ShipX Vessel Responses (VERES)

User's Manual

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Contents

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1 INTRODUCTION

1.1 General

The study of wave induced vessel responses is essential in the design of new ships. To optimize the operability of the vessel in a seaway, it is important to minimize the motions of the ship. If the loads are decreased, the steel weight can be reduced. Further, hydrodynamic loads and motions are important from the standpoint of safety of the ship and its crew. The SHIPX Vessel Responses Plug-In is a SHIPX implementation of the VEssel RESponse program (VERES), which is intended to be a tool which can be used in early design, in defining and evaluating model tests and in obtaining supplementary results. The program calculates:

- Motion transfer functions in six degrees of freedom
- Relative motion transfer functions
- Motion transfer functions at specified points
- Global wave induced loads[1] (forces and moments)
- Short term statistics of the above mentioned
- Long term statistics of the above mentioned
- Postprocessing of slamming pressures
- Operability (operability limiting boundaries, operability diagrams for a given sea state and percentage operability)
- Time simulations of motions and loads including important non-linear effects

Here, *motions* includes both displacements, velocities and accelerations.

Please note that the options you have available will depend on what kind of license you have. Some modules may require an additional license.

All computer programs for calculation of ship motions are based on assumptions and simplifications with respect to theory and hull form representation. In order to use the program in practical design, it is important to be aware of the limitations of the program, and to which extent the results are valid. In theoretical terms the theory applied in the VERES program is said to be based on linear, potential, strip theory. The relevance of these restrictions is that the theory is developed for moderate wave heights inducing moderate motions on a ship with a length which is much larger than the ship breadth and draught. In addition the change in cross-sectional area as function of longitudinal position should be slow. Consequently, large ship motions and large wave heights will restrict the validity of the results. However, ship motions obtained by the program show good correlation with experiments even at wave conditions which are outside the limits of the theory. Hence, the program may be used to investigate a wide range of conditions bearing in mind that the accuracy is reduced as the program is stretched to its limits.

1.2 Installation

ShipX is installed trough the ShipX Website located at http://shipx.marintek.sintef.no/. Please follow the instructions on the website carefully to ensure proper installation of the software.

[1]With *wave induced*, we are referring to the dynamic part of the global loads, as opposed to the steady global loads, which are the loads that are also present in calm water.

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Information about the latest updates on the ShipX Vessel Responses Plug-In can be found through the **Help** Menu in ShipX where a separate **Update Log** submenu gives access to update logs for the installed ShipX Plug-Ins.

1.3 Overview

The SHIPX Vessel Responses (VERES) program is divided in two major calculation utilities. A Main Program that calculates the transfer functions for motions and loads (frequency domain) as well as performs time simulations, and a Postprocessor which helps you with reporting and data presentation as well as further calculations based on the transfer functions.

Figure 1 shows the steps required to calculate the percentage operability for a vessel when applying frequency-domain calculations.

1. The Main Program calculates the motion transfer functions in six degrees of freedom.
2. The Postprocessor combines the motion transfer functions with the specified wave spectra to obtain the response spectra (short term statistics).
3. The response spectra are combined with the specified seakeeping criteria to obtain operability limiting boundaries.
4. The operability limiting boundaries combined with the specified wave scatter diagram are summed up over the sea states to obtain the percentage operability.

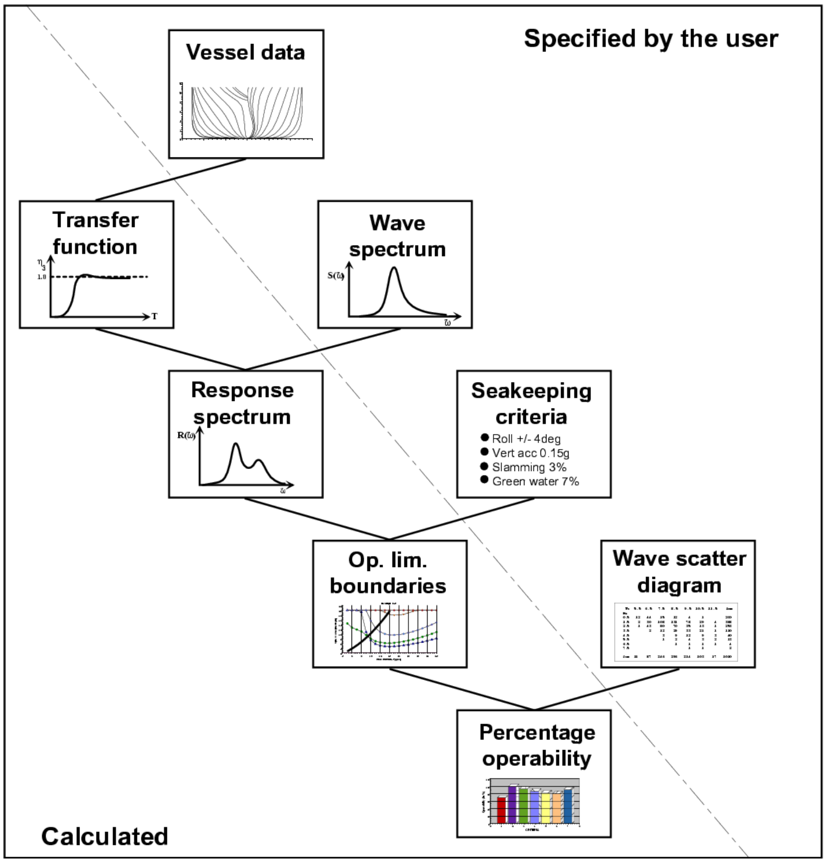

Figure 1: The principal calculations performed by VERES to obtain the percentage operability.

1.3.1 Formulations

VERES can be applied on monohulls and catamarans at low as well as high speed. At low and moderate speeds, Froude numbers [2] up to 0.25 - 0.30, you can solve the problem by the traditional strip theory, developed by Salvesen, Tuck & Faltinsen [21]. At higher speeds, Froude numbers larger than approximately 0.4, the high speed formulation developed by Faltinsen & Zhao [7] can be applied. In the Froude number range of 0.3-0.4, a comparison between the two methods should be carried out. A formulation for high-speed catamarans is also included. This formulation accounts for hull interaction effects between the two hulls. The program offers capabilities of performing calculations in the frequency domain as well as time domain simulations. In the time domain simulations, non-linear effects due to restoring and Froude-Krylov forces are accounted for (i.e. takes account for the above water hull form for these effects).

1.3.2 Roll damping

The program can include viscous roll damping from hull friction and bilge keels, as well as the effects of roll stabilizing tanks and active roll stabilizing fins.

1.3.3 Motion control

The program can include the effects from passive free-surface roll stabilizing tanks, as well as active and passive U-tube tanks, rudder control and active and passive fins such as roll stabilizing fins and T-foils. The program can also include the effects from air cushions on Surface Effect Ships. *To include these effects, they need to be included in your license.*

1.3.4 Short term statistics

Short term statistics of the data from the calculations includes

- Standard deviations
- Significant values
- Expected maximum in a seastate of a given duration (e.g. 3 hours)
- Average of the 1/nth largest values
- Response zero-upcrossing period
- Plotting of response spectra

The calculations are based on selected standard wave spectra (Pierson-Moskowitz/Bretschneider, JONSWAP and Torsethaugen), as well as measured wave spectra, and can be performed for long- and short-crested seas.

1.3.5 Long term statistics

Long term statistics of the data from the calculations can be calculated based on a specified scatter diagram. The long term statistics can be calculated for each wave heading separately, or with a specified probability of each wave heading. A speed curve specifying the vessel speed as function of significant wave height can also be specified.

[2] The Froude number is defined as $Fn = V/\sqrt{gL}$, where V is the ship speed in (m/sec), g is the acceleration of gravity in (m/sec^2) and L is the vessel length between the perpendiculars in (m).

1.3.6 Operability

The calculation of operability is available in three modes:

1. Operability limiting boundaries presented as limiting significant wave heights as a function of the wave period
2. Operability diagram
3. Percentage operability

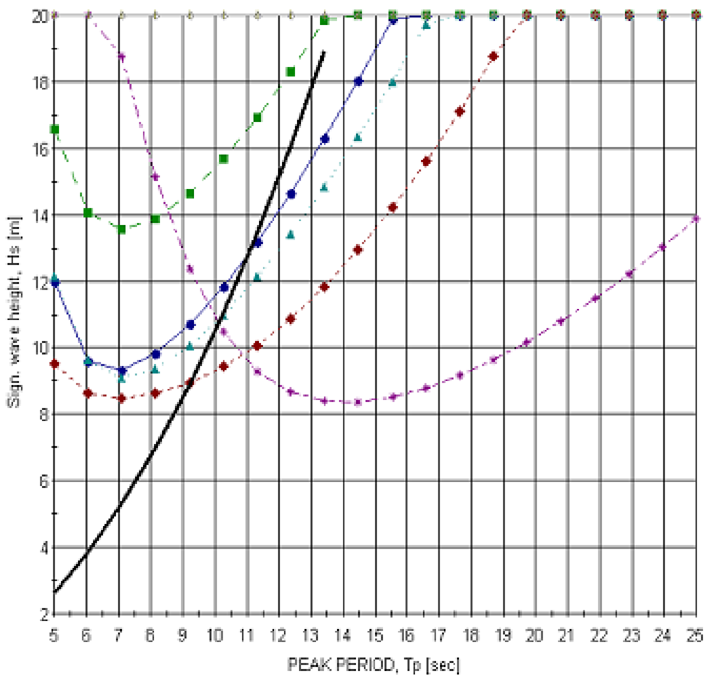

Figure 2: Operability limiting boundaries.

The operability can be calculated based on the following criteria:

- Motions in six degrees of freedom
- Relative vertical motions
- Probability of slamming
- Probability of green water on deck
- Probability of air exposure
- Vertical accelerations according to ISO 2631/3-1985 (motion sickness)
- Forces in body-fixed coordinate system (LON, LFE and VFE)
- Motion-Induced Interruptions (MIIs)
- Motion Sickness Incidence (MSI) according to McCauley et al.
- Motion Sickness Incidence (MSI) according to ISO 2631-1:1997
- Motion Sickness Dose Value ($MSDV_z$)
- Frequency-weighted accelerations a_w, a_{zw} and a_{yzw}

- Combined body-fixed accelerations a_{xyz} and a_{yz}

1.3.7 Time-domain calculations

The ability to perform time-domain calculations is also available in VERES. In the time-domain calculations, the linear hydrodynamic coefficients of the ship hull can be combined with non-linear wave excitation forces and restoring forces, as well as non-linear effects from motion control systems.

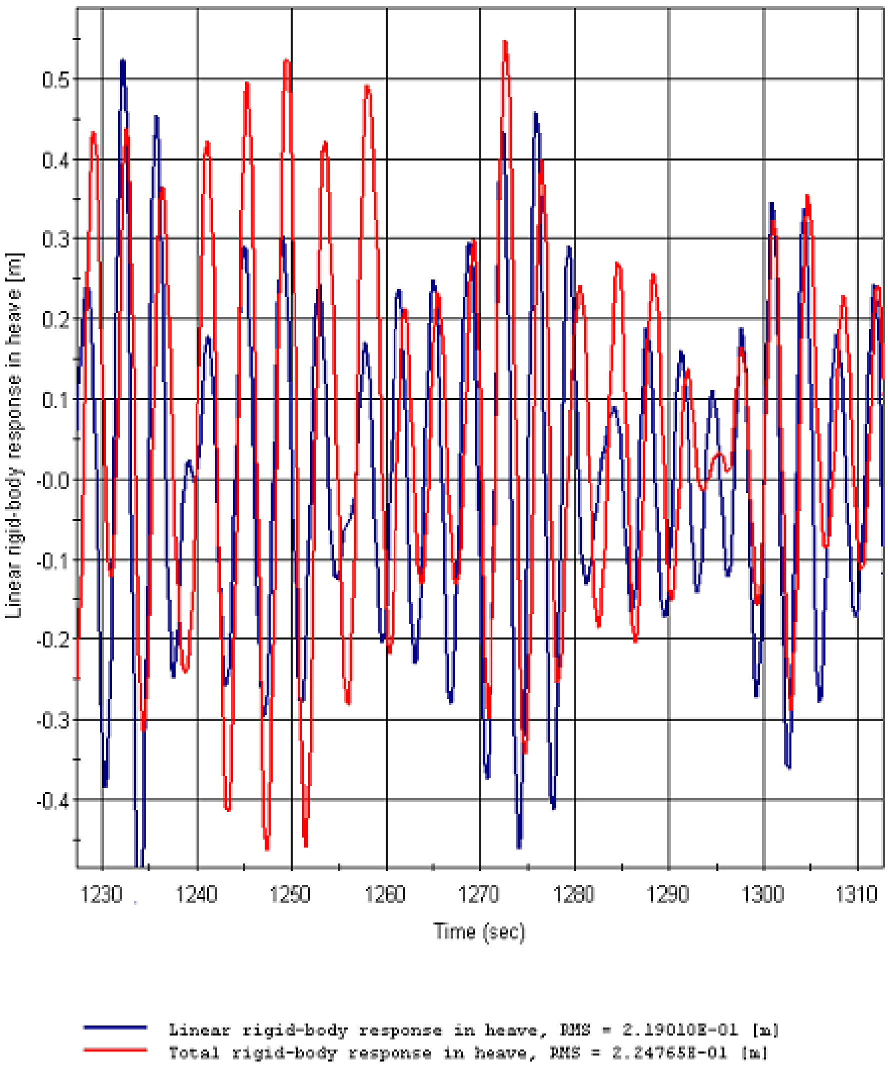

Figure 3: Time-domain simulations (linear and non-linear heave responses).

2 HANDS–ON INTRODUCTION TO VERES IN SIMA

This chapter gives a hands-on introduction to the use of ShipX Vessel Responses in the Sima user interface by going through the process of importing a ship, defining a loading condition, and specifying the input needed to perform a ship motion calculation and operability study. The example is given in a step-by-step manner, trying to point out features of interest as they occur.

Section 2.2 gives the introduction to the main program, while Section 2.3 presents the Postprocessor.

2.1 Outline

A typical application of the VERES program is to calculate the ship motions in regular as well as irregular seas. The example in this section shows the different steps in the calculation process and can serve as training for a new user of the program. The hull used for this exercise is a standard research vessel, called "RV" (Figure 4) and can be found in the ???? folder together with the other files needed for this example. This hull is used throughout the manual as reference calculation, and the main characteristics are given in Table 1.

L_{pp}	B	T	∇	C_B
60.5 m	14.115 m	5.5 m	3100 tonnes	0.640

Table 1: Main characteristics for the S-175

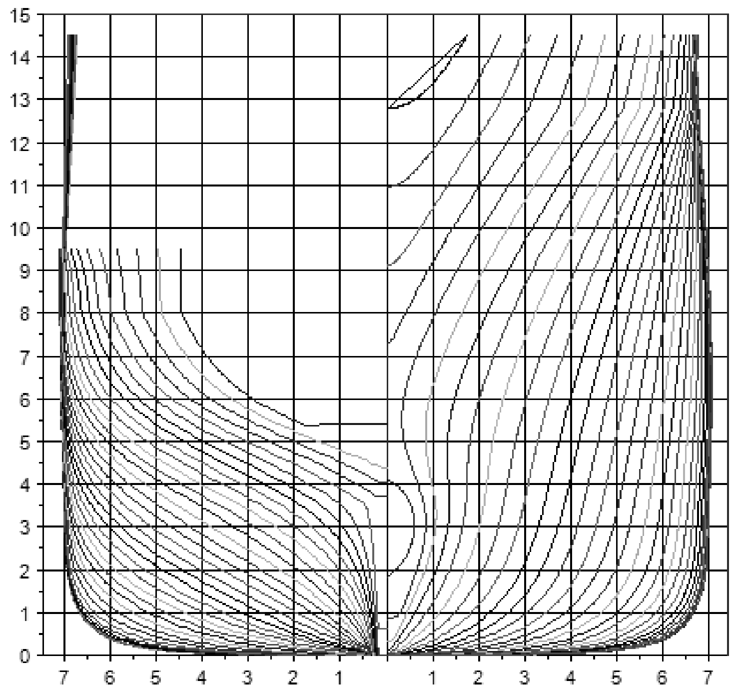

Figure 4: The RV hull form

Section 2.2 gives a brief introduction to the Vessel Response calculation part of the Plug-In, defining input data for the RV vessel and explains how to import the hull lines into ShipX, define the loading condition and run the program. A short description of the Postprocessor is given in Section 2.3.

2.2 Calculating vessel responses in waves

The Vessel Response calculation Run provides an easy way for the user to give and check the input data needed to perform vessel response calculations, as well as performing the actual computations. The example includes the definition of a new input data set in a step–by–step manner, shows how to run a simple data check, and finally, how to run the main computations.

2.2.1 Importing the hull lines and define loading condition

1. Right-click the Navigator window and select **New – ShipX Task**. In the window that appears, us the default name, and press **Finish**.
2. Right-click the **ShipXTask** in the **Navigator** window, and select **Import**. In the **Import** dialog (Figure 5) expand the **ShipX Geometry** option, select the **Ship Exchange File** option and click **Next**. Locate the file RV.shipx_ship in </shipx/install/directory>/plugins/no.sintef.ocean.veres.examples_<version-number>/examples folder and press **Finish**. If you wish to view the geometry file, you can double-click **RV** in the **Navigator** window. You will then see a section view of the offset-points as shown in Figure 4. A 3D view of the ship model may be obtained by pressing **Show hull in 3D** in the upper-left corner of the dialog.

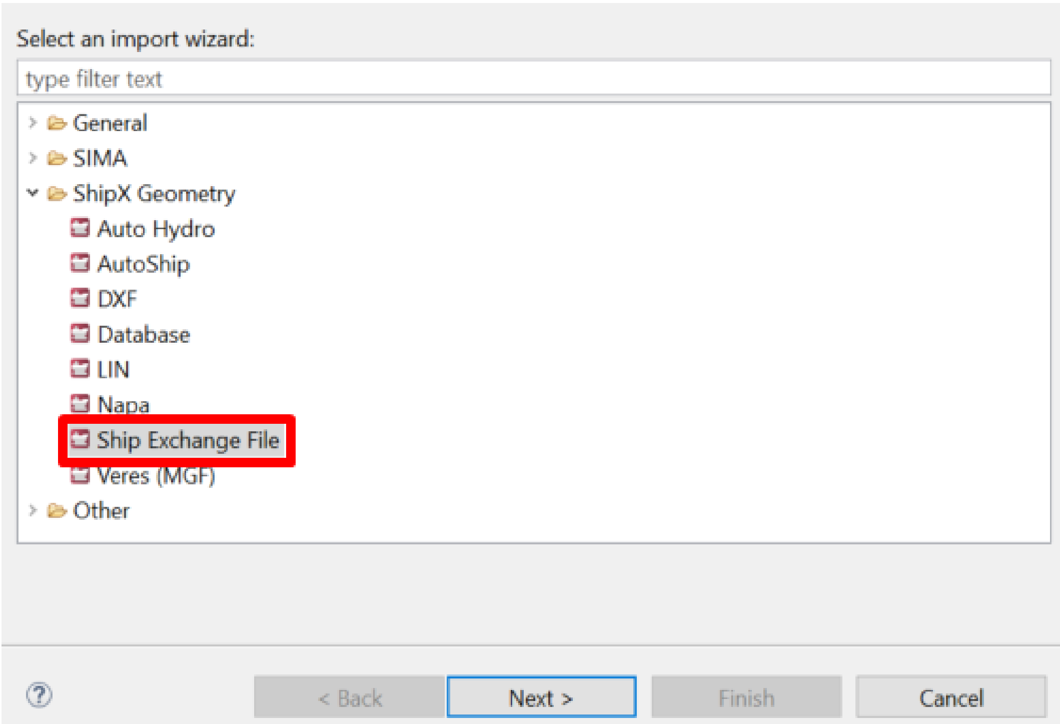

Figure 5: Ship geometry import dialog

3. In the **Navigator** window (Figure 6), double-click the **Design Loading condition** (or right-click and select **Edit**). The loading condition input dialog, shown in Figure 7, will appear in the bottom right window. Click the **Wind force** tab at the top of the input dialog and disable the **Wind Included** option.

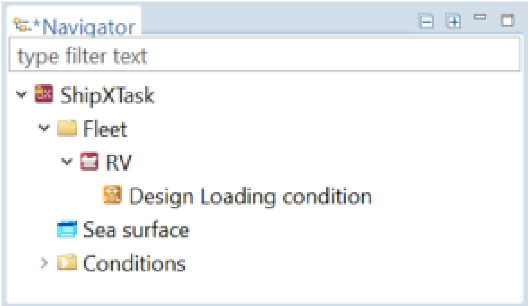

Figure 6: Navigator window

You have now imported the ship hull lines into ShipX and defined the loading condition and should now be ready to create a Vessel Response calculation Run.

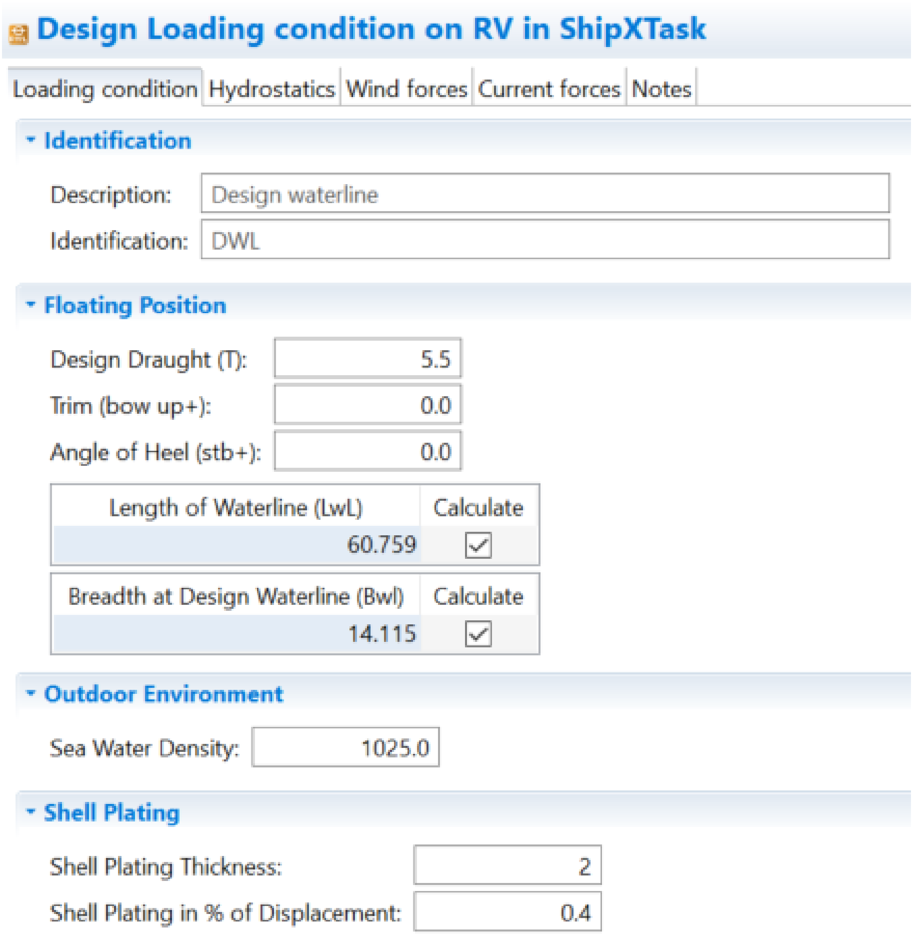

Figure 7: Input of loading condition data

2.2.2 Create a Vessel Response calculation Run

Start by right-clicking **Design Loading condition** in the **Navigator** window, select **New** and then **Veres Run**. The main dialog window for this calculation will appear in the bottom right window.

