Safety at Speed - S@S

IMPLEMENTATION OF MODELS
BROACHING MODELS
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CONTENTS

1. EXECUTIVE SUMMARY SUITABLE FOR PUBLICATION

The present report corresponds to deliverable 2.3.3 of Work Package 2 – Ship Motions Hazards of safety At Speed (S@S). It presents the works carried out in Sub-tasks 2.3.3 for the implementation of a risk model for operational practice. The risk model dealt with in the present document is associated with dynamic stability, and in particular with broaching phenomenon.

The prediction of dynamic stability of a ship is a complex matter which requires sophisticated numerical models. The objective of the project being to implement simple risk models in the Project Tool, a simplified approach has been adopted. It is based on the IMO guidance to the master for avoiding dangerous situations in following and quartering seas. This guidance defines some criteria and associated safe marginal and dangerous zones from various dynamic stability hazards points of view: surf-riding / broaching, successive waves attack, synchronous rolling and parametric rolling.

Numerical simulations using a code developed at SSRC for the ship motions in astern seas have been performed on the SuperseaCat 3 vessel to determine the broaching boundaries (dangerous, marginal and safe zones) for variations of ship length, breadth, draught, speed, as a function of wave incidence. These calculations showed that the IMO rules are very conservative.

The IMO rules have been implemented in two Excel worksheets:

- A first worksheet corresponds to a short term analysis and indicates if the ship is in safe, marginal or dangerous zone for a given wave amplitude and incidence.
- The second worksheet makes a long term analysis of dynamic stability by combining a wave scatter diagram and a wave incidence distribution to provide a global risk of capsize. This risk is weighted by a global crew performance factor (Human Factor Quotient) taken from WP1.

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2. INTRODUCTION

The present report corresponds to deliverable 2.3.3 of Work Package 2 – Ship Motions Hazards of safety At Speed (S@S). It presents the works carried out in Sub-tasks 2.3.3 for the implementation of a risk model for operational practice. The risk model dealt with in the present document is associated with dynamic stability, and in particular with broaching phenomenon.

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These works and the implementation of the two worksheets are described in the following sections.

3. IMPLEMENTATION OF BROACHING MODEL

As part of the research study, numerical simulations were carried out to broadly identify capsizing boundaries of high-speed craft at operational speed and close range. For these purpose, the high-speed vessels were numerically tested using the numerical code developed at SSRC for the ship motions in astern seas [1].

The code in its current form uses frequency dependent coefficients, incorporating memory effects in random waves with a new axis system that allows straightforward combination between seakeeping and manoeuvring model whilst accounting for extreme motions. Wave forces are estimated through incident and diffracted wave components while the PD (proportional differential) type autopilot system is employed to keep the vessel on course. Due to the unique nature of ship motions in extreme astern seas where, since the encounter frequency is very low hydrodynamic lift forces are greater than wave making forces, it is appropriate to employ manoeuvring (hull) force models for the solutions. Therefore, the code also includes manoeuvring (hull) force models. Hydrodynamic coefficients in the model can be obtained either experimentally or using common empirical methods. In the current model, those coefficients have been obtained empirically [1]. Furthermore, other major external force components such as propeller, resistance and wind forces are calculated using semi-empirical methods.

The numerical code has already been verified against a number of different types of vessels. Further details on the code can be found in [1].

3.2. Numerical Prediction

Two kinds of results are presented:
The results for the basis vessel are given below to see capsizing boundary
The basis vessel's dimensions (length, breadth, draft) and speed are changed. These results are also presented in an Excel sheet and explanations are provided how to use these results for designer.

In order to identify a capsizing boundary for the vessel, the vessel has been numerically simulated in a range of environmental parameters for two speeds (40 knots, 35 knots Fn=0.7 and 0.612, respectively). Here, capsizing boundaries were defined in terms of wave steepness, H/λ, with respect to wave direction, χ (angle from stern; 0° is stern waves).. The simulations were carried out for wave direction χ, of 0, 15, 30, 45, 60 degrees, respectively. The wave length to ship length ratio is chosen as 1.0 for which the wave celerity could be close to the vessel speed thus waves may overtake the vessel in which dangerous situations such as broaching-to could occur. The simulation time was set for 300 seconds. The autopilot parameters were selected from similar vessels which were tested previously.

