the encountered waves, wind and current, at a sample rate of typically 1 hour. At this point, we introduce a composed variable, which we call state: The state is a 5-dimensional array build from the loading condition (index) LC, the sustained speed U, the wave heading μ (relative to the ship course), the significant wave height H_s and the peak wave period T_p. A GULLIVER simulation generates a state series which can be sorted into an well-chosen set of 5-dimensional bins, so as to obtain the state distribution. The short term capsize probability is calculated as follows:

$$P_{ST}^{cap} = \sum_{s^*} P_{ST}^{cap}\left(s = s^*\right) \times P_{ST}\left(s^*\right)$$

This formula expresses the short term capsize probability as a sum of products of probabilities; for each state bin, the conditional capsize probability is calculated. This means that we will have to calculate the capsize probability under the assumption that each of the 5 ship state components fall within the state bin limits. The calculation of these conditional probabilities is done with FREDYN, as explained in Section 3.

5 RESULTS

A number of Matlab® routines were written for the processing of the GULLIVER and FREDYN results and the calculation of the short term and long term capsize risks. As already mentioned in Section 2, the scenario adopted in GULLIVER corresponds to a constant power setting of 85% of MCR. Hence, only involuntary speed loss due to adverse weather (waves, wind) is accounted for.

If we follow the calculation procedure outlined in Section 4, we obtain the following values for the short term and long term capsize risks:

$P_{ST}^{cap} = 1.4\%$ and $P_{LT}^{cap} = 100\%$

These number may seem alarming, but one has to keep in mind that they correspond to a "passive captain scenario": no matter what the conditions are, the ship will be kept on its original course at a fixed engine power setting.

A common on board procedure to survive in extreme weather conditions is to change course such that a head seas condition is attained. Clearly, this is only possible if the vessel's steering capacity is sufficient to move away safely from a stern (quartering) or beam seas condition. Once in a head seas condition, the roll motion amplitude will decrease and the capsize risk will be reduced correspondingly.

In our calculation procedure, the effect of this change-to-head-seas procedure on the overall capsize risk can be estimated roughly by selecting all states corresponding to a capsize risk higher than a certain critical level. Each selected state represents an unfavourable condition in which the captain would have decided to change course to head seas, until the conditions have improved such that the capsize risk is on or below the critical level. Therefore, for each selected state we replace the capsize risk value by the critical level value. This will reduce the short term capsize risk and, as a direct consequence, the long term capsize risk.

$P_{ST,crit}^{cap}$	f_{state}	f_{time}	P_{ST}^{cap}	P_{LT}^{cap}
10^{-3}	8.3%	3.4%	3.7E-5	60%
10^{-4}	8.9%	3.9%	4.3E-6	10%
10^{-5}	9.9%	4.6%	5.6E-7	1.4%
10^{-6}	11.0%	6.3%	7.3E-8	0.18%
10^{-7}	12.5%	7.9%	8.9E-9	0.022%
10^{-8}	13.7%	9.5%	1.1E-9	0.0026%
10^{-9}	15.1%	11.3%	1.2E-10	0.00030%

Table 4: Effect of "change to head seas" procedure on capsize risk.

Table 4 summarizes the results for different values of the critical capsize level $P_{ST,crit}^{cap}$. For instance, if we set $P_{ST,crit}^{cap}$ to 10^{-4}, then in 8.9% of the states the capsize risk is too high, which corresponds to 3.9% of the service time. Changing to head seas in these states reduces the short term capsize probability P_{ST}^{cap} to 4.3×10^{-6} and the long term capsize probability P_{LT}^{cap} to 10%. A further reduction is achieved when the critical capsize level is lowered: for 10^{-7} we obtain a long term capsize probability of 0.022%, which requires the captain to take appropriate action in 7.9% of the service time. These numbers indicate the possible impact of the captain on the vessel's safety.

5. CONCLUSIONS

In this paper we have demonstrated the feasibility of a quantitative approach towards the capsize probability of a ship in service. By combining scenario simulations with time domain large amplitude motion simulations, we obtained meaningful numbers for the short term and long term capsize probability. Instead of selecting a wave scatter diagram for a particular area and making assumptions on the distribution of the ship speed and heading with respect to the waves, wind and current, we simulated a large number of round trips to obtain the really encountered conditions.

The capsize probability was calculated for each state, i.e. for each combination of loading condition, speed, wave direction, peak wave period and significant wave height. The results show a good correlation with the findings from model tests. However, since only one specific situation was considered, further investigations into the quality of the numerically predicted ship behaviour are recommended. Specific points of interest are the autopilot model and the manoeuvring model.

The influence of the captain on the short term and long term capsize probabilities was modelled in an approximative way by modification of the encountered wave scatter diagram. Applying a head seas scenario in case of significant capsize risk, the captain may be able to reduce the capsize probability drastically. It should be noted, however, that the adopted approach does not account for the effect of delays due to these scenarios and therefore the numbers are only indicative. Therefore, we recommend the further development of the GULLIVER code to incorporate a true captain's scenario, including realistic measures as course changing and speed reduction.

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REFERENCES

1. Boonstra, H., de Jongh, M.P., Palazzi, L., *Safety Assessment of Small Container Feeders*, PRADS 2004, Lübeck-Travemünde, September 2004.
2. Jinkine, V. and Ferdinande, V., *A method for predicting the added resistance of fast cargo ships in head waves*, International Shipbuilding Progress, Vol. 21, No. 238, pp. 149-167, 1974.
3. De Kat, J.-O., Pinkster, D.J. and McTaggart, K., *Random waves and capsize probability based on large amplitude motion analysis*, Proc. 21st Int. Conf. on Offshore Mechanics and Arctic Engineering OMAE 2002, J.V. Wehausen Symposium on Water Waves, Oslo, 2002.