1. Under the *Main* tab, the vessel geometry and calculation method are specified. By default, ShipX will auto–generate a geometry file for the calculations based on the hull input in ShipX. If you wish to override this auto–generated file, you may remove the checkmark in the checkbox “Automatically generate geometry file” and specify the geometry file name manually or browse for it. The calculation method is selected by clicking on the preferred computational method under **Calculation options**. In the present example, the standard 2D Strip-theory formulation of Salvesen, Tuck & Faltinsen is to be applied (Figure 8).

2. After selecting a geometry file and calculation method, the main particulars of the vessel must be given in the **Vessel** tab. Input the vertical center of gravity (**VCG**), **Roll radius**, **Pitch radius** and **Yaw radius**, as shown in Figure 9. Note that the radii of gyration are given relative to the center of gravity (see Section 3.3.5 for details). GM values can be entered manually by removing the checkmark next to “Calculate GM” under **Metacentric heights** in the input dialog.

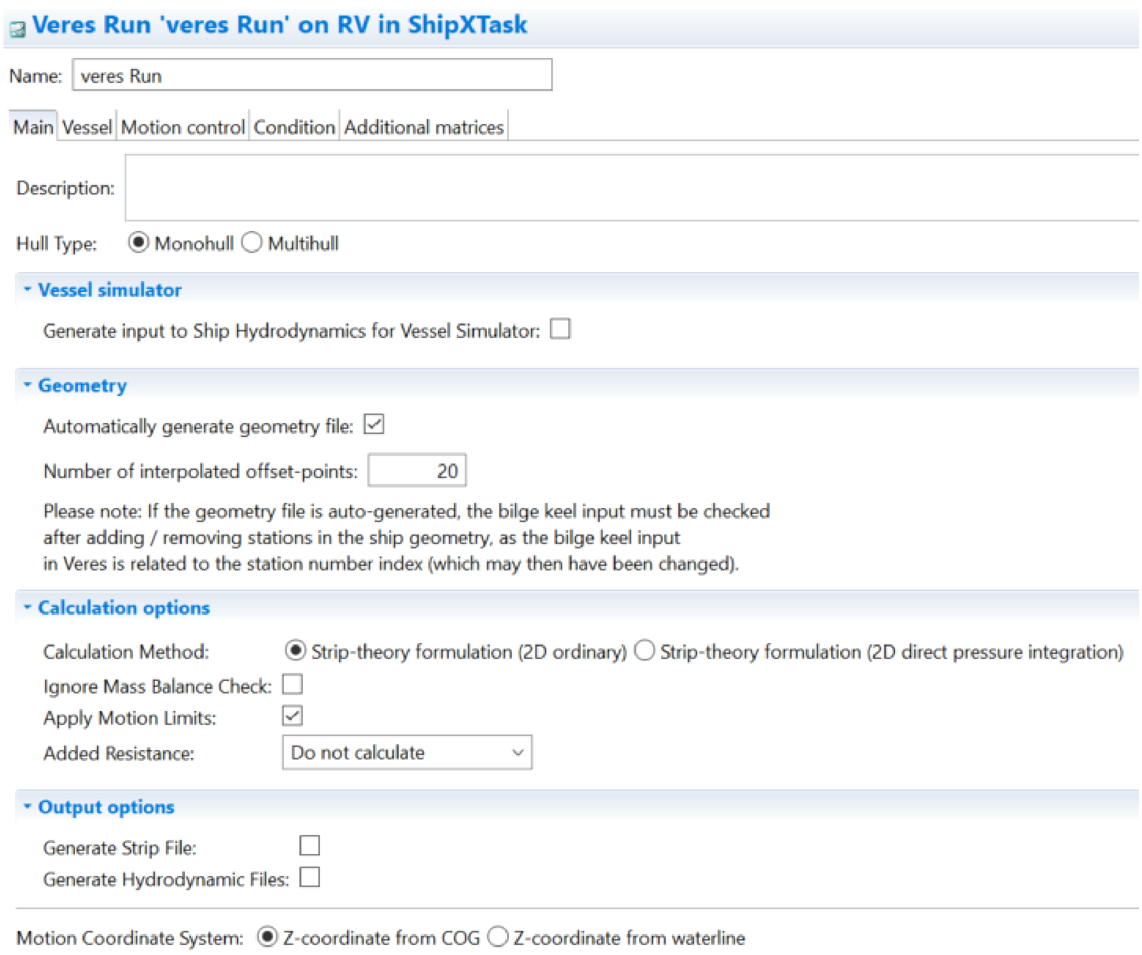

Figure 8: The Main dialog

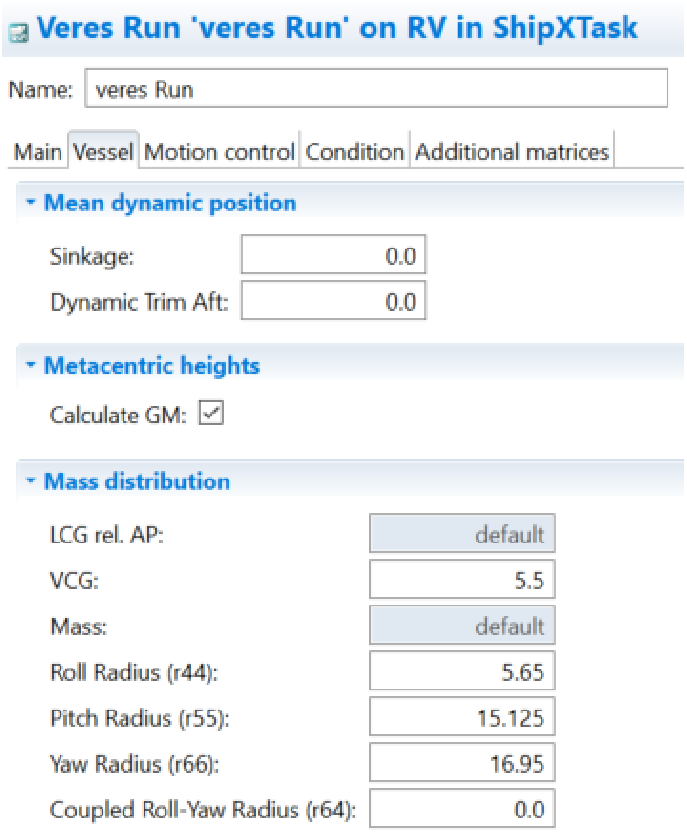

Figure 9: The Vessel description dialog

For the roll motions of a conventional ship, viscous effects are important since the potential damping is low. If selected, VERES may take viscous effects into account by empirical formulas. For further reference, see section 3.5. When the encounter frequency[3] is close to the resonant frequency, the damping will be of major importance for the response level. VERES may give unrealistic roll motions if viscous roll damping is not included.

3. To include viscous roll damping, the following steps are needed:

   (3.1) Select the **Motion control** tab, the editor shown in Figure 10 will appear.

   (3.2) To include viscous roll damping, simply check the “Include viscous roll damping” checkbox.

   (3.3) If viscous roll damping is selected, a wave amplitude must be specified, since some of the viscous effects are non–linear with respect to the wave amplitude. If you plan to perform short term statistics calculations later, the wave amplitude should preferably be chosen with respect to the significant wave height (e.g., by using the mean value of the wave heights you wish to use when calculating the short term statistics).

   (3.4) The next step is to describe the bilge keels (if any). Right-clicking the vessel in the **Navigator** window, select **New** and then **Bilge keel**. You now enter the **Bilge keel** dialog (Figure 11). Give the bilge keel a suitable name. In this example, we apply the default name “bilge_Keel”.

[3]See eqn. (5) for definition.

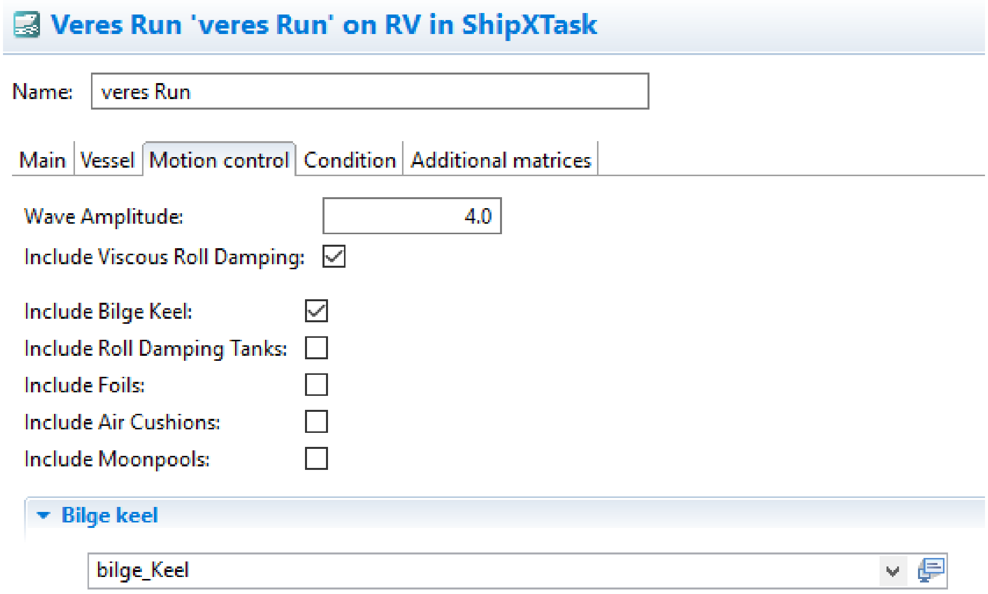

Figure 10: The Motion control dialog

(3.5) The bilge keels are specified by defining the breadth and position at a number of user–defined points along the hull. The position is defined as the intersection between the bilge keels and the hull. The location of each point is given by its longitudinal position (x,z), where the z–position is the height above baseline, and the x–position is the distance from the aft perpendicular (AP). The program automatically determines the y–coordinate based on the hull geometry. To input the bilge keel data, tap the green + sign three times and fill in the table, as shown in Figure 11.

(3.6) Re-enter the **Motion control** tab in the **Veres Run** editor and check the **Include Bilge Keel** checkbox. A Bilge keel input section will appear at the end of the dialog. Here, select “bilge_Keel” from the drop-down menu. The bilge keels will now be visible in the 3D model of the ship hull [4].

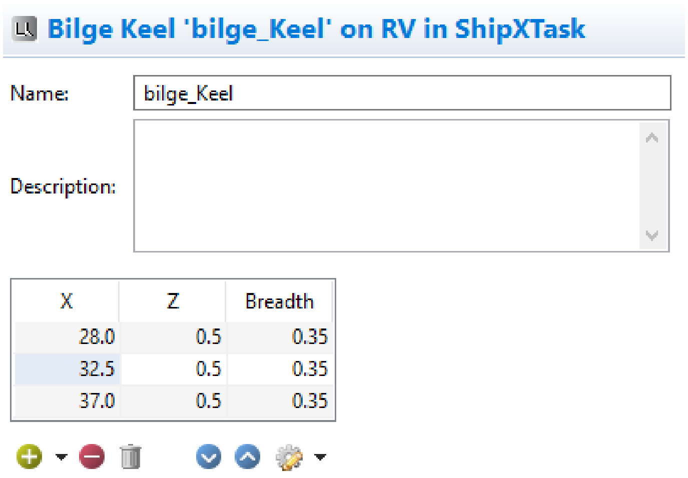

Figure 11: The Bilge Keel dialog

[4]All appendices added to the ship will automatically be added to the 3D model.

The final step before performing the actual computations is the description of the wave environment, which is specified under the **Condition** tab. Here, you can specify the vessel velocities, wave frequencies, and wave headings to be used in the calculations. The wave periods should be chosen so that the range is sufficient for later short term statistics. More points are also needed close to resonant periods for the vessel. Hint: Running the program with only a few headings will help you to find where a better wave period resolution is needed.

4. In the current example, we include the condition information with the following steps:

   (4.1) Open the **Condition** tab and click **Set default conditions values**.

   (4.2) Change the vessel velocity from the default value to 12 kn. You may do this by clicking the rightmost column in the *Vessel velocities* table, type 12, and press enter.

   (4.3) Since the ship is symmetric about the x–z plane, we will only consider wave headings from 0° to 180°. To reduce the wave headings list, press the last row in the *Wave heading* table and tap the - sign located underneath the table. You may also generate input values by clicking the arrow between the + and - sign and selecting **Generate numbers**. In the input dialog that appears, check the **Replace Existing Values** checkbox, set **Delta** and **Number of values** to 15.0° and 13 respectively, and press **Finish**. The **Condition** tab should now look like Figure 12.

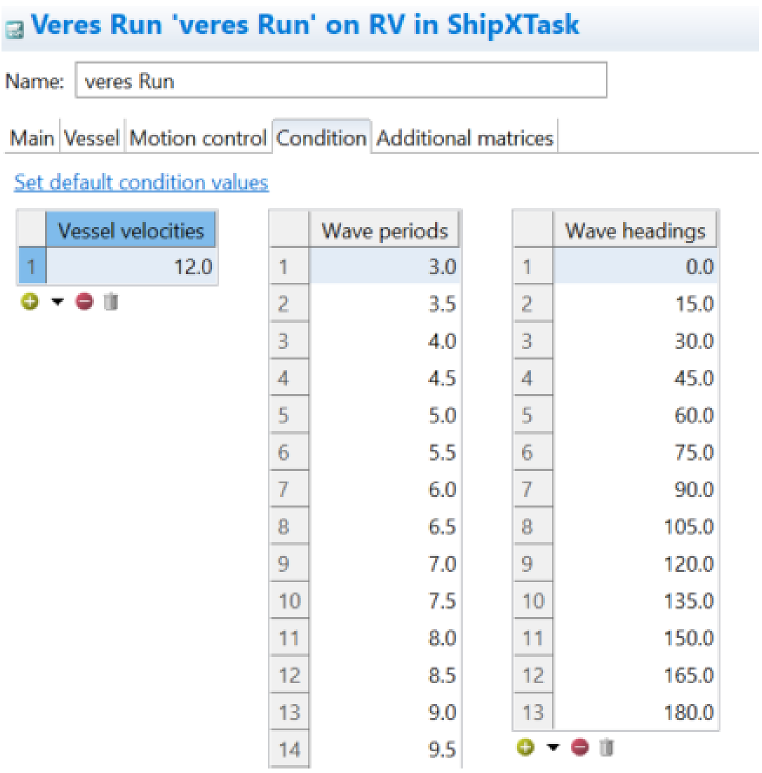

Figure 12: The Condition information dialog

2.2.3 Running a data check

1. After specifying the Veres input data, you should run a data check. In the **Navigator** window, expand the tree so that you can see the **veres Run** input, right-click the **veres Run** icon, and select **Run data check** from the pop-up menu.
2. After the data check is finished, there will be a **Results** folder under the **veres Run** containing the main hydrostatic properties of the vessel (Figure 13). Double click the documents found therein to display them.
3. If selected in the **Main** tab of the **Veres Run** dialog, a geometry output–file with suffix `.str` can be created. This file shows the interpolated coordinates on the wetted surface of the hull, and it can be viewed using the ShipX Plot Program. The coordinates in this file are the actual hull coordinates used by VERES in the calculations.

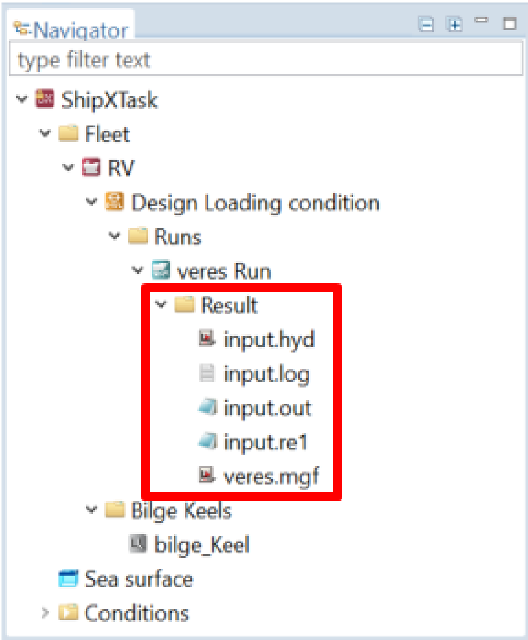

Figure 13: Navigator window after the main calculation

2.2.4 Running the computations

When you have completed the input, and the data check is acceptable, the main computations can be performed. This is done in a similar manner as when running the data check, but clicking **Run calculation** instead of **Run data check** in the pop-up menu. The calculations are started as a separate process, and can be monitored in the *Progress Manager* in ShipX (Figure 14).

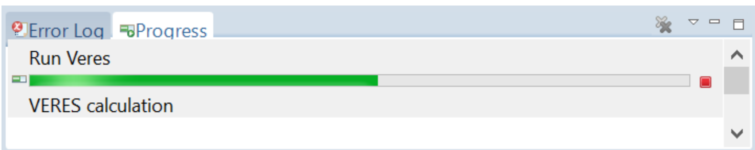

Figure 14: The ShipX Progress Manager

After running the full calculation, result files will be present in the **Results** folder of the Veres Run. Notice that you may start several calculations (as separate ShipX Runs) at the same time.

2.3 Post-processor tutorial

This section gives a brief description of the Post-processor. This is only meant as an introduction. The Post-processor should be quite self–explanatory, and contains a number of options for plotting results from Vessel Response calculations.

2.3.1 Preparing the data for post-processing

1. Right–click the **ShipXTask** in the **Navigator** window and select **New - Motions and Operability Post Processor**. The post-processor will be created in the **Post Processor** folder under the **ShipXTask**.
2. Give the Run a suitable name and plot title. In Figure 15, we have entered the name “veresPostProcessorRV’ and plot title “RV”.
3. You can now add the result file form the Veres run by pressing the + sign in the **Veres runs** tab and selecting **veres Run in RV** from the drop-down menu. Give the Veres run a label by entering “Veres_Run_RV” in the Label cell.
4. To specify a motion point on the hull, right-click the vessel and select **New - Motion point**. Now, you can add a new motion point by giving it a name and the position on the hull in x–, y– and z–coordinates. In this example, let us call the motion point “FP” (Fore Perpendicular). Specify the longitudinal position to be 60.5 m (fwd AP) and the vertical position to be 9.5 m above the baseline. To add a second motion point, you can right–click the **Motion points** folder under the **ShipXTask** (Figure 16) then selecting **New - Motion point**, or you may double–click the folder and add motion points by tapping the + sign. Name the second motion point “FP at baseline” and set the x–coordinate to 60.5 m. Finally, add a third motion point with coordinates (x, y, z)=(60.5, 0.0, 15) and name it “Deck at bow”.
5. In the *Motions and Operability Post Processor* editor, click the + sign in the **Motions points on selection** section three times and select the motion points we just created from the drop-down menu.

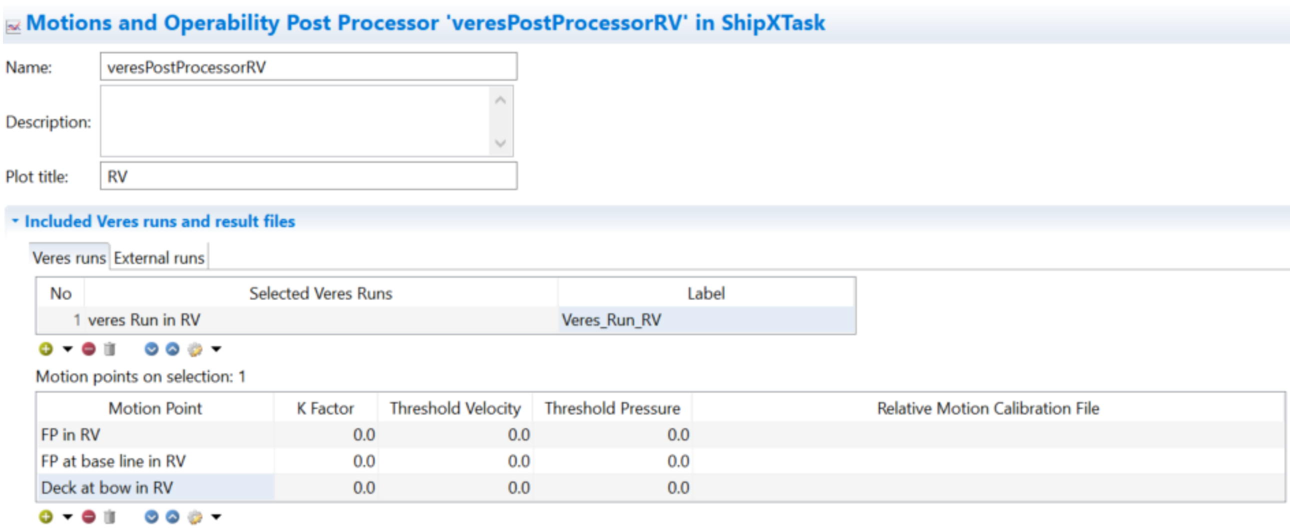

Figure 15: The Vessel Responses Post-processor dialog window

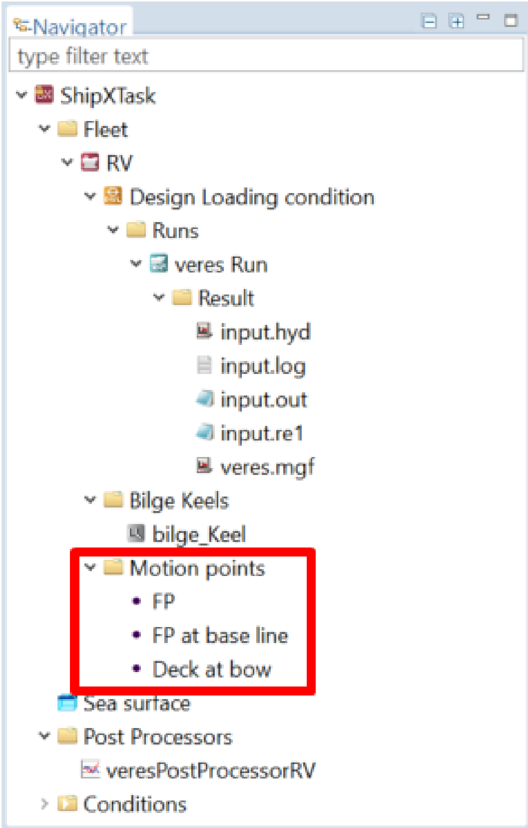

Figure 16: Navigator window after specifying motion points

In the lower half of the *Motions and Operability Post Processor* editor you'll find four tabs; **Criteria**, **Wave spectra**, **Plot settings**, and **Wave statistics**.

6. Click the **Criteria** tab to access the **Criteria** dialog. We want to specify three seakeeping criteria; "V. acc. at FP, 0.15g" at *FP*, "Slamming 3%" at *FP at baseline*, and "Green water 7%" at *Deck at bow*. The criteria information is entered as follows:

   (6.1) Press the + sign, a list of criteria will pop-up, select the type of criterion from the list (in this case, **Translation/Angular motion**).

   (6.2) Boxes customized for the criterion type will then appear[5].

   (6.3) Fill in the name of the criterion ("V. acc. at FP, 0.15g" for the first criterion). The name will be used as legend text on the plot.

   (6.4) Specify the position at which the criterion is to be calculated[6] from the pull–down menu in the rightmost cell of the table (in this case, *FP*).

   You have now entered one criterion, and can fill in the next, starting at (6.1) again. After adding all the criteria, the **Criteria** dialog should look like Figure 17.

[5] Note that accelerations are specified in m/s^2 (0.15g=1.472 m/s^2).
[6] You may of course specify several criteria at one motion point.