It should be noted that these simulations were carried out using steep regular waves. Numerical and experimental studies indicate that the most critical conditions in which the ship is likely to face dangerous situations or capsizing are very steep regular waves, rather than long and short crested irregular waves [2]. Therefore, the numerical runs are executed in regular wave environments but they could be indicator for the irregular wave motions.

Here, Figure 1 illustrates the capsizing boundary for the vessel in Fn=0.7 (40 knots). Figure 2 illustrates the results for Fn= 0.612 (35 knots).

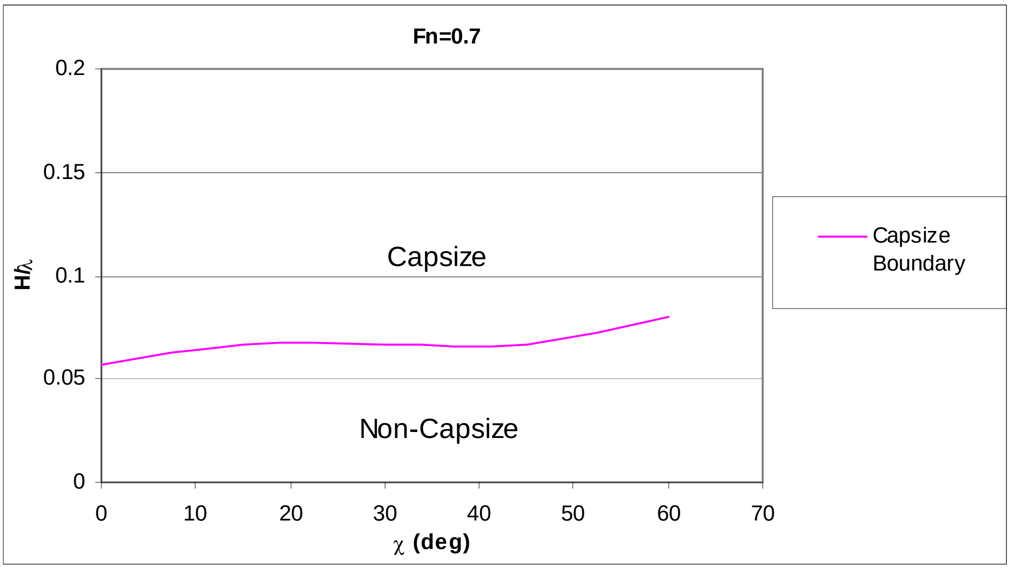

Figure 1: Capsizing boundaries of the vessel with λ/L=1.0 for different wave steepness (H/λ) with respect to the wave direction (χ) in Fn=0.7 (40 knots)