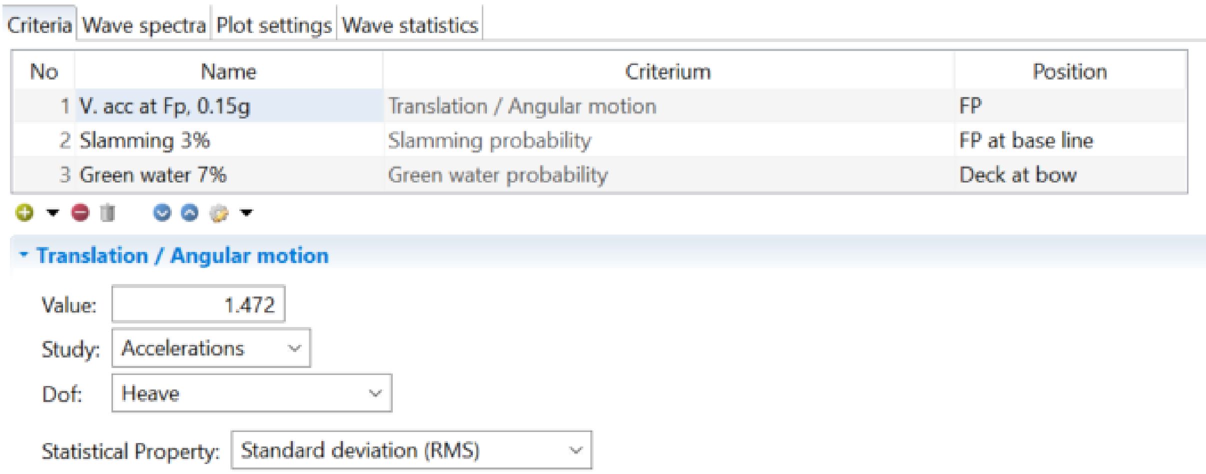

Figure 17: Criteria tab in the Vessel Responses Post-processor dialog

7. To specify the wave environment click the **Wave spectra** tab. The dialog shown in Figure 18 will appear.
   (7.1) Select a long–crested Pierson–Moskowitz wave spectrum[7], for both **Long–term statistics / Operability** and **Short–term statistics**.
   (7.2) Choose **Keep Hs constant** in the **Short–term statistics** part of the input dialog, and set the significant wave height, H_s, to 4.0 m. Further, select peak periods between 5.0 and 15.0 seconds, and set the number of periods to 20.
   (7.3) Under **Operability limiting boundaries**, specify Number of periods, Maximum Hs and Tp range as 20, 18 m, and 5s to 20s, respectively.
8. The units on the plots presented in the following sections can be changed by selecting other options present in the **Plot settings** tab, see Figure 19. In the current example we select **Divided by wave amplitude** for the rational motions in regular waves.

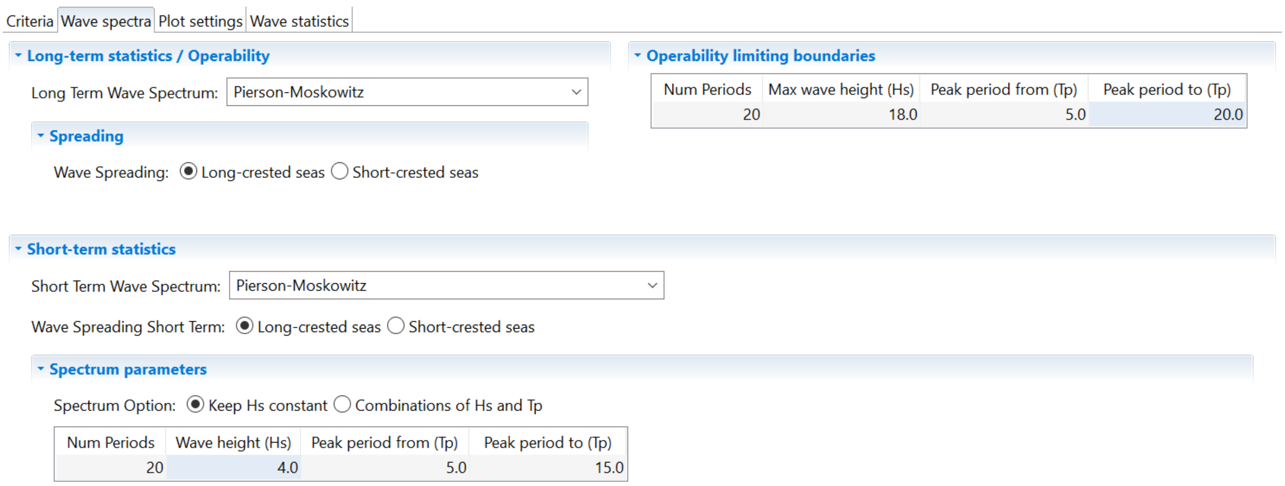

Figure 18: Wave spectra tab in the Vessel Responses Post-processor dialog

[7] You may also select the Bretschneider spectrum, as Veres does not differentiate between the Bretschneider and the Pierson–Moskowitz spectra.

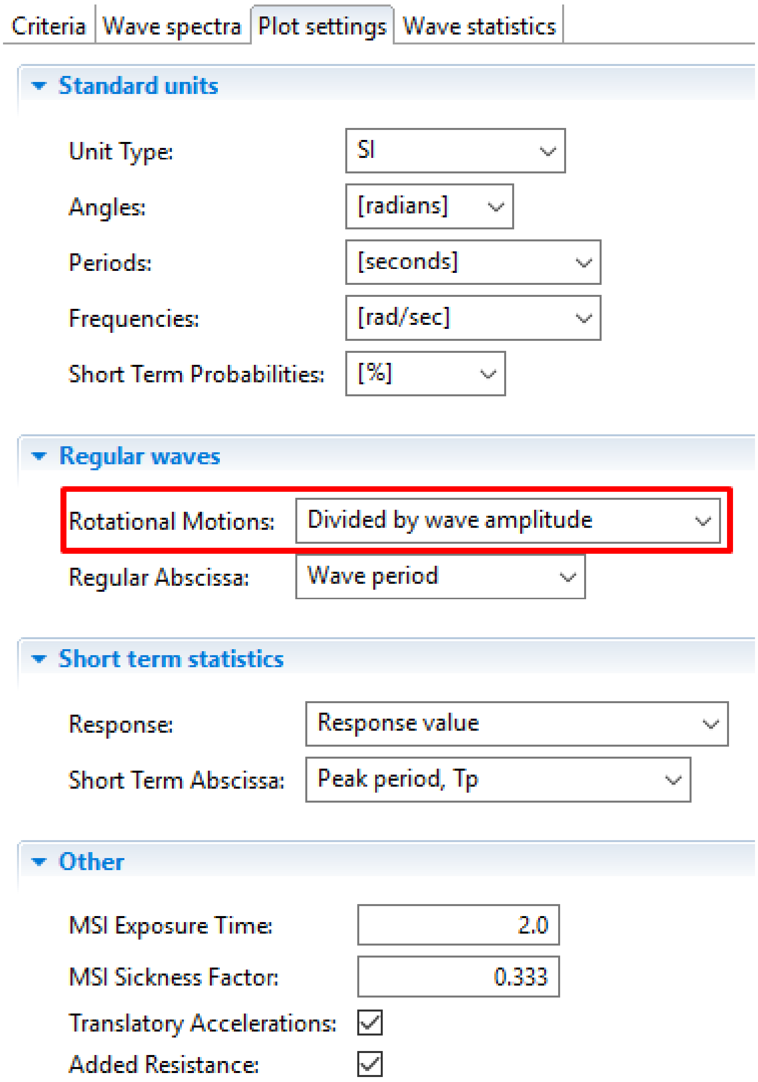

Figure 19: Plot settings tab in the Vessel Responses Post-processor dialog

9. In this example, an annual wave scatter diagram for the North sea is applied (Area 11 in [11], see Fig. 45, p. 63). To add this, click the **Wave statistics** tab, press the + sign, and specify the `a11an.sea` file manually or browse for it. This file is located in the ??? subdirectory.

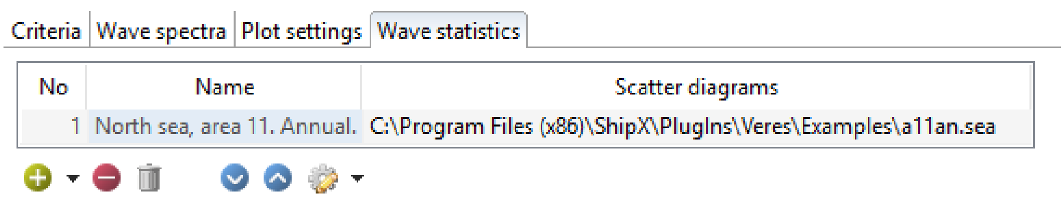

Figure 20: Wave statistics tab in the Vessel Responses Postprocessor dialog

We are now ready to take a look at some of the results for the RV ship.

2.3.2 Response in regular waves

Let us first have a look at the motion responses of the RV hull in regular waves. The motion response is presented for wave headings of 0°, 30° and 60° (0° is head seas). The forward speed is 12 knots. The ship has a sinusoidal response with frequency equal to the frequency of encounter[8]. The amplitudes in heave, roll and pitch are plotted as a function of the wave period. To obtain the results in Figures 23–25, perform the following steps:

1. In the **Navigator** window, right-click the **veresPostProcessorRV** and select **New – Regular Waves** to create a *Regular waves* post-processor run (Figure 21).
2. In the **Options** tab enable heave, roll and pitch only.

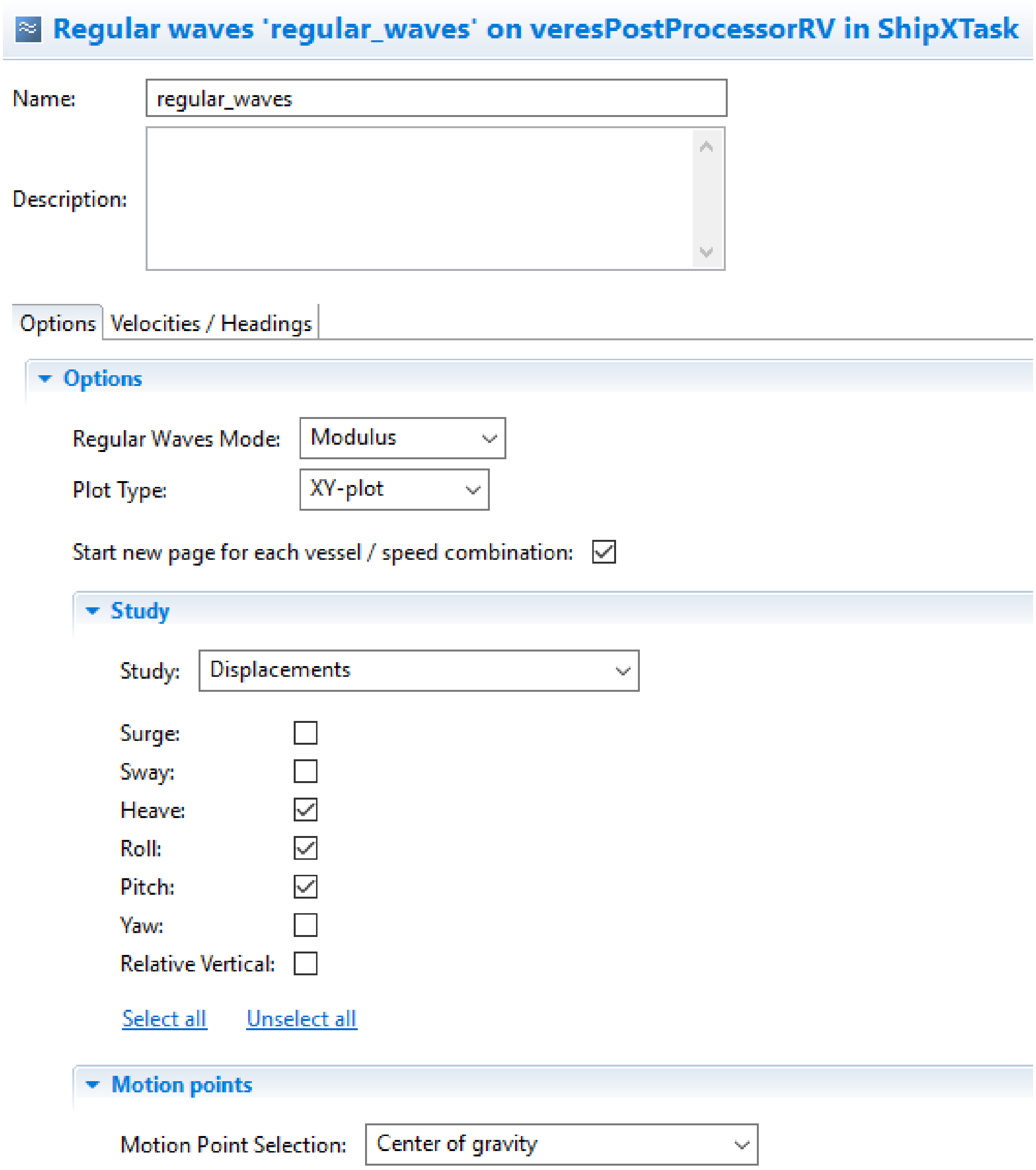

Figure 21: Options tab in the Regular Waves Post-processor dialog

[8]See eqn.(5), p. 40 for definition.

3. Open the **Velocities / Headings** tab (Figure 22). Press **Get velocities and headings** and deselect all headings except for 0°, 30° and 60°. Note that you can disable all headings by clicking the **Unselect all** button underneath the *Headings* table.

4. In the **Navigator** window, right-click the **regular_waves** and select **Run regular waves**.

5. When the calculation has finished, browse the **Results** folder below **regular_waves** to find the plots. Double click the `.mpl` files to look at them in the ShipX Plot Program. Note that you can edit the plots by double–clicking the plot area inside the plot program to, for example, change the range of the x-axis (Chart Properties -> Axis X -> Scale)

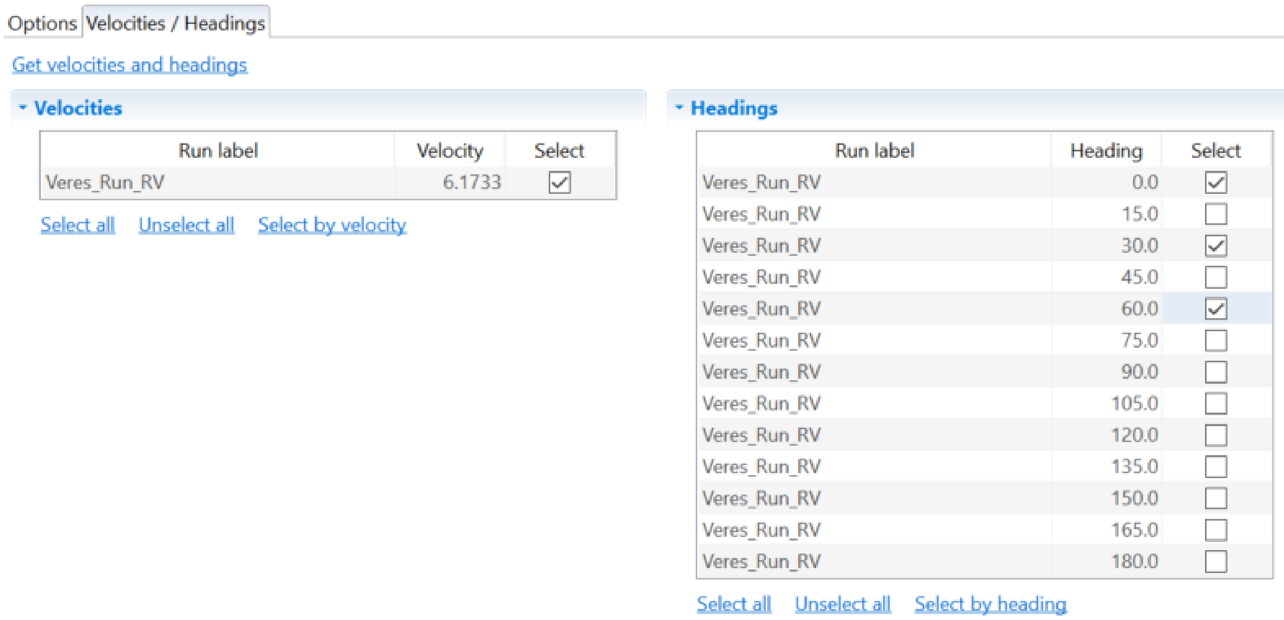

Figure 22: Velocities/Headings tab in the Regular Waves Post-processor dialog

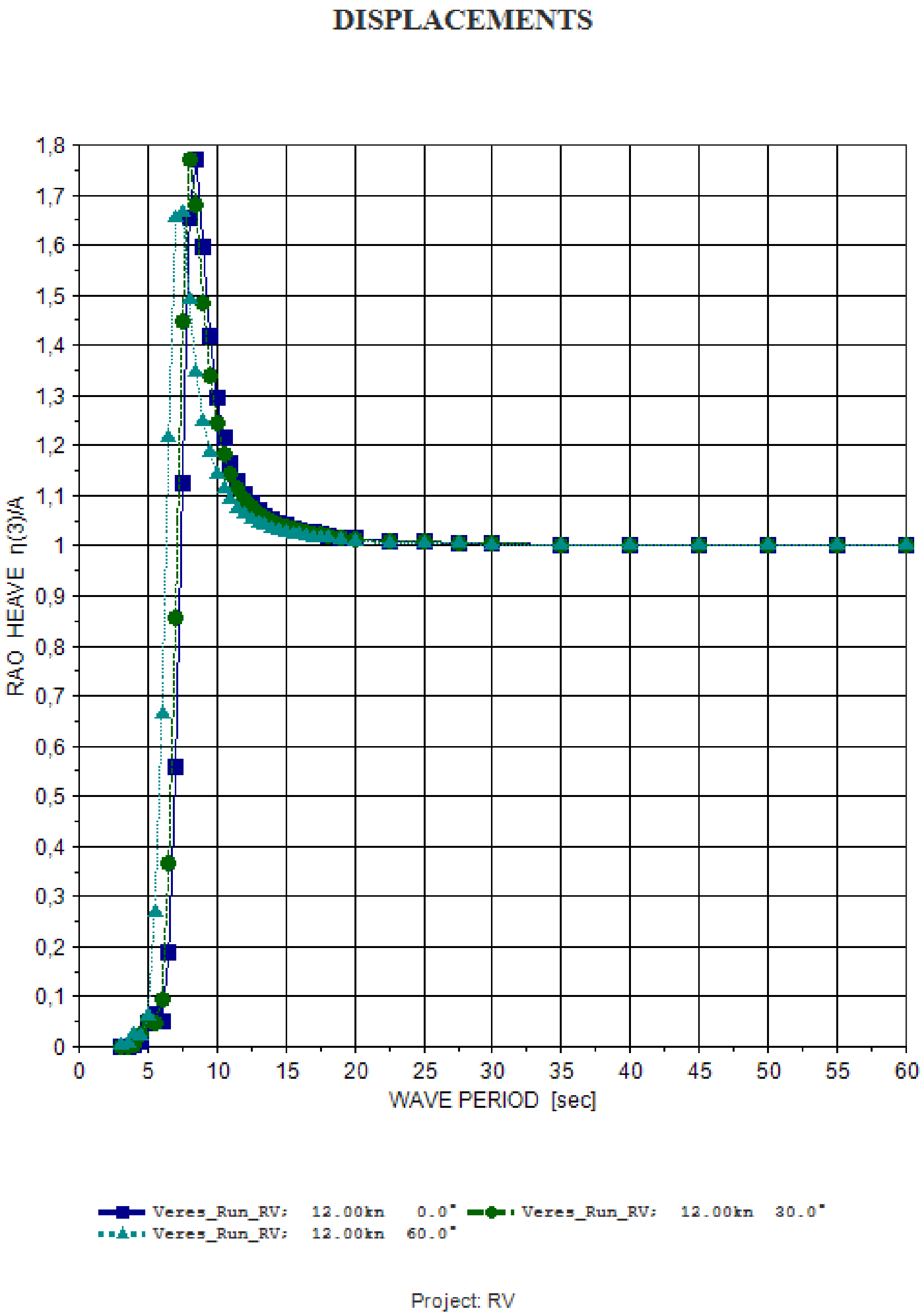

Figure 23: Heave motion characteristics of the RV hull

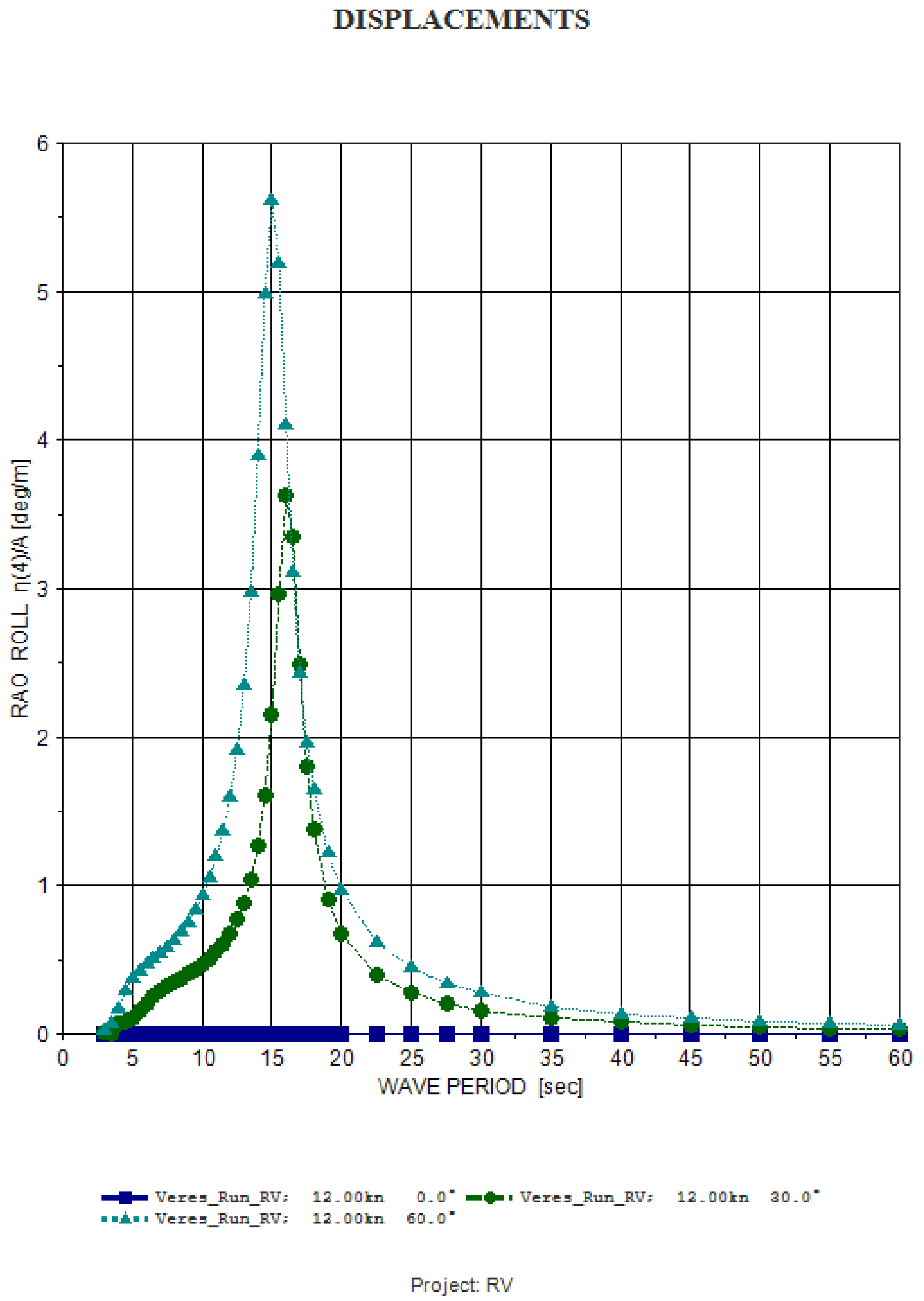

Figure 24: Roll motion characteristics of the RV hull

DISPLACEMENTS

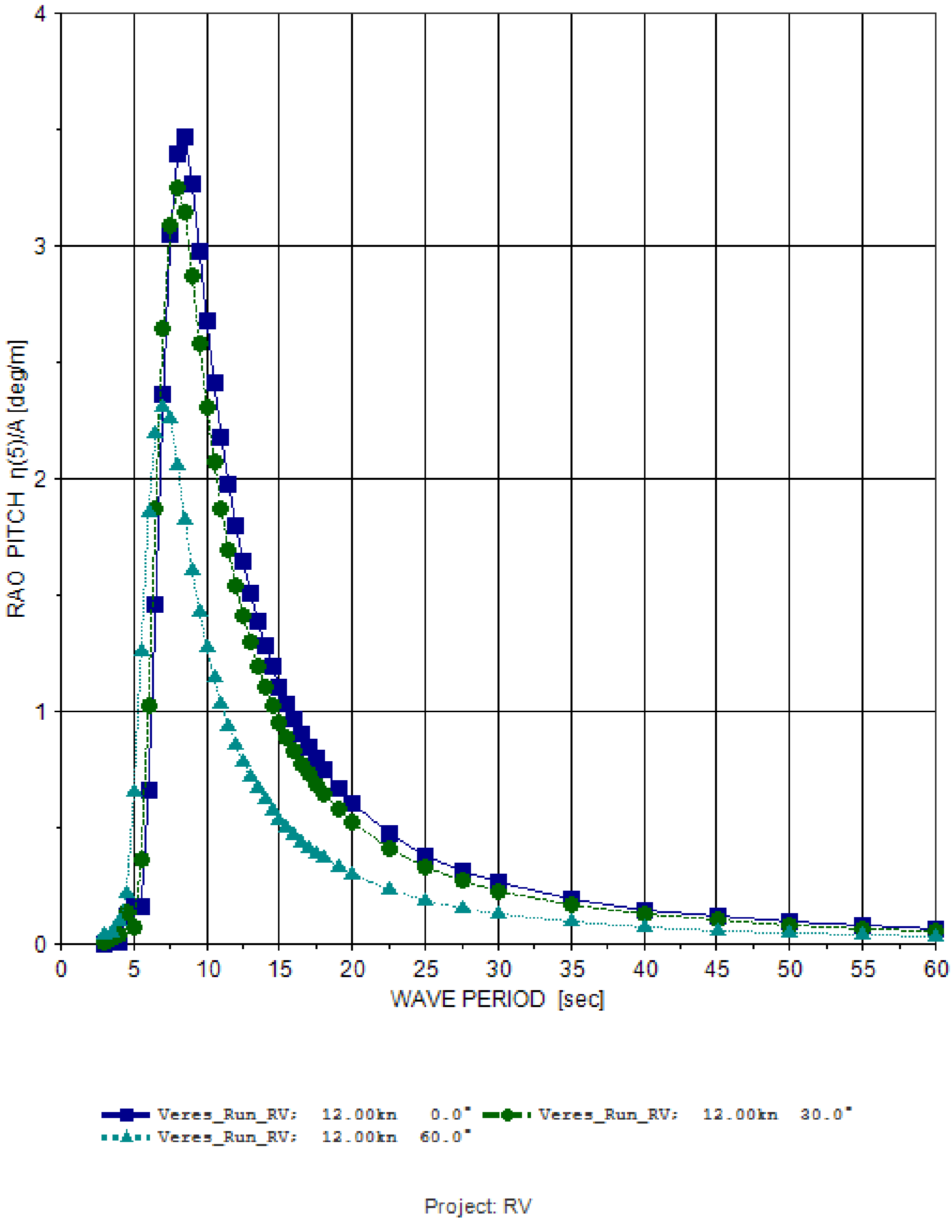

Figure 25: Pitch motion characteristics of the RV hull

2.3.3 Short term statistics

Now, we will show the calculations of short term statistics for the vertical accelerations in the bow. The theory is given in Chapter 4.2, and the results of the calculations are presented as the standard deviation of the vertical acceleration as a function of the peak period in Figure 27. To obtain these results, you have to perform the following steps:

1. To enter the *Short term statistics* post processor input dialog (Figure 26), right-click the **veresPostProcessorRV** in the **Navigator** window and select **New – Short term statistics**.
2. To plot the standard deviation, select **Standard Deviation (RMS)**[9] in the **Present statistical values as** pull–down menu.

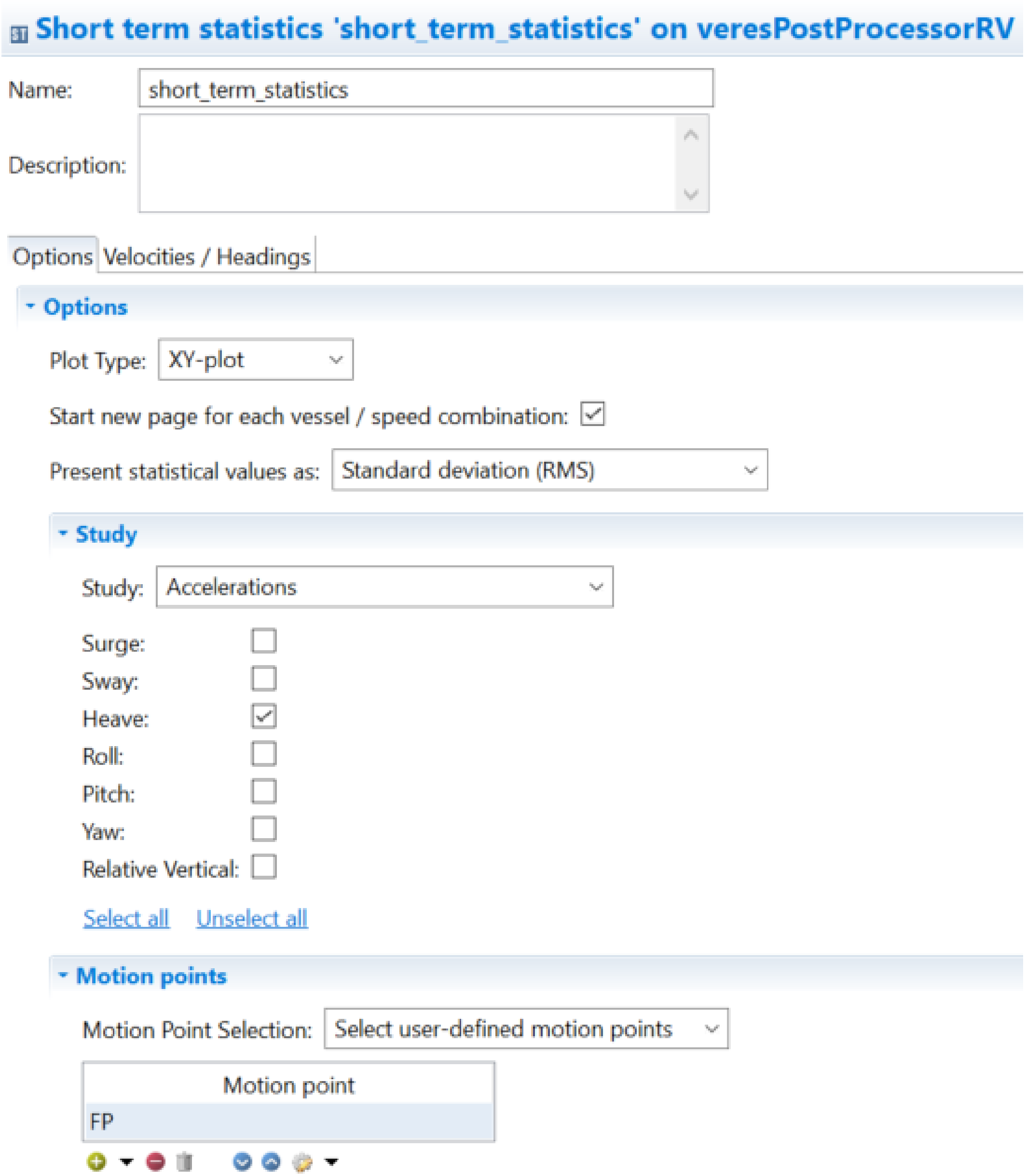

Figure 26: Options tab in the Short Term Statistics Post-processor dialog

[9]For linear frequency–domain calculations, the mean value of the response is zero, and the standard deviation will be equal to the Root Mean Square value (RMS).

3. Select **Accelerations** in the **Study** pull–down menu.
4. Click the *Unselect All* button below the degree of freedom list and select **Heave** to obtain values for the vertical motions.
5. To specify a motion point on the hull, select *Select user–defined motion points* in the **Motion Point Selection:** pull–down menu, located at the end of the **Options** dialog. Press the + underneath the *Motion point* table and select “FP” from the pull–down menu.
6. Open the **Velocities / Headings** tab. Press **Get velocities and headings** and deselect all headings except for 0°, 30° and 60°.
7. In the **Navigator** window, right-click the **short_term_statistics** and select **Run short term statistics**.
8. When the calculation has finished browse the **Results** folder below **short_term_statistics** to find the plot. Double click the `.mpl` file to look at them in the ShipX Plot Program.

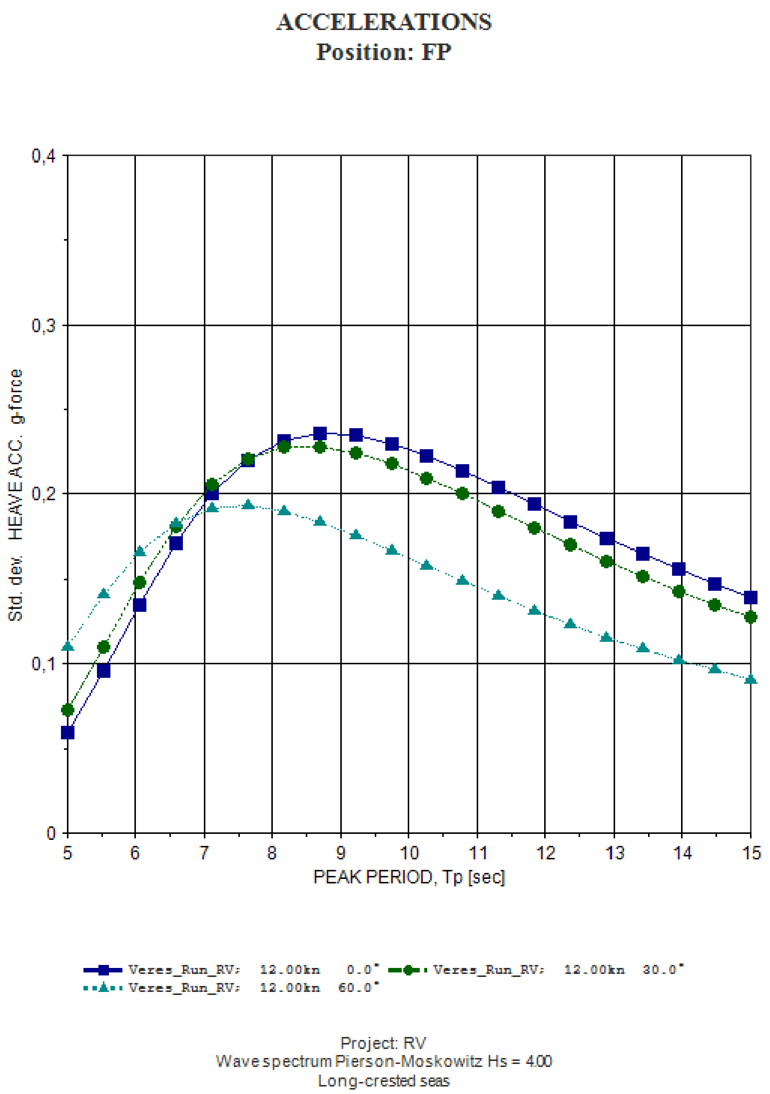

Figure 27: Standard deviation of vertical accelerations in the bow for the RV hull

Figure 27 shows the standard deviation of the vertical accelerations at the bow for a Pierson–Moskowitz wave spectrum with significant wave height, H_s= 4.0 m. The results will change depending on the peak period, T_p, and each combination of H_s and T_p describes the sea state completely. If the sea state is modeled by the Pierson–Moskowitz wave spectrum or the JONSWAP H_s–T_p–γ spectrum, the standard deviation will be proportional with H_s. For the JONSWAP H_s–T_p wave spectrum and Torsethaugen wave spectra this will not be the case, since the peakedness parameter γ is a function of H_s and T_p (See Chapter 4.2 for a discussion on this matter).

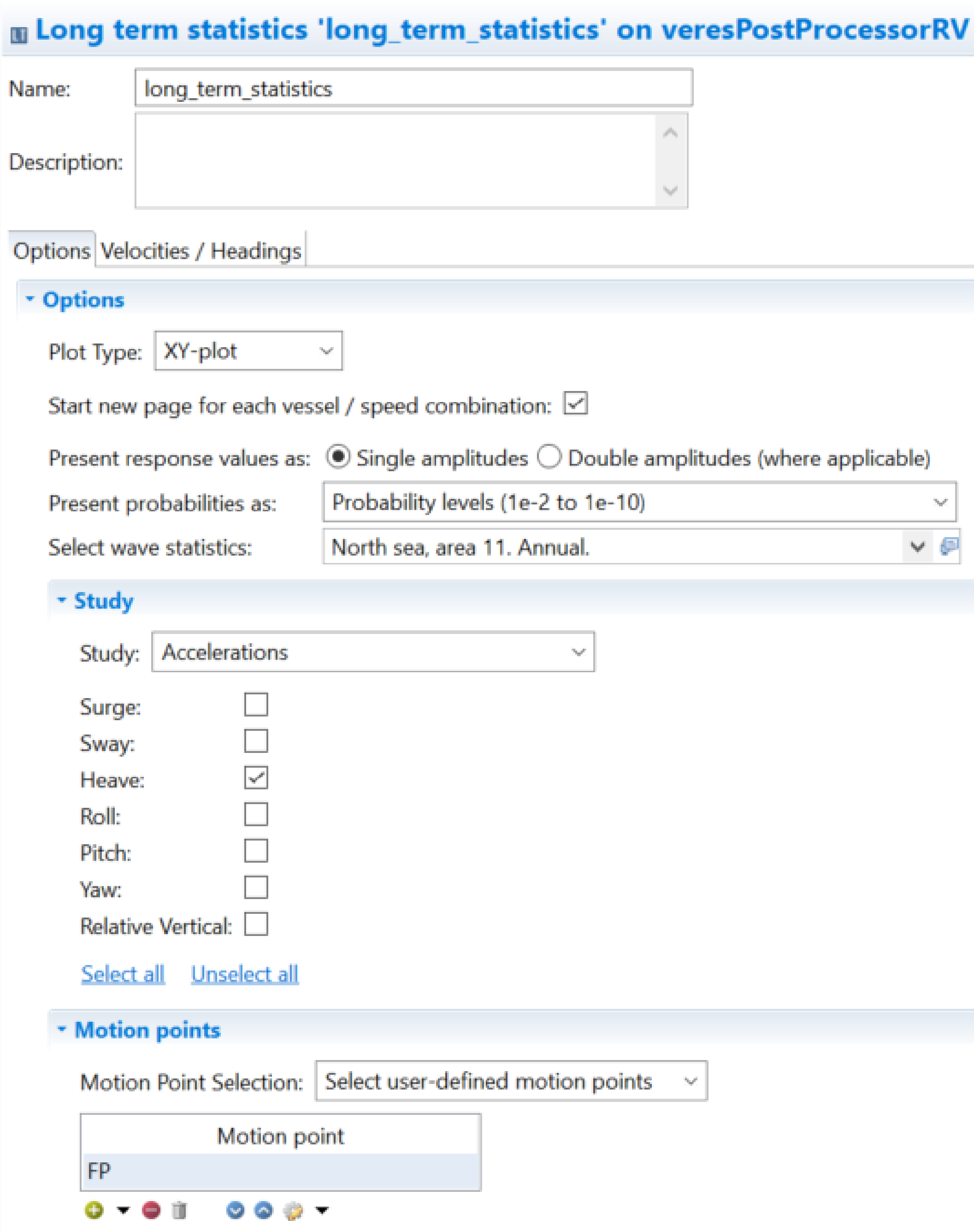

Figure 28: The Long Term Statistics dialog

2.3.4 Long term statistics

As an example of long term statistics results, the vertical accelerations at the bow (FP) are shown in Fig 29. The probability level is presented as a function of the single amplitude of the vertical acceleration, weighted over all wave headings. An annual wave scatter diagram for the North sea is applied (Area 11 in [11], see Fig. 45, p. 63). For further details of the calculation, please refer to Chap. 4.3. To obtain the long term results, you must perform the following steps:

1. In the **Navigator** window, right-click the **veresPostProcessorRV** and select **New – Long term statistics**. This will open the *Long term statistics* post processor dialog shown in Figure 28.
2. In the **Select wave statistics:** drop–down menu select “North sea, area 11. Annual.”.
3. Select **Accelerations** in the **Study:** pull–down menu.
4. Click the *Unselect All* button below the degree of freedom list and select **Heave**
5. Select *Select user–defined motion points* in the **Motion Point Selection:** pull–down menu and select “FP”.

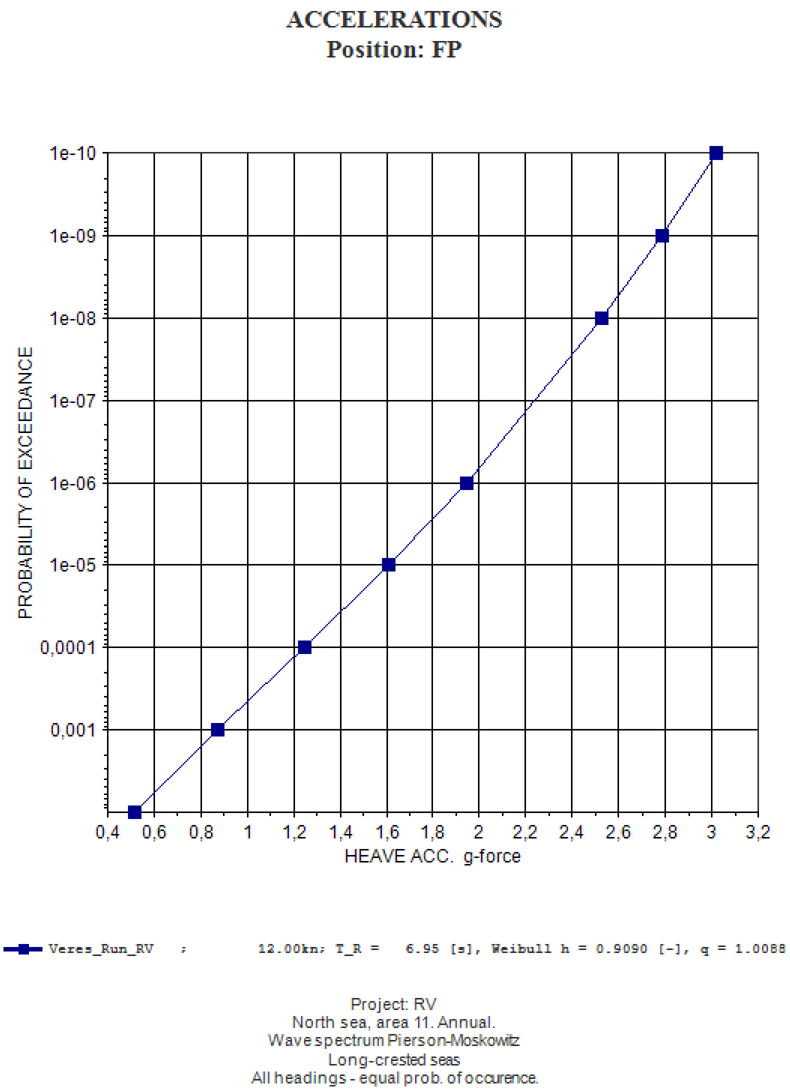

Figure 29: Long term statistics for the vertical accelerations at FP for the RV hull

6. Open the **Velocities / Headings** tab. Press **Get velocities and headings** and select *Sum over all headings (equal probability of occurence)* in the **Headings Operation:** drop–down menu above the *Headings* table.
7. In the **Navigator** window, right-click the **long_term_statistics** and select **Run long term statistics**.
8. When the calculation has finished browse the **Results** folder below **long_term_statistics** to find the plot. Double click the `.mpl` file to look at them in the ShipX Plot Program. The results should now look like Figure 29.

2.3.5 Operability limiting boundaries

An example of operability limiting boundary curves are shown in Fig 31. Different seakeeping criteria appear as limiting curves in a diagram with the limiting significant wave height as the ordinate and with the characteristic wave period along the abscissa. In addition, the theoretical limit of breaking waves may be plotted in the diagram. The vessel meets the seakeeping criteria for the wave height–wave period combinations below (all) the boundary curves. For further details on the seakeeping criteria and operability limit boundaries, please refer to Secs. 4.4.1 and 4.4.2, pp. 68–72. To obtain the operability limits results presented here, you need to perform the following steps:

1. In the **Navigator** window, right-click the **veresPostProcessorRV** and select **New – Operability limiting boundaries**.
2. In the *Options* section of the dialog enable the *Show curve for breaking waves limit* option. This includes the theoretical limit of breaking waves in the plot.

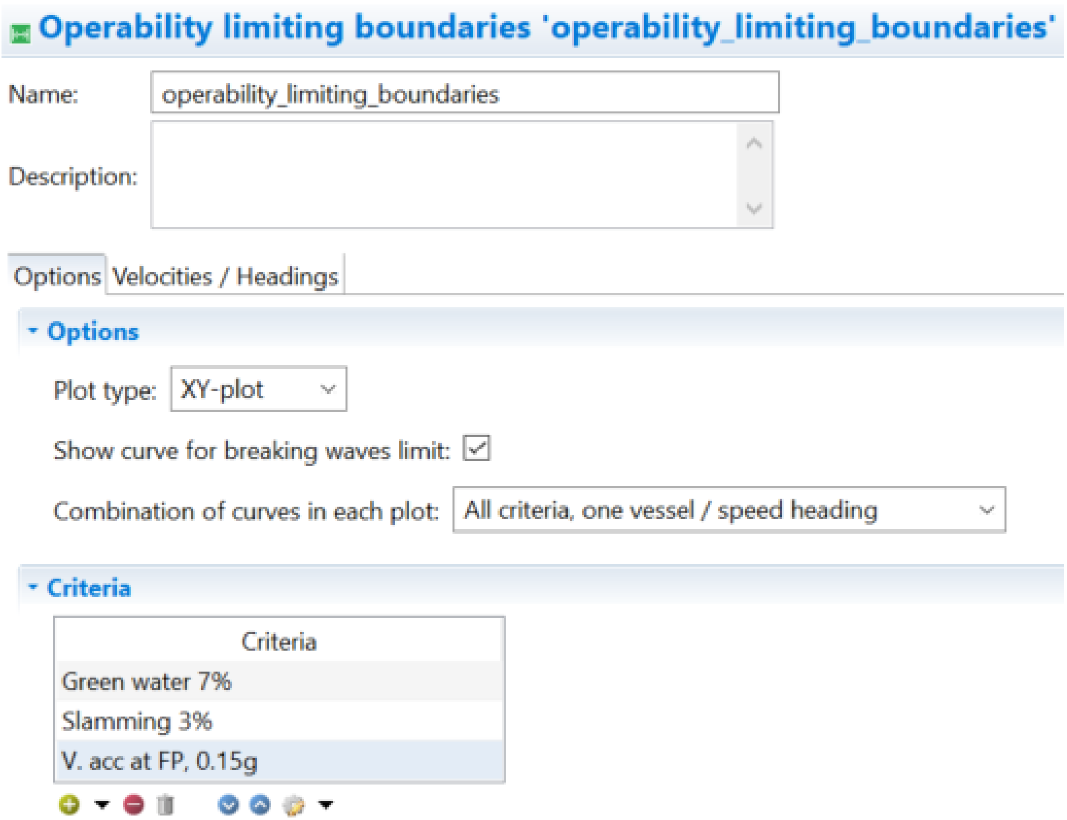

Figure 30: The Specify Motion Points dialog

3. To include the "Green water 7%" criterion we defined in the *Motions and Operability post processor* in the plot, press the + under the *Criteria* table and select "Green water 7%" from the drop–down menu. Include the "Slamming 3%" and "V. acc at FP, 0.15g" criteria in a similar fashion. The *Operability limiting boundaries* dialog should now look like Figure 30.
4. Open the **Velocities / Headings** tab. Press **Get velocities and headings** and deselect all headings except for 0°.
5. In the **Navigator** window, right-click the **operability_limiting_boundaries** and select **Run operability limiting boundaries**.
6. When the calculation has finished browse the **Results** folder below **operability_limiting_boundaries** to find the plot. Double click the `.mpl` file to look at them in the ShipX Plot Program. The results should now look like Fig. 31.