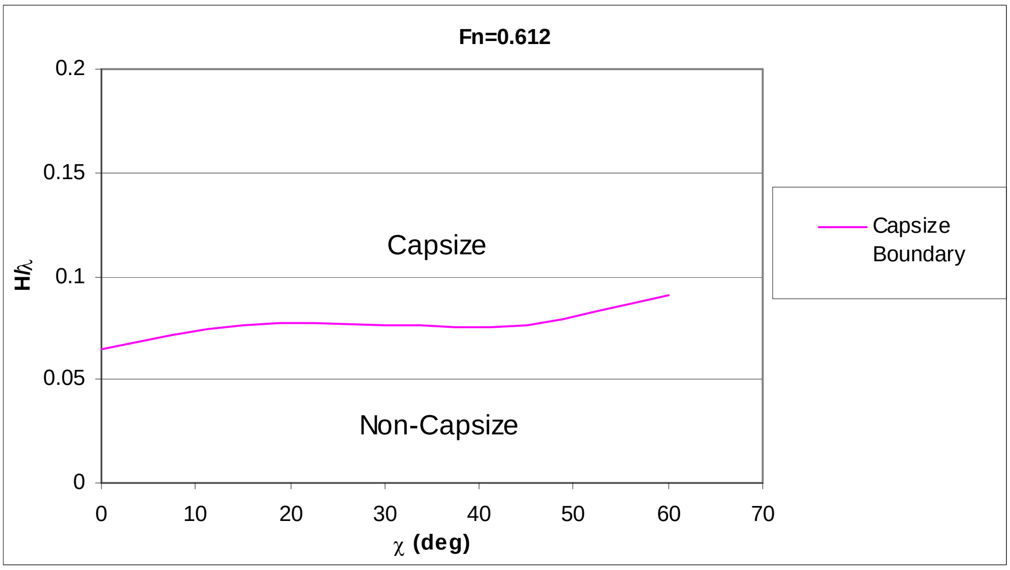

Figure 2: Capsizing boundaries of the vessel with λ/L=1.0 for different wave steepness (H/λ) with respect to the wave direction (χ) in Fn=0.612 (35 knots)

In the above figures capsizing occurs due to either direction of loss (broaching-to) or sudden (sub-harmonic) build-up of roll motion. In terms of occurrence of capsizing mode the latter is more frequent than the former.

In terms of the effect of wave direction, pure following seas or 0 degrees autopilot course to the wave direction is seen as the most dangerous condition. Here, the ship capsizes just over 5 metres wave height for 40 knots operation speed (Figure 1). For a relatively slower speed the threshold of the wave height slightly increases (Figure 2). As wave direction getting closer to beam seas, the vessel can withstand the higher wave heights.

In an attempt to investigate the ship motions in terms of HSC passenger comfort, one of the important parameters, roll acceleration were plotted for aforementioned two conditions in Figures 3 and 4.

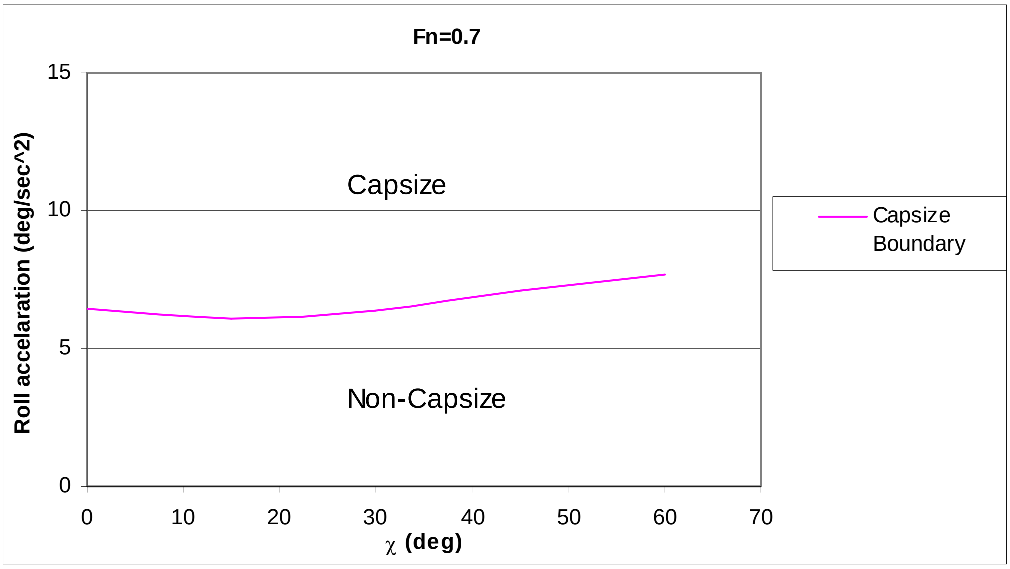

Figure 3: Capsizing boundaries of the vessel with λ/L=1.0 for roll acceleration with respect to the wave direction (χ) in Fn=0.7 (40 knots)