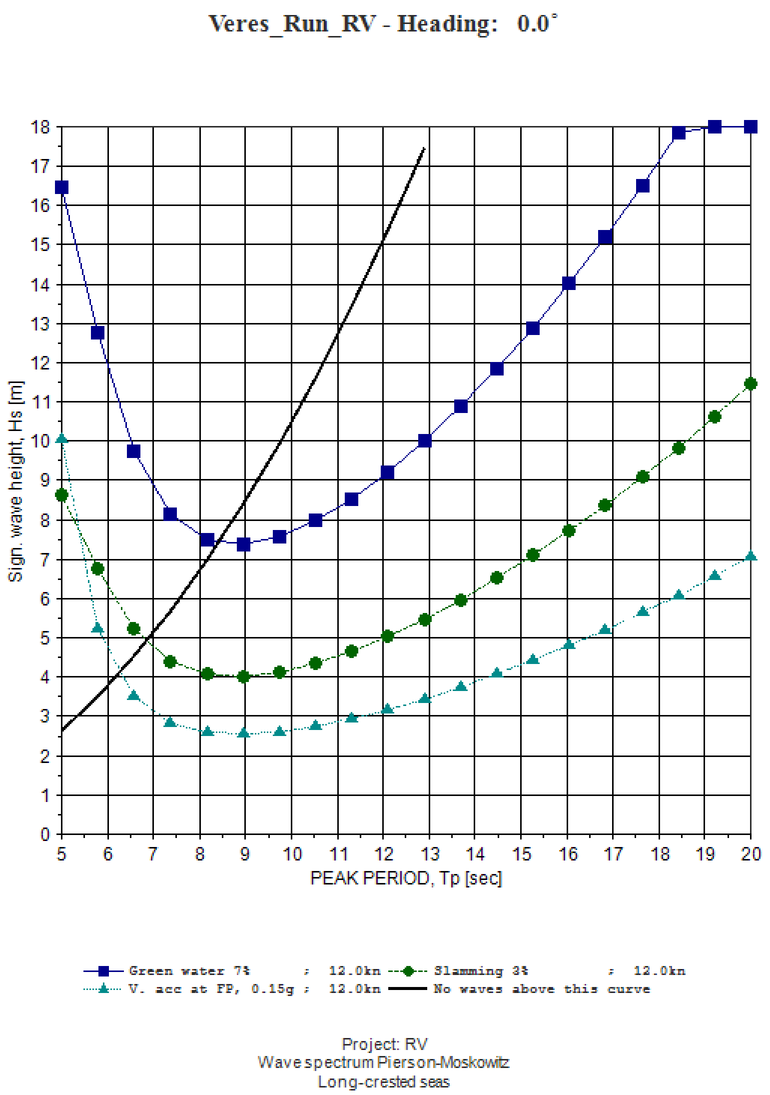

Figure 31: Operability limiting boundary curves and the theoretical limit of breaking waves for the RV hull in head seas.

The results show that the vertical acceleration at FP is the critical criterion in head seas (0° wave heading). The limiting significant wave height is about 2.5 m. The theoretical limit of breaking waves indicates the limit combinations of H_s and T_p, where the waves are becoming too steep to be stable. Above this limit, there should theoretically not exist waves (see Chap. 4.4, p. 68 for further discussion).

2.3.6 Percentage operability

As a last example, let us calculate the percentage operability of the vessel, for the same criteria as in the operability limits example. Each criterion is presented seperately, summed over all wave headings. The same scatter diagram as in the long term statistics example is used. The theory is given in Sec. 4.4.4, p. 77. To obtain the results in Figure 33, you must perform the following steps:

1. In the **Navigator** window, right-click the **veresPostProcessorRV** and select **New – Operability percentage**.
2. In the **Select wave statistics:** drop–down menu select "North sea, area 11. Annual.".
3. Include the "Green water 7%", "Slamming 3%" and "V. acc at FP, 0.15g" criteria to the *Criteria* table in the same way we did in the *Operability limiting boundaries* post processor dialog.
4. Open the **Velocities / Headings** tab. Press **Get velocities and headings** and select *Sum over all headings (equal probability of occurence)* in the **Headings Operation:** drop–down menu above the *Headings* table.

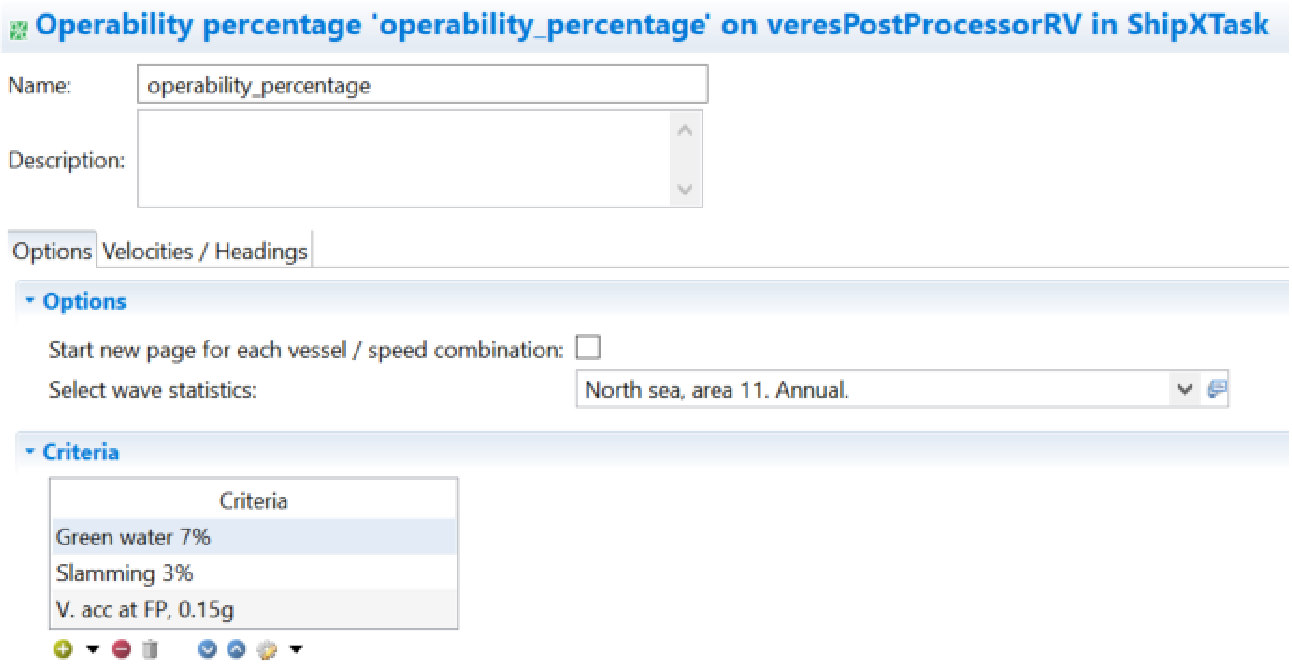

Figure 32: Percentage operability for the RV hull

5. In the **Navigator** window, right-click the **operability_percentage** and select **Run operability percentage**.
6. When the calculation has finished browse the **Results** folder below **operability_percentage** to find the plot. Double click the `.mpl` file to look at them in the ShipX Plot Program. The results should now look like Fig. 33.

The percentage operability plot shows the same trends as the operability limit boundary curves. The worst criterion is the vertical acceleration criterion, with a percentage operability of approx. 90%, while the green water on deck criterion does not affect the operability (close to 100% operability).

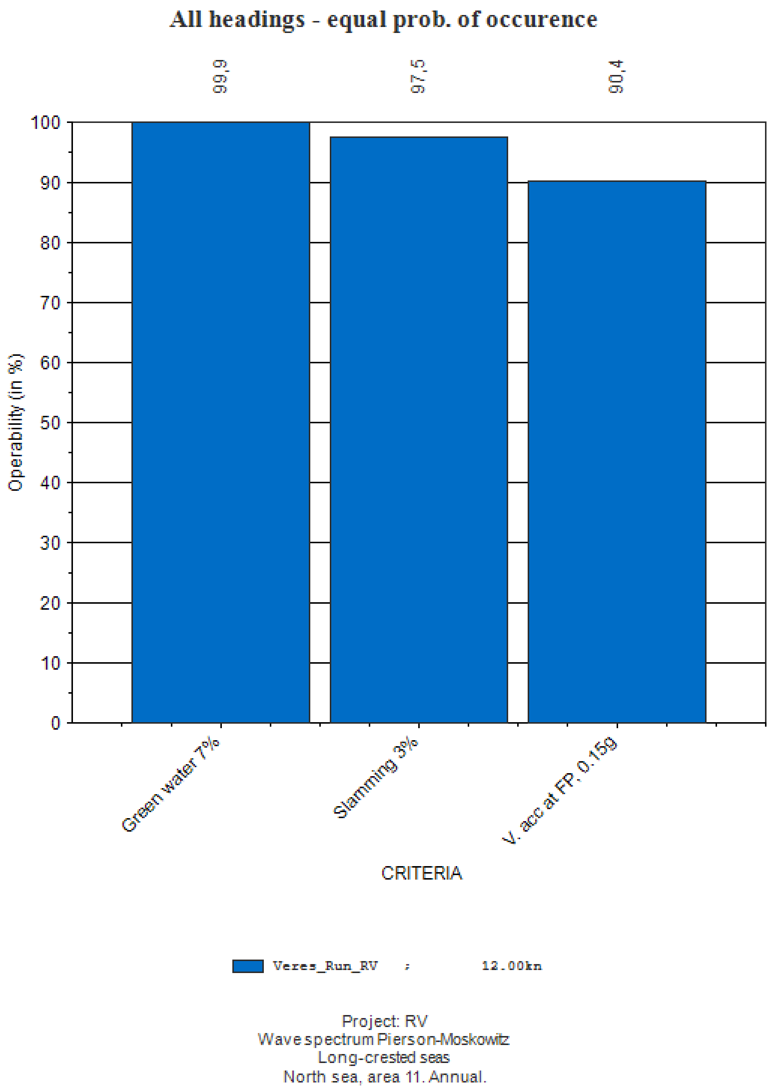

Figure 33: Percentage operability for the RV hull

3 MAIN PROGRAM REFERENCE

This chapter will provide the theoretical background for the VERES computer program. Further reference can be found in the Theory Manual and citations throughout the text.

3.1 Basic assumptions

In short, the basic assumptions in the VERES program are:

- The ship is assumed to oscillate harmonically with frequency equal to the frequency of encounter. No transient effects due to initial conditions are accounted for. No hydroelastic effects are accounted for.
- A linear relation is assumed between the responses and the incident wave amplitude. This will not be correct in high sea states where slamming and water on deck may occur. This also assumes that the hull and should be close to wall-sided at the free surface.
- The superposition principle can be used to derive the loads and motions in a sea-state[10].
- Potential theory can be applied. The fluid is assumed to be homogeneous, non-viscous, irrotational and incompressible. However, viscous roll damping can be accounted for by means of empirical formulas.
- The vessel is assumed to be *slender*, i.e. the length of the hull is much larger than the breadth and the draught.
- In the traditional strip theory [21], the three-dimensional hydrodynamic problem can be reduced to a set of two-dimensional "strips", without interaction between the strips. Total forces can be obtained by integrating cross sectional two-dimensional forces over the ship's length. This means that three dimensional effects are neglected.
- In the high speed theory [7], interaction from the strips upstream is accounted for. Total forces can be obtained by integrating cross sectional two-dimensional forces over the ship's length. The theory therefore denoted as a 2 1/2-dimensional theory.
- The vessel is symmetric about the centerline.
- For multihulls, interaction effects between the hulls are not accounted for (except for catamarans, where a high speed theory including hull interaction is available). At high speeds, this is a reasonable assumption, since the waves will travel downstream, and if the hulls are not too narrow, interaction effects will be small. At low and moderate speeds, interaction effects may be important.

As mentioned, VERES assumes the ship to be *slender*. The motivation for this simplification is that the three dimensional problem may be reduced to a set of two dimensional problems along the hull. This will save a lot of computational time. The disadvantage of this method is that three dimensional effects are neglected. For a tanker, this simplification is acceptable, except locally at the bow and stern. For supply ships and fishing vessels, three dimensional effects can be important.

To calculate hydrodynamic forces, potential theory is used. Potential theory assumes the fluid to be homogeneous, non-viscous and incompressible. Thus, viscous effects are not accounted for. However, in roll, *viscous effects* should be accounted for, since the potential damping is small. VERES may take viscous effects into account by empirical formulas. This is explained in Section 3.5.

Even if some of the above simplifications may be speculative, linear theory has been found to give very good results compared to three-dimensional codes and to model tests.

[10] This assumption is correct when linear theory is correct.

3.2 Definition of coordinate systems, wave heading and motions

The input in the graphical user interface of VERES is related to the same definitions as the rest of ShipX, i.e. a classical Naval Architect system. This is a left-handed coordinate system (x, y, z) with the x-axis positive forwards with its origin at the aft perpendicular (AP), the y-axis positive to starboard (origin at centerline) and z-axis pointing upwards from the baseline.

Internally, VERES uses two right-handed Cartesian coordinate systems; one *global* coordinate system (x, y, z) in which the computations are performed and a *local* coordinate system (x_l, y_l, z_l) used to describe the cross-sectional geometry of the vessel in the hull geometry file (refer to Section 3.3.1 for details).

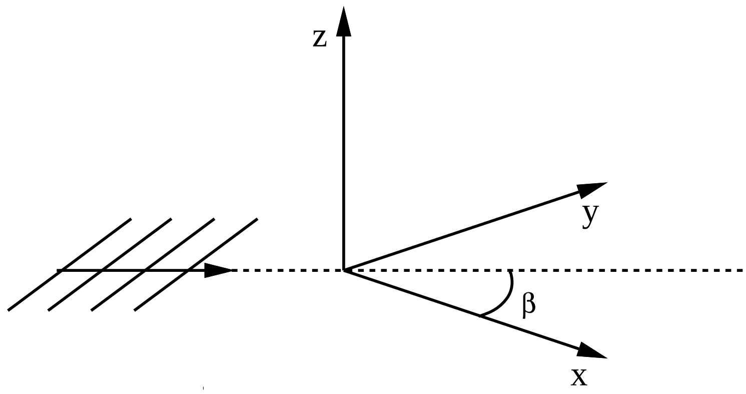

Figure 34: Definition of global coordinate system and wave heading angle

The x-y plane of the global coordinate system coincides with the still water plane, or vertically at the center of gravity, depending on selection of motion coordinate system in the **Calculation Options** dialog. The x-z plane coincides with the center-plane of the vessel. The x-axis is directed towards the stern and the z-axis is pointed vertically upwards through the center of gravity of the vessel.

The optional position of the motion coordinate system is partly historical, since the original formulation of the theory (and the implementation in VERES) was based on the vertical position being at the waterline. To ensure backwards compatibility, this option is therefore still included and it is up to the user to select the most appropriate one.

Please notice that the selection of motion coordinate system also changes the output of hydrodynamic coefficients, as many of these are a function of the vertical position of the motion coordinate system, so if you plan to use these as inputs to other programs you should be aware of your selection here. The position of the motion coordinate system is included in the output files, and the VERES Postprocessor always presents the basic RAOs at the center of gravity, independent of which motion coordinate system that has been applied in the computations.

The wave heading angle is defined as the angle between the positive x-axis and the wave propagation direction. Hence, a wave heading angle of 0 degrees corresponds to head seas, 90 degrees corresponds to beam seas, and 180 degrees corresponds to following seas. A sketch defining the coordinates and the wave heading angle β is shown in Figure 34.

The translatory displacements in the x, y and z directions with respect to the global coordinate system are denoted η_1, η_2 and η_3, where η_1 is the surge, η_2 is the sway and η_3 is the heave displacement. Furthermore, the angular displacements of the rotational motion about the x, y and z axes are denoted η_4, η_5 and η_6, for the roll, pitch and yaw angle, respectively. The translatory and rotational displacements are shown in figure 35.

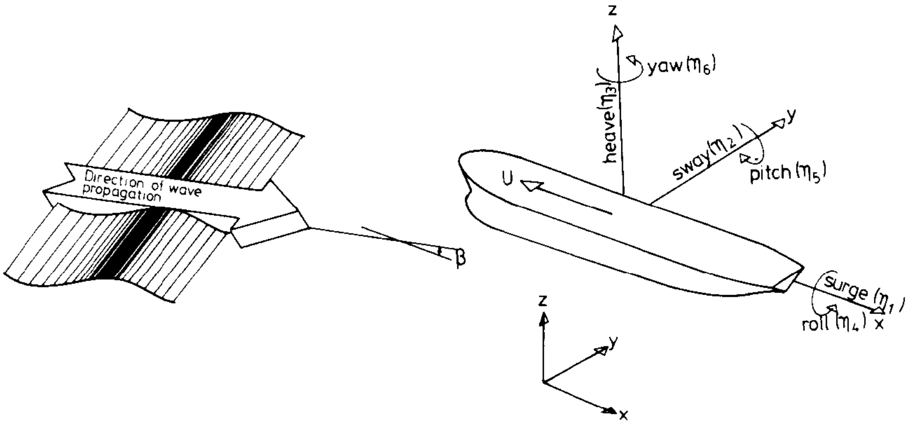

Figure 35: Sign conventions for translatory and rotational displacements

For further reference regarding the definitions for the potential theory, please refer to the Theory Manual.

3.3 Vessel description

The vessel geometry in VERES is specified in a geometry file with extension `.mgf`. The definitions for the input, as well as a description of the geometry file will be given in this chapter. In the end of the chapter, the definitions for the radii of gyration are given.

3.3.1 Coordinate system for the geometry file

The vessel description is given in a local coordinate system to preserve compatibility with previous versions of the program. The user is provided with a certain degree of freedom in choosing the vertical position of this local coordinate system. The origin of the local coordinate system is located at $L_{pp}/2$. The z-axis is pointing upwards, and the x-axis is pointing towards the stern, and is parallel to the baseline. The vertical position of the origin may be taken arbitrarily, and its position relative to the base line may be specified manually in the user interface. To enhance flexibility, the user may also specify sinkage and trim relative to the waterline given by the vessel draught. A positive trim angle implies that the draught is increased at the stern and reduced at the bow. Further, the sinkage and trim are specified relative to the local coordinate system, at $L_{pp}/2$.

3.3.2 Partitioning of the hull into strips

The hull is defined by a set of body lines at freely selected longitudinal positions. The sections (internally in VERES) are labeled from 1, starting at the foremost part of the vessel. The last section is at the aftermost part of the stern. Please notice that this is different from the definitions in ShipX, where the sections are labeled from the stern. In VERES version 4.0 and later, the ShipX definitions are applied in the VERES user interface as well as in output files, error messages etc. However, the input files are unchanged in order to preserve backwards compatibility.

A sufficient number of sections must be used in order to catch the longitudinal position of incoming waves. Also make sure they are more or less evenly distributed over the entire length of the hull. As a “rule of thumb” the minimum investigated regular wave length should be at least five times longer than the distance between the strips. Typically, approximately 30 sections will be sufficient for most cases.

When the high speed theory is used, care should be taken with respect to the longitudinal distribution of the sections, the sections should be as evenly distributed as possible, and large variations of the distance between following sections should not occur.

3.3.3 Description of sections

The cross-sections of the hull are specified by a number of offset points, which are further interpolated upon in VERES. The interpolation algorithm will use constant spacing between the interpolated points on each section.

The user distributes the points on one half of the hull section, and VERES will subsequently mirror them about the center line plane to give a complete description of the hull section. This means that for a monohull half of the hull section needs to be described, whilst for a catamaran one of the hulls, stretching from the hull side to the center line plane, will be required (Figure 36).

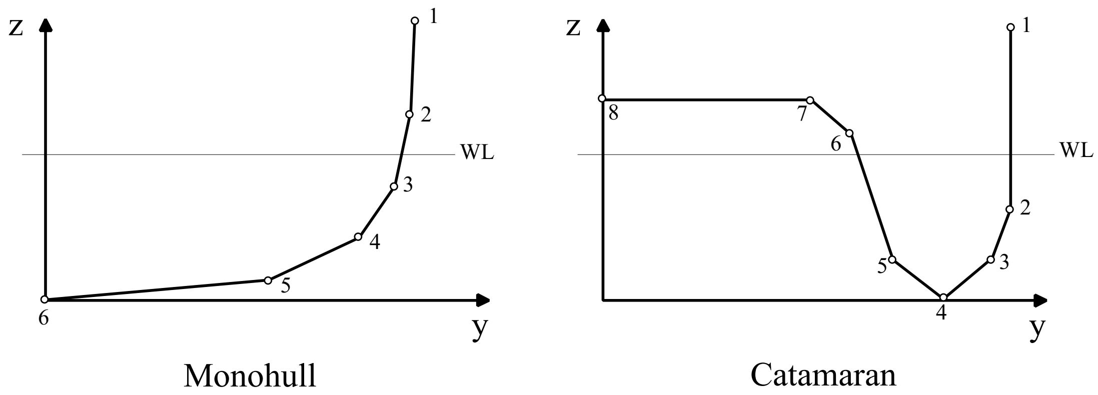

Figure 36: Description of the hull offset points

The specification of offset points requires consideration of the following factors:

- The offset points and the straight lines between them should provide a good geometrical description of the section shape.
- The contours must be specified sufficiently high up on the hull so that interpolation can be performed with the specified waterline, sinkage and trim.
- When seen from the stern, the offset points must be given clockwise along the contour starting from the deck, and with the last point being at the intersection of the section contour and the center line (Figure 36). For bulb sections, and fully submerged sections, the first point must be at the part of the contour nearest the free surface.

Normally 20 offset points on each half section will provide an adequate description of the sectional shape and assure that correct added mass and damping coefficients[11] are obtained. However, when choosing the number of interpolated offset points, attention should be given both to the wavelength of the incident waves and the ship speed. If the frequency of encounter (refer section 3.2), which is the actual oscillation frequency of the

[11]See Section 3.4 for definitions.

ship, is high, more elements on each section will be needed.