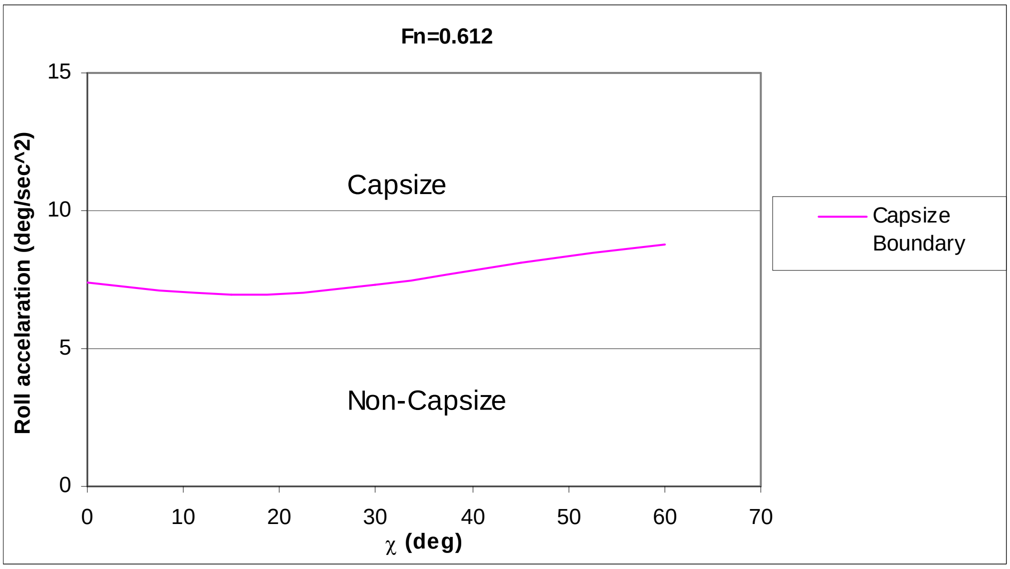

Figure 4: Capsizing boundaries of the vessel with λ/L=1.0 for roll acceleration with respect to the wave direction (χ) in Fn=0.612 (35 knots)

Although, there is small disturbance between 0 and 15 degrees wave direction, overall roll acceleration linearly increases while wave direction is getting closer to beam sea condition. In pure following sea condition, since the ship was captured by the wave and moving with the wave speed, the acceleration threshold seems less than in other sea conditions. While the wave direction is getting closer to beam sea condition there is a harmonic build-up of the roll motion before capsize and that is triggered by the increased roll acceleration. It is seen from Figure 4 that when the ship speed reduces the capsize boundary increases for roll acceleration.

In general, the vessel could be assumed as safe for dangerous conditions if the general guidelines [3], which recommend to reduce the speed and to change the autopilot course towards the beam seas direction in case of following or quartering seas condition, can be followed during the operation.

3.3. Use of Model

A model allowing to identify dangerous situations that likely to occur during ship motion in following and quartering seas has been implemented in the Excel file S@S_WP2_broaching_v*i.ii*.xls. It is based on IMO guidelines [3] and a parametrical study from the in-house numerical tool at SSRC [1].

Here some instructions are given for the reader. The excel graph should be considered at three steps based on IMO guidelines [3] accompanied by the graphs and figures.

First, principal particulars and operational characteristics of the ship can be appointed (L, B, d, χ, V). Here χ indicates the wave direction. All graphs can be used for the conditions of wave length > 0.8 × ship length and $H_{1/3}$ (significant wave height) > 0.04 ship length.

First step:

Here the figure presented for surf-riding occurrence boundaries with respect to ($V/\sqrt{L}$). For any chosen **V (speed), L (ship length)** parameters **at the beginning** the zone can be identified.

Second step:

Here, for the period described and estimated in the IMO guidelines [3], whether vessel operates in the dangerous or safe zones can be identified. **Wave length (λ)** and **speed (V)** which are appointed **at the beginning** are used for this step

Third step:

Following the IMO guidelines, further numerical simulations were carried out for various parameters (L, B, d, V) to clarify the knowledge on their effects.

However, it should be noted that this parametrical study has been carried out independently of previous criteria and considering the design values of the SSC3. Here, for instance when the effect of L (ship length) is investigated other design parameters were assumed constant, therefore no hull optimisation was carried out. The aim of this study was to identify the boundaries of dangerous zones (mainly broaching) for the SSC3 in each of those 4 design parameters. These zones are only identified for this vessel. Another important point is to determine how to define the marginal and dangerous zones for the vessel. Here, it based on the assumption that, for marginal zone, while vessel can capsize in one condition, she might not capsize if initial positions of the vessel or/and control parameters (heading/rudder) are changed for the same condition. As for dangerous zone, the vessel capsizes despite the changes in the aforementioned parameters.