3.3.4 Geometry file

The VERES geometry file format looks as follows:

```
Text string 1
Text string 2
Text string 3
Text string 4
LPP (i.e. the value of Lpp, NEW IN VERES VERSION 4!)
Section_number
X-position
Number_of_points
y(Section_number,1)                   z(Section_number,1)
y(Section_number,2)                   z(Section_number,2)
       .                                      .
       .                                      .
y(Section_number,Number_of_points)    z(Section_number,Number_of_points)
Next_section_number
       .
       .
       .
```

Here is an example of the first lines for the S-175 hull with a few comments to the right:

```
Geometry file
Demo
S-175 Container Ship
Basic design, Draught = 9.5 m
175.0                                Lpp
          1                          section number 1
  -87.5                              x-location for section 1
        15                           number of offset-points
  0.280      11.000                  (y,z) for offset-point 1
  0.110      10.000                  (y,z) for offset-point 2
  0.100       9.000                             ''
  0.200       8.000                             ''
  0.350       7.000                             ''
  0.560       6.000                             ''
  0.820       5.000                             ''
  1.100       4.000                             ''
  1.320       3.000                             ''
  1.340       2.000                             ''
  1.050       1.000                             ''
  0.910       0.750                             ''
  0.660       0.500                             ''
  0.540       0.250                             ''
  0.000       0.130                  (y,z) for offset-point 15
          2                          section number 2
  -83.125                            x-location for section 2
        15                           number of offset-points
  1.210      11.000                  (y,z) for offset-point 1
  0.960      10.000                  (y,z) for offset-point 2
  0.800       9.000                             ''
```

```
0.670        8.000                    ''
    .            .
    .            .
```

3.3.5 Radii of gyration

The mass moments of inertia are specified by the radii of gyration about the center of gravity [12], and are transformed by VERES to the motion coordinate system. The values are given as input in the *Vessel Description* dialog. The following values are specified:

Value	Description	Typical values
r_{44}	Radius of gyration in roll (m)	$0.30B - 0.45B$
r_{55}	Radius of gyration in pitch (m)	$0.20L_{pp} - 0.30L_{pp}$
r_{66}	Radius of gyration in yaw (m)	$0.25L_{pp} - 0.30L_{pp}$
r_{64}	Coupled radius of gyration in roll-yaw (m)	≈ 0.00

Typical values for a *monohull* are given in the last column, where B is the vessel breadth, and L_{pp} is the vessel length between the perpendiculars.

The radii of gyration are defined as follows:

$$r_{44} = \sqrt{\frac{\sum(y^2+z^2)\cdot \Delta M}{M}}, \tag{1}$$

$$r_{55} = \sqrt{\frac{\sum(x^2+z^2)\cdot \Delta M}{M}}, \tag{2}$$

$$r_{66} = \sqrt{\frac{\sum(x^2+y^2)\cdot \Delta M}{M}}, \tag{3}$$

$$r_{64} = \begin{cases} \sqrt{\frac{I}{M}} & \text{if } I \geq 0 \\ -\sqrt{\frac{|I|}{M}} & \text{if } I < 0 \end{cases} \quad \text{where } I = -\sum x \cdot z \cdot \Delta M, \tag{4}$$

where the coordinates x,y and z are given relative to the center of gravity in a coordinate system similar to the input coordinate system (ref. Section 3.3.1). ΔM is the weight of an item located at (x, y, z) and M is the total weight of the vessel.

[12]This definition differs from VERES Version 1.0, where the radii of gyration were given relative to the motion coordinate system (i.e. the waterline).

3.4 Equations of motion

VERES is based on *linear strip theory*. The basic assumptions of the linear theory are:

- The wave-amplitudes are small compared to some characteristic dimension of the vessel. The resulting motions will then be proportionally small.
- The wave steepness is small, i.e. the waves are far from breaking.

In linear theory, the wave loads and motions are linearly proportional to the wave amplitude. As a consequence of this, we can obtain results in irregular waves simply by adding together results from regular waves of different amplitudes, wavelengths and propagation directions.

To simplify the problem further, *steady-state conditions* are assumed, i.e. there are no transient effects present due to initial conditions. This implies that the linear dynamic loads on the body are harmonically oscillating with the same frequency as the wave loads that excite the body (i.e. the frequency of encounter), and thus allows us to perform our computations in the frequency domain. The *frequency of encounter*, ω, is the frequency the ship will oscillate with. ω is given from the relation :

$$\omega \;=\; \omega_0 + \frac{\omega_0^2 U}{g}\cos\beta \tag{5}$$

where ω_0 is the wave frequency, U is the forward velocity of the vessel, and g is the acceleration of gravity.

Under the assumptions that the responses are linear and harmonic, the six linear coupled differential equations of motion can be written:

$$\sum_{k=1}^{6}\left[(M_{jk}+A_{jk})\ddot{\eta}_k + B_{jk}\dot{\eta}_k + C_{jk}\eta_k\right] = F_j e^{i\omega t}, \quad j = 1,\ldots,6, \tag{6}$$

where

M_{jk} are the elements of the generalized mass matrix

A_{jk} are the elements of the added mass matrix

B_{jk} are the elements of the linear damping matrix

C_{jk} are the elements of the stiffness matrix

F_j are the complex amplitudes of the wave exciting forces and moments, with the physical forces and moments given by the real part of $F_j e^{i\omega t}$. F_1, F_2 and F_3 refer to the amplitudes of the surge, sway and heave exciting forces, while F_4, F_5 and F_6 are the amplitudes of the roll, pitch and yaw exciting moments, respectively.

ω is the angular frequency of encounter

η_k are surge, sway, heave, roll, pitch and yaw motion amplitudes, respectively. The dots stand for time derivatives, so that $\dot{\eta}_k$ and $\ddot{\eta}_k$ are velocity and acceleration terms, respectively.

The different contributions to the equations of motion are:

- **Mass forces:**
  The mass forces are forces due to the mass of the vessel, and follows directly from Newton's law. We can formally write the mass forces due to the harmonic motion mode η_k as

$$F_j = -M_{jk}\ddot{\eta}_k \tag{7}$$

  where M_{jk} are the generalized mass coefficients.

  Assuming that the vessel is symmetric about the $x - z$ plane and that the center of gravity is located at $(0, 0, z_G)$, the *generalized mass matrix* may be written as

$$M_{jk} = \begin{bmatrix} M & 0 & 0 & 0 & Mz_G & 0 \\ 0 & M & 0 & -Mz_G & 0 & 0 \\ 0 & 0 & M & 0 & 0 & 0 \\ 0 & -Mz_G & 0 & I_4 & 0 & I_{64} \\ Mz_G & 0 & 0 & 0 & I_5 & 0 \\ 0 & 0 & 0 & I_{64} & 0 & I_6 \end{bmatrix}. \tag{8}$$

  Here M is the mass of the vessel, I_j is the moment of inertia in the jth mode, and I_{64} is the yaw-roll product of inertia. I_{64} will vanish if the vessel has fore-aft symmetry and is otherwise small for conventional ships.

- **Added mass and damping forces and moments:**
  The added-mass and damping forces are steady-state hydrodynamic forces due to forced harmonic rigid body motions when there are no incident waves present. The forced motion of the vessel generates outgoing waves and oscillating fluid pressures on the hull surface. Integrating these pressures over the wetted surface of the hull gives forces on the body proportional to the body acceleration and body velocity. We can formally write the hydrodynamic added mass and damping due to the harmonic motion mode η_k as

$$F_j = -A_{jk}\ddot{\eta}_k - B_{jk}\dot{\eta}_k \tag{9}$$

  where A_{jk} and B_{jk} are the added mass and damping coefficients respectively.

- **Restoring forces and moments:**
  When a vessel is freely floating, the restoring forces will follow from hydrostatic and weight considerations. The restoring force coefficients are independent of the velocity potential and wave frequency, and depend only on the body geometry and mass distribution. We may write these force and moment components as

$$F_j = -C_{jk}\eta_k \tag{10}$$

  where C_{jk} are the restoring coefficients.

- **Linearized wave exciting forces and moments:**
  The wave exciting forces and moments are the loads on the body when the body is *restrained* from oscillating and there are incident waves. These forces can be divided in two effects. One effect is the force due to the undisturbed pressure field from the incident waves, and the second because the body changes this pressure field. These forces are referred to as the *Froude-Krylov* and *diffraction* forces respectively.

After having determined these coefficients, the equations of motion (6) may be solved numerically by a direct equation solver after substitution of

$$\eta_k = \tilde{\eta}_k e^{i\omega t}, \tag{11}$$

where $\tilde{\eta}_k$ is the complex motion amplitude. Non-linear roll damping is added as additional linearized damping by using equivalent linearization (more about these viscous contributions in the Theory Manual). This requires an iteration technique to solve the equations of motions. A wave amplitude for the linearization is required as one of the inputs in VERES.

The motion transfer functions are then given by the amplitude η_a and phase angle θ, defined by

$$\eta_k(t) \quad = \quad \eta_{ka} \cos(\omega t + \theta_k), \qquad k = 1, \ldots, 6. \tag{12}$$

For a ship with lateral symmetry (i.e. symmetry about the $x - z$ plane), surge, heave and pitch are not coupled with sway, roll and yaw. Thus any error in the sway, roll and yaw motion computations will not affect the accuracy of the surge, heave and pitch results.

For further reference, see the Theory Manual.

3.5 Viscous roll damping

In order to predict the roll motions, VERES can include viscous roll damping from the hull and from bilge keels.

The roll equation of motion is be written as

$$\begin{gathered}(M_{42}+A_{42})\ddot{\eta}_2+B_{42}\dot{\eta}_2+\\(M_{44}+A_{44})\ddot{\eta}_4+(B^P_{44}+B^{V1}_{44})\dot{\eta}_4+B^{V2}_{44}|\dot{\eta}_4|\dot{\eta}_4+C_{44}\eta_4+\\(M_{46}+A_{46})\ddot{\eta}_6+B_{46}\dot{\eta}_6=F_4,\end{gathered} \tag{13}$$

where the superscripts P, $V1$ and $V2$ denotes the potential, linear and quadratic viscous damping terms, respectively.

This equation is nonlinear due to the quadratic viscous damping term, and is linearized by using equivalent linearization. The final solution is then found by using an iteration technique.

A brief summary of the theory for the viscous roll damping follows. Further information can be found in the references.

The following components of viscous roll damping are included in VERES:

- Frictional damping caused by skin friction stresses on the hull
- Eddy damping caused by pressure variation on the naked hull
- Lift damping
- Bilge keel damping

The analysis is carried out for two dimensional cross sections. The different components are briefly discussed in the following, and their contributions to the linear and nonlinear roll damping coefficients B^{V1}_{44} and B^{V2}_{44} are presented in the Theory Manual. For further reference, see Aarsnes [1] and Himeno [10].

Frictional roll damping The frictional roll damping accounts for the damping caused by skin friction on the hull. For the frictional damping, Kato's[15] formulas for turbulent flow are used. In full scale, the flow may usually be assumed to be turbulent, and the frictional roll damping will be nonlinear.

Eddy damping This damping component is caused by flow separation at the bilge of the cross section. Based on results from forced roll tests for a number of two dimensional cylinders without bilge keels, Ikeda et.al. [12] has proposed a prediction method, which is applied in the VERES program.

Lift damping The lift forces acting on a hull with forward speed, represents a contribution to roll damping. The roll damping due to lift effects is presented in Himeno [10], where the contribution from the lift effects is expressed in terms of an equivalent linear damping term (see Theory Manual for details).

Bilge keel damping Bilge keel damping accounts for the increase in roll damping due to the bilge keels. The bilge keel damping can be divided into two components:

- **Damping due to normal forces on bilge keels:**
  This component represents the drag forces obtained by the bilge keels.
- **Damping due to hull pressure created by bilge keels:**
  This component represents the difference in hull pressure with and without bilge keels, and can therefore be regarded as an effect of the bilge keels.

3.6 Moonpools

3.6.1 Introduction

VERES can include the effects of monpools in a simplified manner. The main intention is to enable input of correct displacement and restoring terms using the Moonpool module, ensuring better calculation of roll motions (e.g. correct natural period) etc. Dynamic effects due to water motion in the moonpools are not accounted for in the current version.

The following effects are included:

- The volume displacement of the vessel is corrected by to subtraction of the volume of the moonpools.
- The center of buoyancy is corrected.
- The longitudinal and transverce metacentric heights are corrected.
- The mass and restoring matrices are updated.
- The Froude-Krylov forces at the bottom of the moonpool are subtracted from the wave exciting forces by calculating these forces on a flat plate located at the bottom position.
- Added mass in surge, sway and yaw include the mass of the water in the moonpools.

3.6.2 Input description

A moonpool with an off-center transverse position is treated as a pair with one on each side of the centerline. An off–center moonpool will be restricted so that it can not cross the centerline. The monpool is described using the following dimensions:

- Position of the center of the moonpool in longitudinal and transverse direction
- Vertical position of the bottom opening
- Definition of the geometry in the waterline (length and width)
- Definition of the geometry at the bottom opening (length, width and height of restriction)

The input dialog is shown in Figure 37, while Figure 38 displays a side view of a moonpool defining the various parameters applied to describe a moonpool. The parameters used in the user interface are shown with bold letters.

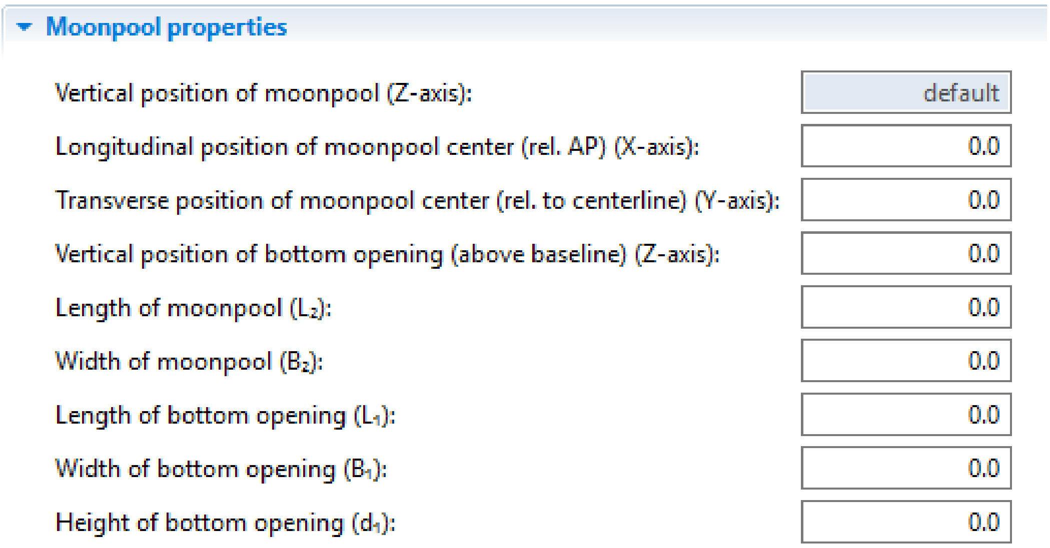

Figure 37: The Moonpool Input dialog

The following parameters are defined in Figure 38:

D	Depth of the moonpool
$A(0)$	Area of the monpool opening in the waterline
$A(-D)$	Area of the moonpool opening at the bottom
$L2$	**Length of moonpool**
$B2$	**Width of moonpool**
$L1$	**Length of monpool bottom opening**
$B1$	**Width of moonpool bottom opening**
$d1$	**Height of moonpool bottom opening**
$d2$	Height of moonpool above bottom opening restriction

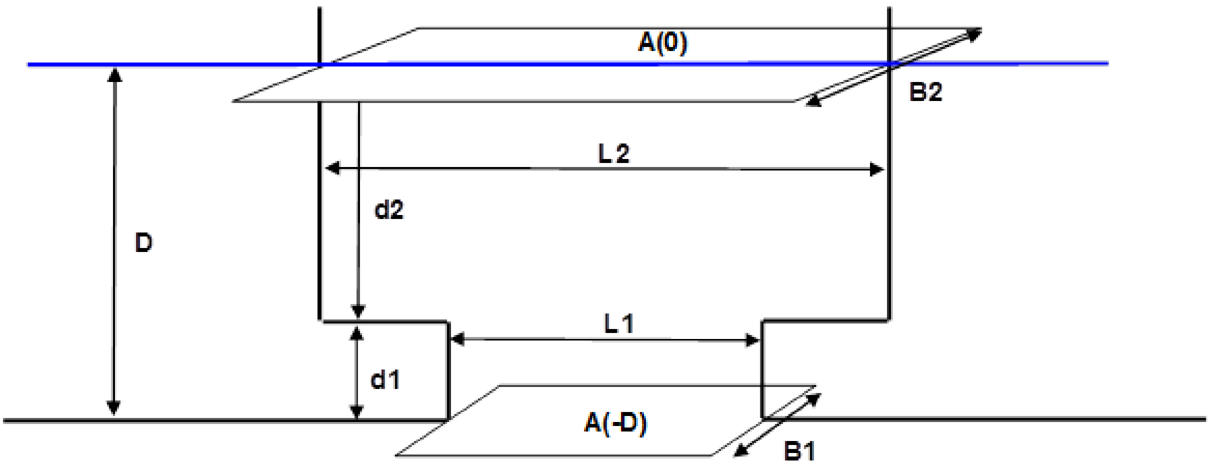

Figure 38: Scematic side view of a rectangular Moonpool

3.6.3 Natural period of moonpool

The natural period of the moonpool can be calculated with available methods. A simple method that can be applied for a moonpool with two different cross sections is given in DNV Recommended practice DNV-RP-H103.

$$T_0 = \frac{2\pi}{\sqrt{g}} \sqrt{\int_{-D}^{0} \frac{A(0)}{A(z)} dz + \frac{A(0)}{A(-D)} \cdot \kappa \sqrt{A(-D)}}. \tag{14}$$

According to DNV-RP-H103 [13] the parameter κ can be used equal 0.46 for all realistic rectangular moonpools with typical structural openings in the damping zone, while κ equal 0.48 can be applied for circular a moonpool. In the text report that can be generated in VERES a value of 0.46 has been applied.

[13] DNV Recommended Practice DNV-RP-H103, Modeling and analysis of marine operations, DRAFT December 2008.

4 POSTPROCESSOR REFERENCE

4.1 Responses in regular waves

This chapter describes some definitions concerning the responses in regular waves as a reference when using the Postprocessor. Some of the definitions here are already defined earlier in the text, but they are briefly summarized here to give a quick reference.

4.1.1 Transfer functions

The ratio of the response amplitude per amplitude of excitation is known as the *transfer function*. Physically, it is the complex amplitude of e.g. the vessel motion, or a global load in response to an incident wave of *unit amplitude*, with frequency ω and direction β.

The wave elevation at the origin (i.e. at LCG) is defined as

$$\zeta = \zeta_a \sin(\omega t) \tag{15}$$

and the motion transfer functions are defined in Section 3.4 as

$$\eta_k(t) = \eta_{ka} \cos(\omega t + \theta_k), \quad k = 1, \ldots, 6. \tag{16}$$

Here, η_a is the the motion amplitude per unit wave amplitude and θ is the phase angle. *The motion transfer functions give the proportion of wave amplitude or wave slope "transferred" by the ship "system" into the ship motions.* The response amplitude per unit wave amplitude is often referred to as the *response amplitude operator (RAO)*.

When the motions are presented as motion transfer functions, the motion response in a regular wave of e.g. 2 meters amplitude (wave height of 4 meters) can be obtained by selecting the RAO value for a given vessel velocity, wave period and heading and multiply with the factor 2.

4.1.2 Definition of phase angles

The phase angle θ_k in eqn. (16) gives the phase relationship between the motion and the wave: a positive value means that the maximum positive motion occurs θ_k/ω seconds before the maximum wave elevation is experienced at the longitudinal center of gravity. Negative values implies that the motion lags the wave elevation.

Examples: A phase angle of ± 180 degrees means that the response is opposite of the wave elevation, while 0 degrees is in phase with the wave elevation.

A table presenting typical asymptotic values of the phase angles in head, beam and following seas is shown below.

Degree of freedom	Wave heading		
	Head seas	Beam seas	Following seas
Surge	-90		90
Sway		-90	
Heave	0	0	0
Roll		-90	
Pitch	90		-90
Yaw			

Table 2: Asymptotic phase angles for long periods. The places where the phase angles have no meaning are left blank.

4.1.3 Relative motions between the ship and the wave

Slamming and deck wetness are of considerable importance in assessing the seakeeping performance of a ship. These qualities are largely determined by the magnitude of the relative motions and velocities between the hull and the adjacent sea surface.

The relative vertical motions between the ship and the waves can be calculated in the postprocessor, assuming that the waves are undisturbed by the presence of the ship. The relative motions, as well as velocities and accelerations, can be presented as transfer functions, with RAOs and phase angles.

The relative vertical motions at a position (x, y, z) on the vessel are calculated as:

$$\eta_{3r}(x, y, z) = \eta_3(x, y, z) - \zeta(x, y) \tag{17}$$

where η_{3r} is the complex amplitude of the relative vertical motions, η_3 is the complex amplitude of the local vertical motions, and $\zeta(x, y)$ is the undisturbed wave elevation at the given position, which can be expressed as

$$\zeta(x, y) = e^{-ik(x\cos\beta + y\sin\beta)} \tag{18}$$

where k is the infinite-depth wave number, β is the wave heading and the calculations are performed with a unit wave amplitude.

For correct calculation of slamming statistics, the relative vertical velocities are calculated as suggested by Faltinsen [6]:

$$V_R(x, y, z) = \dot{\eta}_3(x, y, z) - w(x, y) - U\eta_5 \tag{19}$$

where U is the ship speed and w is the vertical component of the undisturbed wave velocity in the free-surface at the point considered. The relative vertical accelerations are calculated by taking the time derivative of the relative vertical velocity.

In practice the prescence of the hull causes a considerable distortion of the waves close to the ship and the above equations are only likely to be reliable at the forward perpendicular. Further aft, the error in the relative motions may be considerable. For bottom slamming in the bow region, the above assumptions are relevant, since the bow is assumed to go out of the water and re-enter with a certain velocity. The waves will then be undisturbed by the prescence of the ship at the time of impact. See also the next section regarding calibration of relative vertical motions.

Calibration of relative vertical motions The VERES Postprocessor includes an option to include a calibration file (*.rmc) to calibrate the relative motion transfer functions at a given motion point on the ship. In this case, the transfer functions are multiplied with a calibration factor which can be dependent on speed, heading and frequency. This option can be applied to calibrate relative motions with model test results and thus enable the user to perform calculations with more realistic relative motions e.g. behind the ship's stern or to account for water pile-up in the bow region (deck wetness studies). A description of the file format can be found in Appendix 5.2.4, page 107.

4.1.4 Forces in the body-fixed coordinate system

When dealing with criteria regarding persons or objects in a frame of reference fixed to the ship (which is usually the case), the accelerations (or forces per unit mass) in this reference frame must include the gravity forces if there are roll- and/or pitch motions present. We will denote these forces as the Longitudinal, Lateral and Vertical Force Estimators, since the accelerations can be thought of as forces per unit mass. The expressions for the acceleration RAOs in the body-fixed system (when removing higher order terms) are shown below.

The Longitudinal Force Estimator (LON) is given by

$$LON(x, y, z) = -\ddot{\eta}_1(x, y, z) + g\eta_5, \tag{20}$$

the Lateral Force Estimator (LFE) by

$$LFE(x, y, z) = -\ddot{\eta}_2(x, y, z) - g\eta_4, \tag{21}$$

and the Vertical Force Estimator (VFE) by

$$VFE(x, y, z) = -\ddot{\eta}_3(x, y, z), \tag{22}$$

where g is the acceleration of gravity. It should be noted that the total vertical force is actually including a g-component if you look at this in the time-domain. However as we are only dealing with the dynamic part in the postprocessor, the acceleration of gravity is not present in the calculation of VFE. One should remember though, that the vertical forces are oscillating about a non-zero value (g), as opposed to the LON and LFE. This should be accounted for if one wishes to calculate the total vertical forces on an object.