First, the effect of length can be seen for a value appointed **at beginning**. The model will display the zones for this appointed value.

Here, it could be seen that while ship length (L) falls into the surf-riding zone in actual IMO criteria, the parametric analysis indicates that ship length (L) is in marginal zone. There are numbers of factors that could explain this difference.

First, the IMO criteria were given for surf-riding zone which could be seen transiently and does not always result in capsizing or associated with broaching phenomena. Furthermore, the IMO criteria were specifically given to ship's master to guide in terms of operation rather than to try to define stability and design criteria [1]. However, the boundaries of dangerous situations in the parametrical study were defined in terms of occurrence of capsizing. It could be said that for marginal zone, there is also chance to face dangerous situation like surf-riding which does not always results with capsizing.

Second, the IMO criteria, which are based on recorded marine accidents and extensive numerical studies, are rather conservative to provide broad safety zone in terms of operation. For instance, if we do not change any other parameter, the ship length (L) should be more than 450 m to avoid surf-riding zone which is extremely unrealistic. As aforementioned in first condition, design parameters are not fully taken into account. The modification for high-speed crafts, especially in aft hull form, could significantly change directional stability capability of the ship which is defining indicator for surf-riding and broaching. These kinds of effects are not fully reflected in IMO guidelines.

Following this condition, thirdly, it could be mentioned that since model experiments, which are the most accurate prediction methods, are not available for hydrodynamic coefficients and also a realistic optimisation was not carried out for the change of ship length (L), the outcome of the parametric study should be considered with caution. Marginal zone means obviously that the ship could still face capsizing due to the change of some control and operational parameters.

Later, the same procedure is followed for ship beam (B) appointed **at beginning**. It will display the zones for this appointed value.

The third part of step 3 involves the effect of draught. Similarly, for ship draught (d) appointed **at beginning**, it will display the zones for this appointed value.

The same approach is applied for the effect of speed as the last part. When, it is required to see these effects, in case of change of parameter at the beginning, each parameter should be consulted separately. For instance, when L and B are changed, the tool will display the results for L and B, respectively. This is due to the fact that in the developing of these graphs, the parameter concerned (such as L) is changed while other parameters and speed are assumed constant.

It should also be emphasized throughout the studies on broaching and other dangerous conditions in following and quartering seas that the capsizing phenomenon has been exploited using boundaries rather than identifying percentage of capsizing risk. For instance, IMO guidelines [3] display the boundaries where vessel can face dangerous conditions or ultimately capsize. Throughout the studies on broaching and other dangerous conditions in astern seas, the priority was to define boundaries of those dangerous conditions in terms of design and operational (speed, heading) parameters. IMO guidelines were defined based on data obtained from marine accidents and extensive experimental studies in Japan [1], [3]. Percentage of capsize risk due to broaching was given as percentage of capsizing occurred due to broaching in recorded marine accidents.

4. IMPLEMENTATION OF THE LONG TERM DYNAMIC STABILITY RISK MODEL

4.1 General description of the model

In order to deliver a probability of capsize due to dynamic stability failure, the IMO guidance rules have been implemented in a long term analysis, in the same way as implemented for the availability model [4].

Thus, the operating and sea state conditions that will be encountered by the ship are defined as a probability distribution of wave incidences with respect to the ship and by a wave scatter diagram (probability distribution of (Tz, Hs), Tz – zero up-crossing period, Hs – significant wave height). The ship speed is considered constant for all these conditions (ship speed input by operator). Wave incidence and sea state (Tz, Hs) are considered to be independent variables.