The LFE is important in determining the ability of the crew to work effectively as well as estimating the likelyhood of a secured object sliding across the deck or topling over. As an example: The transverse loads on a container can be determined as the LFE times the mass of the container. Furthermore, if the position of the center of gravity is known, the tipping moment can be evaluated.

The absolute longitudinal (surge) and lateral (sway) accelerations evaluated by the VERES Postprocessor differ from the LON and LFE in that the accelerations are relative to the ship's mean position (i.e. horizontal) and not parallel to the deck when the ship is rolling and pitching. For this reason, *the LON and LFE should be applied rather that the surge and sway accelerations as seakeeping criteria which are specified by means of horizontal accelerations*, as these criteria are based on measurements on the ship and are measured in the ship's reference frame. The accelerations used in seasickness criteria such as MSI and MSDV$_z$ also use the body-fixed accelerations.

4.2 Short term statistics

This chapter describes the theory related to the calculation of short term statistics in the VERES Postprocessor. When calculating short term statistics, the transfer functions calculated in VERES are combined with sea states (selected by the user, and characterized by a standard wave spectrum) which are appropriate for the ocean area and operation characteristics of the vessel. Short term statistics expresses the behaviour of the vessel in a seaway in terms of statistical properties such as the RMS–value or the significant value, and may be compared with e.g. operational demands.

The three available standard wave spectra, as well as the option to include a user defined wave spectrum are described in Section 4.2.1. Short-crested seas are discussed in Section 4.2.2, and the calculation of result quantities are presented in Section 4.2.3. At the end of the chapter, Motion-Induced Interruptions and Motion Sickness Incidence are defined (Sections 4.2.4 and 4.2.6).

4.2.1 Representation of sea states

The regular waves on which the transfer functions (see Chapter 4.1) are based, do not exist at sea. The wave amplitude and period vary over time, and this is referred to as irregular waves. An irregular sea state may be characterized by a standard wave spectrum such as the Pierson–Moskowitz[14] , the JONSWAP (Joint North Sea Wave Project) wave spectrum or the two peaked Torsethaugen wave spectrum which are all available in the VERES Postprocessor. The wave spectrum expresses the distribution of wave energy (which is proportional to the wave amplitude squared) for different wave frequencies. The standard spectra are suitable for different types of irregular sea, i.e. different ocean areas:

The JONSWAP spectrum is assumed to be especially suitable for the North Sea, and does not represent a fully developed sea. It has a peakedness parameter γ, which determines the concentration of the spectrum about the peak frequency. The formulation of the JONSWAP spectrum is given in Section 4.2.1

The Pierson–Moskowitz spectrum or Bretschneider spectrum is suitable for a fully developed sea, i.e. a sea state where the wind has been blowing long enough over a sufficiently open stretch of water, so that the high frequency waves have reached equilibrium. At this point, the waves are breaking slightly. In the part of the spectrum where the frequency is greater than the peak frequency ($\omega > \omega_p$), the energy distribution is proporsional with ω^{-5}. For a given significant wave height and peak period, the Pierson–Moskowitz spectrum is identical with the Bretschneider, ISSC and ITTC spectrum models. The Pierson–Moskowitz spectrum appears for $\gamma = 1$ in the JONSWAP formulation. The naming option for this spectrum can be selected in the program Preferences.

The Torsethaugen spectrum is a two peaked spectrum which includes both wind generated sea and swell. An option is included to enable long crested swell from a direction different from the principal wave direction (direction of the wind generated waves).

Figure 39 shows the JONSWAP spectrum for γ=1–7, where γ=1 is equivalent to the Pierson–Moskowitz spectrum. The concentration of wave energy with increasing γ can easily be seen.

[14] The formulation in VERES is identical to JONSWAP with $\gamma = 1$ which is also identical to the Bretschneider spectrum. You can use Bretschneider as the naming for this spectrum by selecting this option in the program Preferences.

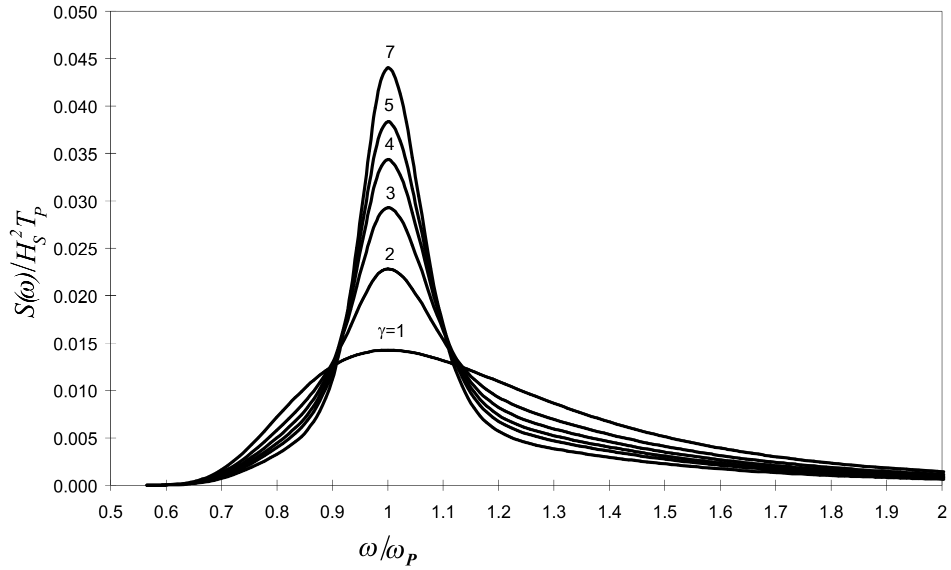

Figure 39: The JONSWAP spectrum for $\gamma=1$–7. The spectrum for $\gamma=1$ equals the Pierson–Moskowitz spectrum.

In addition to the standard sea spectra, the VERES Postprocessor includes the option to import a **user defined wave spectrum** for a specific seastate from file. This enables e.g. comparisons between model (or full-scale) tests and calculations applying the same measured wave spectrum. The file format is presented in Appendix 5.2.2, page 105. Unidirectional spectra as well as short-crested spectra are included in this option. Since the user-defined spectrum only defines one sea-state, some of the postprocessor options are not available when this option is chosen.

In addition to the Torsethaugen wave spectrum to represent two peaked spectra, one can also combine two JONSWAP spectra when calculating short term statistics. The JONSWAP two peaked spectrum is simply a summation of two JONSWAP wave spectra, where the swell component can be explicitly defined (as opposed to the Torsethaugen formulation). The options for the two peaked JONSWAP spectra are the same as for the Torsethaugen spectrum; i.e. the swell component can either have the same long- or shortcrestedness as the wind component, or one can choose to have a long-crested swell component with either a constant offset direction from the wind direction, or a constant offset direction relative to the ship.

Hint: If you want to plot the spectrum shape for a specified wave spectrum in the VERES Postprocessor, then select the *Combinations of Hs and Tp* option in the **Specify Wave Spectrum** dialog. There you can click the *Plot* button to view the spectra you have entered.

Formulation of the JONSWAP wave spectrum According DNV Classification Notes 30.5 [22], the spectral density function for the JONSWAP (Joint North Sea Wave Project) spectrum can be written as:

$$S_\zeta(\omega_0) = \alpha g^2 \omega_0^{-5} e^{-\frac{5}{4}\left(\frac{\omega_p}{\omega_0}\right)^4} \gamma^{e^{-\frac{1}{2}\left(\frac{\omega_0-\omega_p}{\sigma\omega_p}\right)^2}} . \qquad (23)$$

The wave spectrum parameters are

α	–	Spectral parameter (generalized Phillips' constant)
g	–	acceleration of gravity
ω_0	–	Wave frequency (rad/sec)
ω_p	–	Peak frequency, $\omega_p = 2\pi/T_p$
γ	–	Peakedness parameter
σ	–	Spectral width parameter, $\sigma = 0.07$ for $\omega_0 < \omega_p$ and $\sigma = 0.09$ for $\omega_0 > \omega_p$

The Pierson–Moskowitz spectrum appears for $\gamma = 1$.

The spectral parameter α is computed as

$$\alpha = \frac{5}{16}\frac{H_s^2\omega_p^4}{g^2}(1 - 0.287\ln\gamma) \tag{24}$$

$$= 5.061\frac{H_s^2}{T_p^4}(1 - 0.287\ln\gamma), \tag{25}$$

where H_s is the significant wave height.A standard value of the peakedness parameter γ is 3.3. However, a more correct approach is to relate the peakedness parameter to the significant wave height and the peak period:

$$\gamma = \begin{cases} 5 & \text{for } T_p/\sqrt{H_s} \le 3.6, \\ e^{5.75-1.15T_p/\sqrt{H_s}} & \text{for } 3.6 \le T_p/\sqrt{H_s} \le 5, \\ 1 & \text{for } 5 \le T_p/\sqrt{H_s}. \end{cases} \tag{26}$$

In the VERES Postprocessor, you can choose either to specify the peakedness parameter γ directly, or the γ value can be calculated from (26) based on the significant wave height and peak period. Figure 40 shows how the γ–value varies with H_s and T_p.

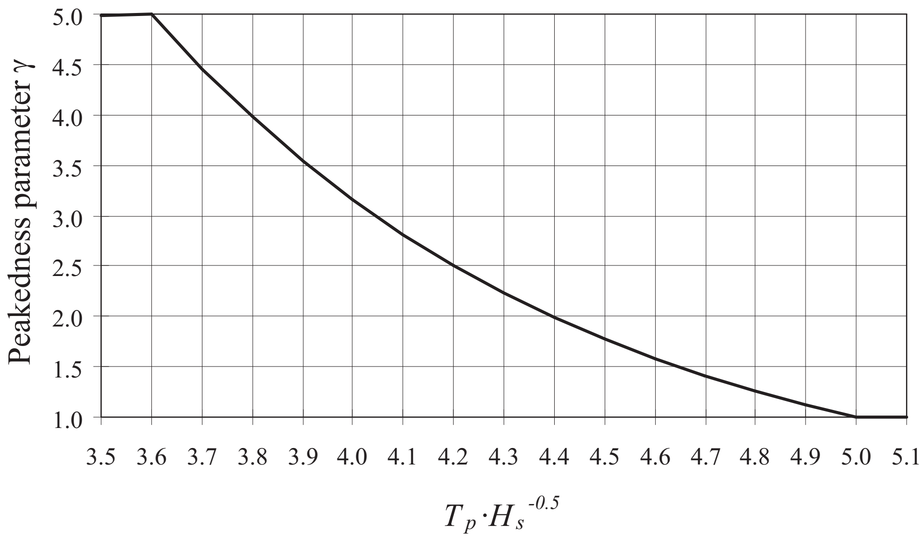

Figure 40: The γ–value as a function of $T_p/\sqrt{H_s}$, calculated from equation (26).

The spectral moments of general order n are defined as:

$$m_n = \int_0^\infty \omega_0^n S(\omega_0) d\omega_0 \qquad n = -1, 0, 1, 2, ... \tag{27}$$

For the JONSWAP spectrum as formulated above, the spectral moments m_0, m_1 and m_2 can be approximated by:

$$m_0 = \frac{1}{16} H_s^2 \tag{28}$$

$$m_1 = \frac{1}{16} H_s^2 \, \omega_p \, \frac{6.8 + \gamma}{5 + \gamma} \tag{29}$$

$$m_2 = \frac{1}{16} H_s^2 \, \omega_p^2 \, \frac{11 + \gamma}{5 + \gamma} \tag{30}$$

The mean wave period T_1 and the mean zero-crossing period T_z can be calculated from the spectral moments above, giving:

$$T_1 = 2\pi \frac{m_0}{m_1} = \frac{5 + \gamma}{6.8 + \gamma} T_p, \tag{31}$$

$$T_z = 2\pi \sqrt{\frac{m_0}{m_2}} = \sqrt{\frac{5 + \gamma}{11 + \gamma}} T_p. \tag{32}$$

Thus, if H_s and T_z or T_1 are specified as input to the two-parameter JONSWAP spectrum[15], the corresponding T_p and γ values are found by iteration.

Formulation of the Torsethaugen two–peaked wave spectrum Waves are usually generated by the wind blowing over an open stretch of the ocean for a period of time, and this is referred to as wind generated waves, with periods usually ranging from 1.0–10.0 sec. When the wind dies, the energy of the sea state will be transferred slowly to lower frequencies until only very long waves are left (10–100 sec). This type of waves are referred to as swell. In many ocean areas (e.g. the Heidrun oil field), the sea state is actually a combination of both swell and wind generated sea, meaning that an "old" sea state (in reality an old storm from somewhere else) is interferring with the developing sea state. A correct wave spectrum would then have two peaks, one at a low frequency, and one at a "normal" frequency. The standard spectra are not able to model such sea states, which require two–peaked spectra.

In the Torsethaugen model, a two peak model is introduced for all sea states. The wave spectrum is a sum of a primary peak and a secondary peak. The input to VERES is given by specifying the peak period for the *primary peak*. The primary peak or the highest peak, located at T_p, is either generated by local wind fields (sea Type I), or is a result of swell (sea Type II). The *secondary peak* for sea of Type I represents the contribution from swell and for sea of Type II the contribution from local wind. For fully developed wind sea the secondary peak vanishes. Fully developed sea is represented by a narrow band of T_p for a given H_{m0} where there is an equilibrium between energy input and energy losses.

To identify wether a given combination of H_{m0} and T_p represents wind dominated sea (Type I) or swell dominated sea (Type II), the following boundary is applied:

$$T_f = 6.6 H_{m0}^{1/3}. \tag{33}$$

[15]When γ is to be calculated by means of (26), we refer to this as the *two–parameter* JONSWAP spectrum, as only H_s and a characteristic period (T_p,T_z or T_1) are specified as input.

Thus, when $T_p \leq T_f$, a wind dominated sea model (Type I) is applied, and when $T_p > T_f$, a swell dominated sea model (Type II) is applied. When a Torsethaugen spectrum model is applied with long–crested swell, the VERES Postprocessor provides an option to specify an offset direction for the swell. The wind generated sea can then be short– or long–crested, and the swell part of the spectrum will be applied as long–crested from the specified direction relative to the primary (wind generated) wave direction.

The spectral model used in the Torsethaugen spectrum is the extended JONSWAP model given by

$$S(f) = ES_n(f_n), \tag{34}$$

where S_f is the wave energy density, E is the wave energy density normalization given by

$$E = \frac{m_0}{f_p} = \frac{1}{16}\frac{H_{m0}^2}{f_p}, \tag{35}$$

where f_p is the spectral peak frequency (Hz) and H_{m0} is the significant wave height defined by

$$H_{m0} = 4\sqrt{m_0}. \tag{36}$$

m_0 is the zero order moment of the wave spectrum

$$m_0 = \int_0^\infty S(f)df. \tag{37}$$

$S_n(f_n)$ is the distribution of normalized wave energy according to the extended JONSWAP model which can be written as

$$S_n(f_n) = G_0 A_\gamma \Gamma_s(f_n; N, M)\gamma_F(f_n; \gamma, \sigma), \tag{38}$$

where Γ_s is the Pierson-Moskowitz (or Bretschneider) form of the wave spectrum and γ_F is the JONSWAP peak enhancement factor. f_n is the nondimensional frequency

$$f_n = \frac{f}{f_p}, \tag{39}$$

where f_p is the peak frequency

$$f_p = \frac{1}{T_p}. \tag{40}$$

$$\Gamma_s(f_n; N, M) = f_n^{-N} \exp\left[-\frac{N}{M} f_n^{-M}\right], \tag{41}$$

$$\gamma_F(f_n) = \gamma^{\exp\left[-\left(\frac{1}{2\sigma^2}\right)(f_n-1)^2\right]}. \tag{42}$$

Here, the parameter $\sigma = 0.07$ for $f_n < 1$ and $\sigma = 0.09$ for $f_n \geq 1$. The normalizing factor related to be the P-M form is

$$G_0 = \left[\frac{1}{M}\left(\frac{N}{M}\right)^{-\frac{N-1}{M}} \Gamma\left(\frac{N-1}{M}\right)\right]^{-1}, \tag{43}$$

where Γ is the gamma function. N represents the frequency exponent for the high frequency range of the spectrum and is found to be in the range 4 to 5. The factor M may usually be given a value 4. A_γ is a function of γ, N and M and is found numerically by integration of the spectra for different values of γ, N and M. Regression analyses shows that A_γ can be approximated by

$$A_\gamma \gamma - 1 \approx f_1(N, M)(\ln\gamma)^{f_2(N,M)}, \tag{44}$$

for a wide range of γ, N and M. The functions f_1 and f_2 are found as

$$f_1(N, M) = a_1(M)(N - b_1(M))^{c_1(M)}, \tag{45}$$
$$f_2(N, M) = a_2(M)N^{b_2(M)} + c_2(M). \tag{46}$$

The parameters a_1 - c_2 are found to be well represented by

$$a_1(M) = 4.1, \tag{47}$$
$$b_1(M) = 2.0M^{0.28} - 5.3, \tag{48}$$
$$c_1(M) = -1.45M^{0.1} + 0.96, \tag{49}$$
$$a_2(M) = 2.2M^{-3.3} + 0.57, \tag{50}$$
$$b_2(M) = -0.58M^{0.37} + 0.53, \tag{51}$$
$$c_2(M) = -1.04M^{-1.9} + 0.94. \tag{52}$$

4.2.2 Short-crested seas

In reality, long-crested seas are rarely encountered at sea. A certain wave spreading is more likely to be present, such that the waves are travelling in several different directions simultaneously. The *primary* wave direction can easily be recognised, and is usually more or less aligned with the wind direction. Changes in wind direction, topological influence due to e.g. the coastline and bottom and the prescence of wave systems coming from elsewhere will all lead to a certain amount of wave spreading.

The interaction between different long-crested wave systems results in alternate enchancement and cancellation of wave crests and troughs, commonly referred to as *short-crested seas*, to describe a wave system with a spread of wave directions.

A common way to describe a short-crested sea state is to apply a cosine power spreading function so that the directional spectrum can be written as

$$S_\zeta(\omega_0, \nu) = D\ cos^m\left(\frac{\pi}{2\nu_{max}}(\nu - \mu)\right) S_\zeta(\omega_0), \tag{53}$$

where ν is the wave direction, μ is the primary wave direction and ν_{max} is the wave spreading angle.

To simplify the expression, we define the *relative wave direction* ν' as

$$\nu' = \frac{\pi}{2\nu_{max}}(\nu - \mu), \tag{54}$$

giving the equation for the directional spectrum as:

$$S_\zeta(\omega_0, \nu') = D\ cos^m(\nu')S_\zeta(\omega_0). \tag{55}$$

The constant D is a normalization factor, so that the total integrated wave energy over all the wave headings from $-\nu_{max} < \nu - \mu < \nu_{max}$ is the same for all values of m and ν_{max}:

$$D = \frac{1{\cdot}3{\cdot}5{\cdot}7\cdots m}{2{\cdot}4{\cdot}6\cdots(m-1)}\frac{\pi}{4\nu_{max}} \quad \text{if } m \text{ is odd} \tag{56}$$

$$D = \frac{2{\cdot}4{\cdot}6{\cdot}8\cdots m}{1{\cdot}3{\cdot}5{\cdot}7\cdots(m-1)}\frac{1}{2\nu_{max}} \quad \text{if } m \text{ is even} \tag{57}$$

Further, m is the wave spreading index; $m = 0$ represents an uniform spreading with equal contributions to the wave energy from all directions. As m is increased, the energy becomes increasingly concentrated about the primary wave direction (see Figure 41). Thus, a nearly long-crested sea state can be obtained by choosing a small wave spreading angle v_{max} and a high value of m.

For ship design purposes, the most common practice is to use $m = 2$ and $v_{max} = 90^{\circ}$. This 'cosine squared' spreading is apropriate for typically occurring conditions in the open ocean. However, spreading angles as low as 60° or as high as 120° may frequently be found (Lloyd [16]). Figure 42 shows a directional cosine squared spectrum for discrete heading intervals of 15° and $v_{max} = 90^{\circ}$.

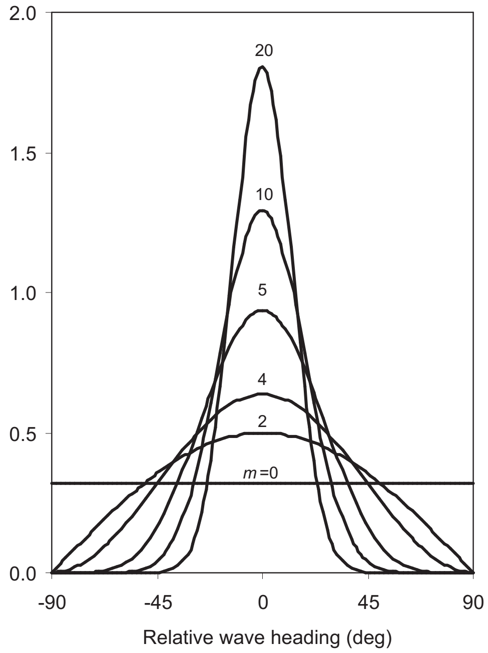

Figure 41: Wave energy spreading function $D\ cos^{m}(v')$ for different values of m as a function of the relative heading v'.

If wave headings from 0° to 180° are used in the calculations of the transferfunctions in VERES, the postprocessor will try to apply symmetry properties to obtain transfer functions for waves from the opposite side of the hull centerplane. This can be done for the motion transfer functions, since these are calculated at the centerplane. In addition, global loads calculated at the centerplane can be mirrored. For other quantities as e.g. forces and moments in longitudinal cuts which are not on the centerplane, calculations of all wave headings from 0° to 360° must be performed if one wishes to apply short-crested seas for all wave headings.

PLEASE NOTE: To get reasonable results when performing calculations with short-crested seas, it is important to make sure that enough wave headings are applied to give a good resolution over the wave spreading function (Figure 41). As an example, for a cosine squared distribution (i.e. $m = 2$) with a wave spreading angle of $\pm 90^{\circ}$ one should have a resolution of at most 30° between each wave heading, and minimum 7 wave headings within the wave spreading interval.

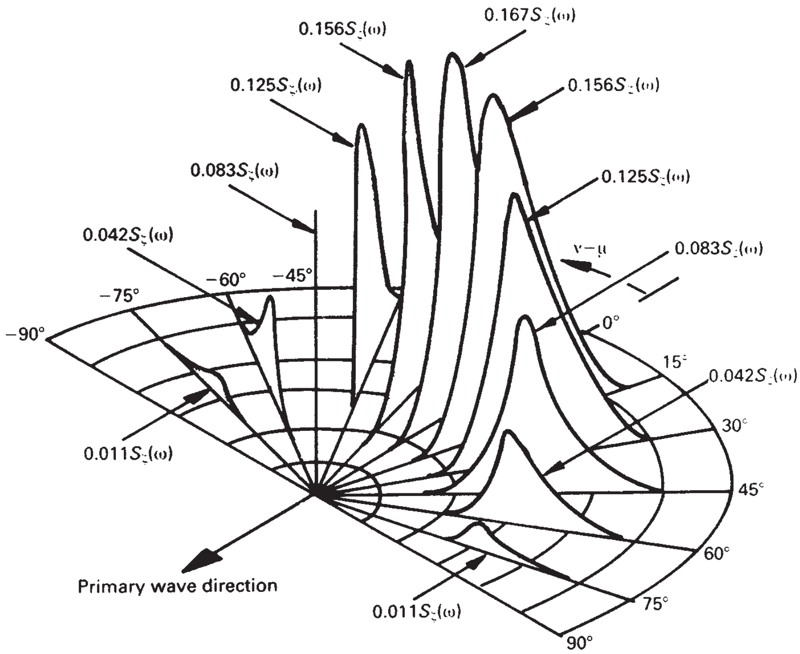

Figure 42: Representation of directional spectrum at discrete heading intervals of 15°; cosine squared distribution over ±90° (from Lloyd [16]).