The probability of being in dangerous surf-riding/broaching, marginal surf-riding/broaching, dangerous successive waves attack, dangerous synchronous rolling and dangerous parametric rolling zones is determined separately for each phenomenon by applying the IMO procedure for each condition wave_incidence(i), and wave characteristics Tz(j), Hs(i). For each phenomenon, and each condition, the occurrence Γ(i,j) is either 0 (safe) or 1 (dangerous or marginal). Then, the global probability of occurrence of each phenomenon is given by:

$$\sum_i \sum_j P(wave\_incidence(i)) \times P(Tz(j), Hs(j)) \times \Gamma(i, j)$$

Then these probabilities are weighted with a factor giving the risk of capsizing when the phenomenon occurs (1 means capsize at each occurrence).

Then the weighted probabilities are summed to obtain a global probability of capsizing.

The obtained probability of capsizing assumes that the crew does not follow the IMO guidance. Otherwise, the dangerous or marginal (for surf-riding / broaching) situations should be avoided and the risk of capsizing due to dynamic stability loss would be zero. Consequently, the probability of capsizing is weighted by the factor (1-HFQ), where HFQ is the Human Factor Quotient calculated in WP1 and demonstrating the crew performance. For a very performing crew, HFQ=1 and the weighting factor is zero. For a poor performing crew, HFQ=0 and the weighting factor is 1, which means that the dangerous or marginal situations will not be avoided.

Following the IMO procedure, dangerous or marginal surf-riding/broaching and dangerous successive waves attack situations are investigated only if:

- The wave length is larger than 0.8 x ship length between perpendiculars
- The significant wave height is larger than 0.04 x ship length between perpendiculars
- The wave direction is 0° to 45° from the stern

It is not clear from the IMO guidance whether the constraints applied for broaching should be applied also on synchronous and parametric rolling. Since this does not seem physically relevant, it has been decided to search the occurrence of synchronous rolling and of parametric rolling whatever the wave length, height and direction with respect to the ship.

The IMO guidance indicates that synchronous (resp. parametric) rolling occurs when the wave encounter period is close to the roll natural period (resp. half the roll natural period). This has been implemented as synchronous (resp. parametric) rolling occurs when the difference between the wave encounter period and the roll natural period (resp. half the roll natural period) is lower or equal than 10% of the roll natural period (resp. of half the roll natural period).

For successive waves attack, a difference has been detected on the dangerous zone boundaries given in the text (encounter wave period/mean wave period between 1.5 and 2.8) and the ones represented on figure 3 of the guidance (encounter wave period/mean wave period between 1.36 and 3.08). The latter have been assumed to be correct.

4.2 Implementation of the model

The dynamic stability model has been implemented in the Excel file S@S_WP2_Dynamic_stab_v*i.ii*.xls and coded in Visual Basic. The file contains three worksheets:

- Main: where the design parameters, speed and HFQ value are input by the operator, the capsizing calculation is run and the results displayed.
- Scatter diag.: where the wave scatter diagram is input.
- Incidence distrib.: where the wave incidence distribution with respect to the ship is input.

4.3 Use of the model

The colour code used is as follows:

- Light green cells: input data – to be entered by operator.
- Yellow cell: result of the model
- Grey cells: intermediate data calculated by the model.
- Green cells: information for guiding the operator.

Some 'input' cells present comments defining their contents and their default values when applicable.

The model should be used as follows:

- In 'Main' worksheet, input of design parameters values, of ship speed and of the HFQ value to be used.
- Check/modifications of wave scatter diagram ('Scatter diagram.' worksheet), wave incidence probability distribution ('Incidence distrib.' worksheet).
- In 'Main' worksheet, press 'DYNAMIC STABILITY CALCULATION' button. The number of conditions (wave incidence, Tz, Hs) to be calculated and the progress (in %) of the calculation is displayed. Once the calculation is finished, 'Completed' appears for progress and the capsizing probability value is displayed in the yellow cell.

4.3.1 Worksheet 'Main'

This worksheet is the main interface with the user. It contains fields corresponding to input parameters, a button 'DYNAMIC STABILITY CALCULATION' which starts the dynamic stability calculation, and fields presenting the results.

The input parameters are set to default values corresponding to the SuperSeaCat 3. The default values are indicated in comment cells which are displayed when the mouse pointer is located on the input cells.

If the roll natural period is unknown, set it to zero. The program will then estimate it from the waterline breadth and the transverse metacentric height by the IMO recommended formula:

$T_N=2 \times (0.373 + 0.023 \times B / T - 0.043 \times Lpp / 100) \times B / (GM_T)^{1/2}$.

Where Lpp is the length between perpendicular, B is the waterline breadth, T is the draught and GM_T is the transverse metacentric height.

It should be noted that the main design parameter used by the IMO criteria is the ship length. The ship breadth, draught and GM_T are used only to calculate the roll natural period (if not given by the operator), which is used only for synchronous and parametric rolling.

Intermediate results are also displayed in grey cells:

- Number of calculated conditions: this corresponds to the number of wave Hs, Tz and incidence conditions for which the horizontal and vertical accelerations will be calculated at each user selected location. This number corresponds to number_Hs x number_Tz x number_wave_incidences.
- Progress: this value represents the progress of the calculation in percent. It is updated continuously during the calculation and displays 'Completed' when finished

The results are presented in a chart. First, the probability for the ship to be in the various dangerous/marginal zones is presented for each phenomenon. Each probability is then weighted by a factor corresponding to the probability of capsize when in the corresponding zone. Then the weighted probabilities are summed and multiplied by (1-HFQ) to obtain the total capsizing probability.

The weighting factors are set to 1, except for the marginal broaching zone for which the factor is set to 0.5. This means that the ship will capsize each time it is in the dangerous zones and therefore probably represents an overestimation of the risk of capsizing, due to the conservative nature of the IMO guidance. The operator can adapt these weighting factors to obtain more realistic probabilities.

4.3.2 Worksheet 'Scatter diag.'

In this worksheet, the operator defines the scatter diagram of the waves that the ship will encounter. The scatter diagram gives the probability of occurrence of each couple Tz – zero up-crossing period, Hs – significant wave height.

The operator should input the Tz (in seconds) and Hs (in meters) values, as well as the corresponding probabilities. The maximum number of Hs and Tz is 15, but it is possible to use fewer values, provided that the probabilities are always filled from the upper left corner of the chart. The sum of probabilities should be equal to 1. The actual sum is displayed in the lower right corner of the diagram. If the sum is different from one, the program will automatically divide all the probability values by the sum. This can also be done by pressing the 'Read diagram' button from the worksheet.

As default, a Mediterranean Sea wave scatter diagram, modified for more resolution at the lower end of the spectrum, is used.

4.3.3 Worksheet 'Incidence distrib.'

In this worksheet, the operator defines the wave incidences that the ship will encounter. The wave incidences are defined with respect to the ship longitudinal axis and 180° is head sea.

The wave incidences are considered independent from the sea state, that is all combinations of defined wave incidences and (Tz, Hs) will be calculated.

Up to 8 incidences can be used. The operator has to input the wave incidence (in deg.) and the corresponding probability of occurrence. Less than 8 incidences can be used, provided that the chart is filled from the first left column of the chart.

The sum of probabilities should be equal to 1. The actual sum is displayed in the lower right corner of the diagram. If the sum is different from one, the program will automatically divide all the probability values by the sum. This can also be done by pressing the 'Read' button from the worksheet.

4.4 RESULTS AND SENSITIVITY

Using all default values for SSC3, the predicted risk of capsizing is 0.012 and comes mainly from dangerous surf-riding/broaching zone and from dangerous synchronous roll zone. It is probable that this value overestimates the risk of capsizing and that the weighting factors should be reduced.

Since, for the SSC3 default value and the operational conditions used, the main risk is broaching, the main parameters affecting the capsizing risk are the ship length, speed and the crew performance (and of course the operational conditions, in particular for wave incidences between 0° and 45° from stern).

A 20% increase of the ship length will reduce the capsizing risk by 42%.

5. CONCLUSIONS

The works performed in Sub-tasks 2.3.3, presented in this document, concern the implementation of models related to dynamic stability and in particular to broaching.

The models are based on IMO guidance to the master for avoiding dangerous situations in following and quartering seas, and on numerical simulations performed by SSRC using a manoeuvrability code.

A short term and a long term model have been implemented in two separate Excel worksheets and are joined to the present deliverable 2.3.3 for integration in the Project Tool.

6. REFERENCES

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