4.2.3 Short term statistics of the response

Short term statistics of the response is found by combining the response transfer function with a wave spectrum to obtain a response spectrum as a function of the wave frequency. The short term statistics quantities are derived from the moments of the response spectrum. The calculation prinsiple is shown schematically in Figure 43. Note that the response–values are high when the peak frequency of the transfer function is near near the peak frequency of the wave spectrum, i.e. when the wave periods are close to the natural period of the response in question.

PLEASE NOTE: In order to calculate the short term statistics of the response, it is extremely important that the resolution of the transfer function is sufficiently good. In addition, the transfer function must cover a sufficient range of wave periods, especially in the range where the wave spectrum contains most of its energy. VIOLATION OF THIS MAY LEAD TO MEANINGLESS RESULTS FROM THE CALCULATIONS OF SHORT TERM STATISTICS. The highest wave period should therefore be at least 2.5–3 times the highest peak period. The lowest wave period should be selected so that the transfer function value is low. This low range is especially important when studying velocities and accelerations.

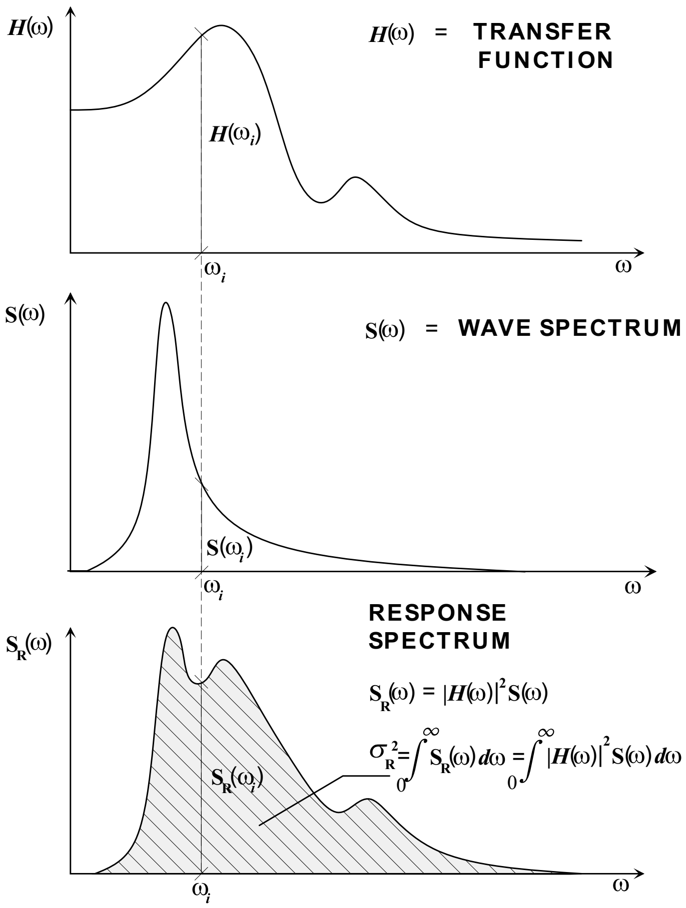

Figure 43: Prinsiple proceedure to obtain the response spectrum $S_R(\omega)$, and integrating to find the RMS–value of the response σ_R.

The following results are available in the VERES Postprocessor:

- Standard deviation of the response (RMS–value)
- Significant value of the response

- Expected maximum of the response
- Average of the $1/n$th highest response amplitudes
- Response zero–upcrossing period
- Spectral values (wave frequency)
- Spectral values (encounter frequency)

Where applicable, both single and double amplitude can be presented.

The kth moment of the response spectrum is defined by

$$m_k^\eta = \int_0^\infty |\omega|^k |H_{\eta\zeta}(\omega_0)|^2 S_\zeta(\omega_0) d\omega_0 \qquad k = 0, 2, 4, ..., \tag{58}$$

where $H_{\eta\zeta}(\omega_0)$ is the transfer function between the wave elevation ζ and the response η. The transfer functions are given as function of the wave frequency ω_0 for a given wave heading and forward speed.

The statistical properties of the responses may now be calculated from the moments of the response spectra. The square root of the zeroth order moment of the response spectrum, m_0^η represents the *standard deviation* (equals the RMS–value for linear response) expressed as

$$\sigma_\eta = \sqrt{m_0^\eta} \tag{59}$$

The *significant value* of the response (double amplitude[16]) may be calculated from the standard deviation as

$$\eta_s = 4\sigma_\eta = 4\sqrt{m_0^\eta}. \tag{60}$$

Expected maximum value $E\left(\eta_{max}\right)$ (double amplitude) in a sea state with duration T hours can be found by using the Rayleigh probability function as an approximation to the probability density function for the maxima of the responses.

$$E\left(\eta_{max}\right) = 2\sigma_\eta \left[\sqrt{2\ln N} + \frac{0.5772}{\sqrt{2\ln N}}\right], \qquad N = \frac{T \cdot 3600}{T_z^\eta} \tag{61}$$

where T_z^η is the zero–upcrossing period of the response which for forward speed will differ significantly from the zero–upcrossing period of the waves, T_z. The *zero–upcrossing period of the response* may be calculated from

$$T_z^\eta = 2\pi\sqrt{\frac{m_0^\eta}{m_2^\eta}}. \tag{62}$$

Average of the 1/nth highest response amplitudes $\overline{\eta}_{1/n}$ (double amplitude) can be found by:

$$\overline{\eta}_{1/n} = 2n\sigma_\eta \left(\sqrt{\frac{\pi}{2}}(1 - \operatorname{erf}(\sqrt{\ln n})) + \frac{1}{n}\sqrt{2\ln n}\right) \tag{63}$$

The calculated response values will be linear with respect to the significant wave height H_s if a fixed value of the peakedness parameter γ is used. Thus, the corresponding value for a different value of the significant wave height can be found by multiplying the response value by the actual significant wave height.

[16]The single amplitude values of the responses are simply half the double amplitude in linear theory.

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4.2.4 Motion Induced Interruptions – MII

Section 4.1.4 describes the calculation of the lateral force estimator (LFE) which is the lateral acceleration percieved in the plane of the ship's deck by an object or person. It is this acceleration which makes objects topple or slide across the deck and people lose their balance. Graham [9] presents the concept of using the number of Motion Induced Interruptions (MIIs) per minute as an operability criterion in frequency-domain calculations.

The MIIs can be thought of as the occasion when a crewman will have to stop working at his current task and hold on to some convenient anchorage to prevent loss of balance. In order to compare the operational performance of different vessels when no specific deck operation is being analyzed, Graham [9] has proposed to establish a standard deck operation for comparison purposes. This standard operation is defined as a one minute operation with a tipping coefficient of 0.25 resulting in the unit "MIIs per minute" for deck operations criteria. Proposed values for different risk levels are shown in Table 3.

Risk level	MIIs per minute
1. Possible	0.1
2. Probable	0.5
3. Serious	1.5
4. Severe	3.0
5. Extreme	5.0

Table 3: MII risk levels (Graham [9]).

It is suggested in [9] that deck operations are to be considered substantially degraded when the MII incidence exceeds one per minute.

4.2.5 Sliding or Toppling of Equipment

The sliding or toppling of equipment criterion applies the MII formulas, but the duration is set to one hour instead of one minute, so that the criterion value specifies number of "'events per hour"'. The tipping coefficient in the MII formula is replaced by a *sliding or toppling coefficient* which is be specified as part of the criterion input.

4.2.6 Motion Sickness Incidence – MSI according to McCauley et al (1976)

One approach to calculate the motion sickness incidence, MSI as a function of the frequency and acceleration of vertical sinusoidal motion was suggested by O'Hanlon and McCauley [20] in 1974. The concept was later refined, and a mathematical model was proposed in McCauley *et al* [17] in 1976. This model has been implemented in VERES, and it gives the opportunity to calculate the percentage MSI for a certain exposure time (exposure times of 2 and 4 hours are frequently used in the litterature). Figure 44 shows the MSI as a function of frequency and vertical acceleration level for a 2 hour exposure time.

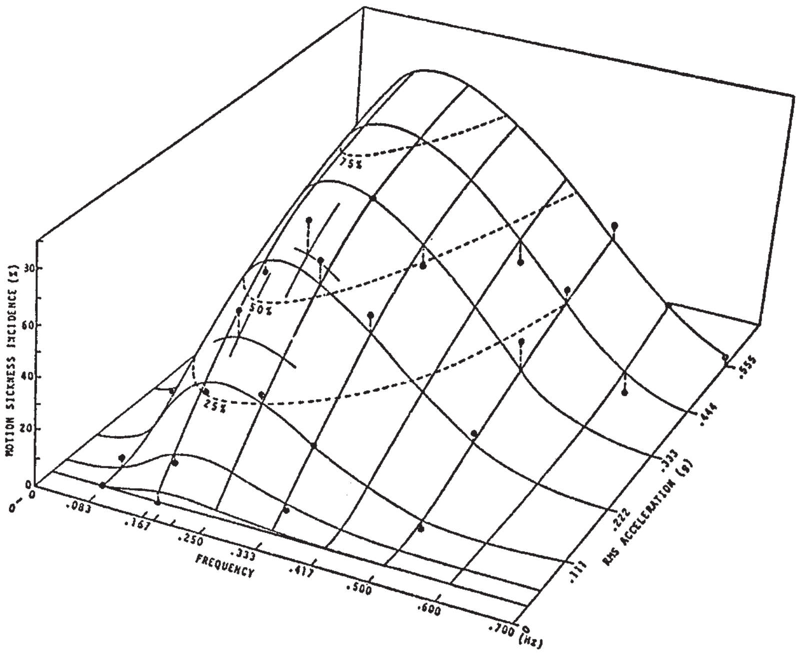

Figure 44: Motion Sickness Incidence (MSI) as a function of frequency and acceleration for 2-hour exposures to vertical sinusoidal motion (from McCauley *et al* [17]).

4.2.7 Motion Sickness Incidence – MSI according to ISO 2631-1:1997

ISO 2631-1:1997 [14] suggests an approach to calculation of the incidence of motion sickness (Annex D in [14]). A frequency–weighted sum of the r.m.s. values of vertical accelerations is calculated using specified frequency weightings for one-third octaves of the encounter frequencies. By multiplying this sum with the square root of the exposure duration (in seconds) we end up with the motion sickness dose value, MSDV_z (see section below for further reference). The percentage of people who may vomit is approximately $\mathrm{K}_m \cdot \mathrm{MSDV}_z$ where K_m is a constant which may vary according to the exposed population. According to [14] the K_m value for a mixed population of unadapted male and female adults is $\mathrm{K}_m = 1/3$. These relationships are based on exposures to motion lasting from 20 min to about 6 h with the prevalence of vomiting varying up to about 70%. In VERES, the duration of exposure as well as the K_m value can be specified manually by the user.

4.2.8 Motion Sickness Dose Value – MSDVz

The Motion Sickness Dose Value (MSDV_z) is calculated from the frequency-weighted r.m.s. value of the vertical acceleration (a_{zw}). The vertical Motion Sickness Dose Value MSDV_z in $m/s^{1.5}$ for the exposure period T_0 (s) is defined by the following expression:

$$\mathrm{MSDV}_z = a_{zw}\sqrt{T_0}. \tag{64}$$

The frequency weighting used to evaluate the z-axis motions with respect to motion sickness, W_f, specified in ISO 2631-1:1997 [14] is the same filter as specified in BS 6841:1987 [2].

4.2.9 RMS Accelerations in the ship's reference frame

An additional set of accelerations are available for short-term statistics calculations and operability studies. These are *Weighted RMS Accelerations* and *RMS Accelerations* in the ship's reference frame.

For the weighted accelerations, frequency weightings according to BS 6841:1987 [2] are applied. This means the W_b filter is applied to the z-component of the accelerations and W_d is applied for x-axis and y-axis accelerations (in the ship's reference frame). The a_x, a_y and a_z r.m.s. accelerations referred to here are the same as the LON, LFE and VFE defined in Section 4.1.4 (subscript w indicates that frequency–weighting has been applied).

The following weighted accelerations are defined:

- Weighted RMS multi-axis acceleration, a_w
- Weighted RMS vertical acceleration, a_{zw}
- Weighted RMS lateral/vertical acceleration, a_{yzw}

The multi–axis acceleration values are calculated from the root–sums–of–squares of the weighted r.m.s. acceleration values in each axis (a_{xw}, a_{yw} and a_{zw}) at the specified motion point. The a_{yzw} accelerations are similar, but only including the weighted lateral and vertical components $a_y w$ and $a_z w$ in the summation.

In addition, the following RMS accelerations can be applied:

- RMS multi-axis acceleration, a_{xyz}
- RMS lateral/vertical acceleration, a_{yz}

The multi–axis acceleration values are calculated from the root–sums–of–squares of the r.m.s. acceleration values in each axis (a_x, a_y and a_z) at the specified motion point. The a_{yz} accelerations are similar, but only including the lateral and vertical components a_y and a_z in the summation.

4.3 Long term statistics

4.3.1 Calculation of long term statistics

This chapter describes the theory related to the calculation of long term statistics which is applied in the VERES Postprocessor. The short term statistics discussed in the previous chapter are calculated for a certain sea state, where the significant wave height and mean period are assumed constant. A sea state has a limited duration (often set to three hours), and a ship will encounter many sea states on a voyage, during a year in service or during its lifetime. Long term statistics provide predictions about the ship responses in such scenarios.

When calculating long term statstics, the period of time considered is longer than the duration of one sea state, i.e. the significant wave height and mean period will vary. The probability of occurrence of the sea states is therefore needed. The joint probability of significant wave heights H_s and characteristic periods T_x is commonly presented as a wave scatter diagram. The scatter diagram is suitable for a certain ocean area, and may be given for a year or for a certain season. Figure 45 shows the annual wave scatter diagram for the North sea [11]. The number of occurrences are given for combinations of H_s and the zero–upcrossing period T_z. The peak period T_p is also commonly used in wave scatter diagrams.

North sea, area 11. Annual.

Number of occurences

Tz / Hs	3.5	4.5	5.5	6.5	7.5	8.5	10.0	Sum
0.5	19	86	94	41	10	2		252
1.5	3	49	121	99	40	10	2	324
2.5	1	17	63	73	40	13	4	211
3.5		6	27	39	26	10	4	112
4.5		2	11	19	14	6	3	55
5.5		1	4	9	7	4	1	26
6.5			2	4	4	2	1	13
7.5			1	2	2	1	1	7
8.5				1	1	1		3
9.5				1	1			2
Sum	23	161	323	288	145	49	16	1005

Hs and Tz values are the middle values in each interval

Figure 45: Annual wave scatter diagram for the North sea.

Long term distribution Following the descriptions given by DNV for fatigue assessment [4], the long term probability distribution is obtained by a weighted summation over all sea states and headings:

$$P(R) = \sum_{\substack{i=1 \\ j=1}}^{\substack{\text{all seastates} \\ \text{all headings}}} r_{ij} \cdot F_{Rij}(R) \cdot p_{ij} \tag{65}$$

where:

p_{ij}	is the probability of occurrence of a given sea state i combined with heading j,
$r_{ij} = \nu_{ij}/\bar{\nu}$	is the ratio between the crossing rates in a given sea state and the average crossing rate,
$\bar{\nu} = \sum p_{ij} \cdot \nu_{ij}$	is the average crossing rate,
$\nu_{ij} = \frac{1}{2\pi}\sqrt{\frac{m_{2ij}}{m_{0ij}}}$	is the response zero-crossing rate in sea state i and heading j,
m_{kij}	is the kth order moment of the response (see Equation (58)).

The short term probability distribution for the maxima (peak values) of the response is assumed to be Rayleigh distributed. The probability distribution for a given sea state i and wave heading j can then be written:

$$F_{Rij}(R) = 1 - \exp\left(\frac{-R^2}{2\sigma_{Rij}^2}\right) \tag{66}$$

where σ_{Rij} is the standard deviation of the response for a certain sea state i and wave heading j. Further, the long term probability of exceeding the response R, $Q(R) = P(r > R)$ is found by

$$Q(R) = 1 - P(R) \tag{67}$$

Figure 46 shows the long term probability of exceedance of the vertical bending moment midship for a container vessel. To determine the response for a specified long term probability level, iteration is applied.

Fitting of Weibull parameters A Weibull distribution is found to describe the estimated long-term distribution well. The fitting of the Weibull distribution to the sum of Rayleigh distribitions in (65) is done by a least square technique for a selected range of probability levels. The Weibull distribution is described by:

$$P(R) = 1 - \exp\left(-\left(\frac{R}{q}\right)^h\right) \tag{68}$$

where R is the response corresponding to a certain probability level, q is a scale parameter, and h is a shape parameter (also referred to as the Weibull *slope*). In all long-term plots from the VERES Postprocessor, the Weibull parameters are included in the legend for each curve.

The Weibull parameters are estimated based on the probability levels applied in the long term plots. This means that to estimate Weibull parameter for a Fatigue Limit State (FLS) one should choose a long term plot with corresponding probability levels. The following options are especially included for fatigue assessment in the VERES Postprocessor:

- Probability limits - Fatigue Limit State (FLS); applying probability levels of exceedance of 10^{-2}, 10^{-3} and 10^{-4}.

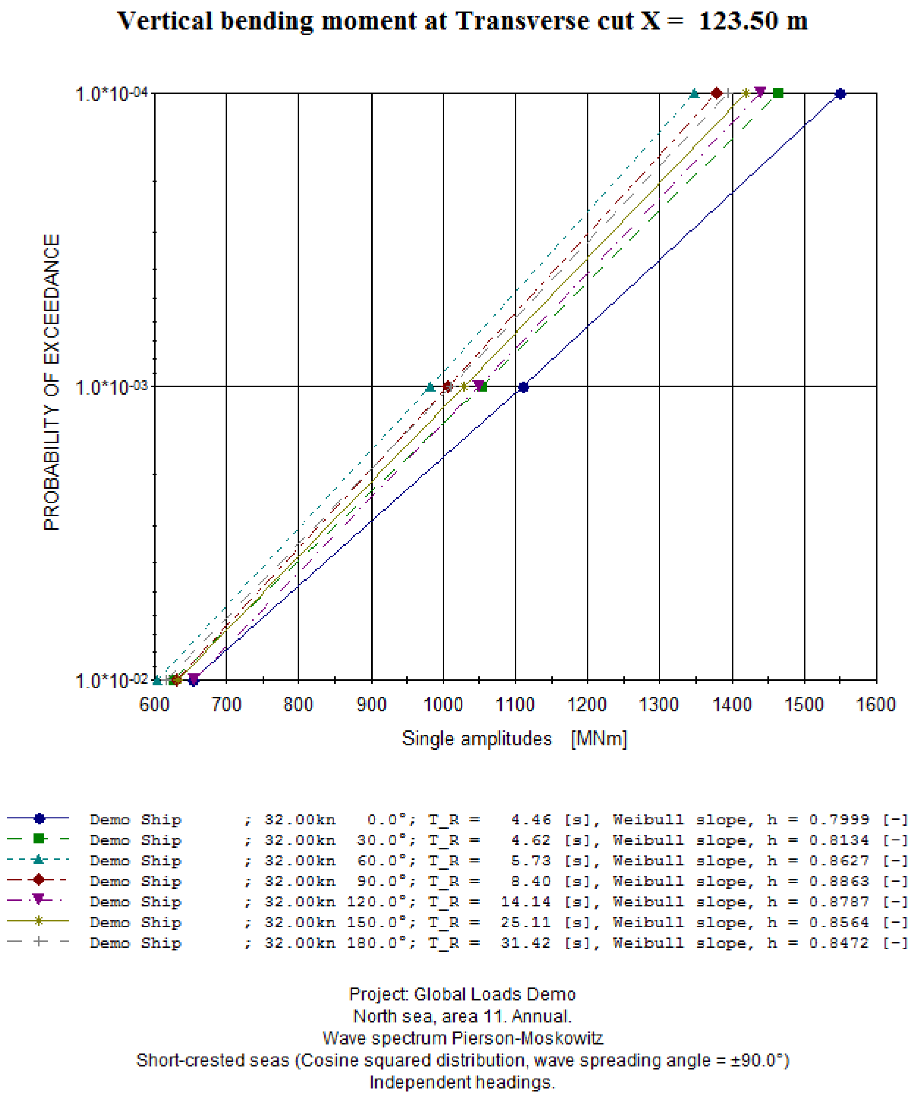

Figure 46: Long term probability level of the vertical bending moment at midship.

- Probability limits - Ultimate Limit State (ULS); applying probability levels of exceedance of 10^{-2}, 10^{-4}, 10^{-5}, 10^{-6} and 10^{-8}.

Long term return period The VERES Postprocessor can plot long term results as a function of the long term return period (in years) rather than probability level or probability of exceedance. In this case, the number of response cycles in a long term period (e.g. 20 years) can be calculated as:

$$N = \frac{20[\text{years}] \cdot 365[\text{days/year}] \cdot 24[\text{hours/day}] \cdot 3600[\text{sec/hour}]}{\overline{T}_R[\text{sec}]} \tag{69}$$

where $\overline{T}_R$ is the average long term response period, which is found as a weighted average of the zero-crossing periods of the response

$$\overline{T}_R = \sum_{\substack{i=1 \\ j=1}}^{\substack{\text{all seastates} \\ \text{all headings}}} T_{zRij} \cdot p_{ij} \tag{70}$$

where T_{zRij} is the zero-crossing period of the response and p_{ij} is the probability of occurrence for a given sea state i combined with heading j. In all long-term plots from the VERES Postprocessor, the long term response period is included in the legend for each curve.

The probability level of exceedance corresponding to the specified return period is simply calculated as:

$$Q(R) = \frac{1}{N} \tag{71}$$

Hence, when the number of response cycles N is found from (69), the required probability level of exceedance is known, and the corresponding long term response R can be found as described above.

Regular design waves The VERES Postprosessor can be applied to find regular waves that correspond to a certain long term probability level, design value or return period in years. Where neccesssary, the program calculates the long term responses based on the mentioned choices, and applies the response amplitude operators (RAOs) for regular waves to find the regular wave height for different wave periods that correspond to this design value.

The long term responses may be based on a given operability profile (see Section 4.3.2 for details) if required. Thus, the design value may be based on short-crested seas, different heading probabilities and a speed curve defining the vessel speed for different significant wave heights if required. This design value is then combined with different RAOs to find corresponding regular design waves for a certain vessel speed and heading.

The results are presented as a plot with design wave height as a function of the wave period. The plot includes the theoretical limit of breaking waves, which for a regular wave is set to a steepness $H/\lambda = 1/7$ where H is the wave height and λ is the wave length of the regular wave[17]. The lowest wave height which satisfy the steepness criterion is considered to be the recommended design wave, and this value is specified in the legend for each curve.

The above mentioned procedure to find a design wave conforms with the recommendations made by DNV concerning fatigue assessment [4].

4.3.2 Operational profile

Heading probabilities During a long term period, a vessel will meet waves of different headings with certain probabilities. This may be due to the weather statistics at the given route where the vessel will operate or

[17]For a regular wave, the wave length $\lambda = 1.561 \cdot T^2$ where T is the wave period.

because the vessel will try to keep a certain heading relative to the waves (e.g. support vessels with dynamic positioning (DP) system). Thus, three different approaches are implemented in the VERES Postprocessor in order to meet the needs of different users. These are:

- Calculations on each heading separately
- Input of the probability of each heading
- All headings have equal probability of occurrence

The calculation method is specified in the **Long Term Statistics** dialog. The first and last method needs no further input from the user. If the user chooses to input the probability of each heading separately, the fraction of time of each heading angle must be specified. The resulting long term responses will then be a weighed sum of each heading response multiplied with its probability of occurrence.

Please note: It is common practice to perform calculations on wave headings 0° to 180° rather than 0° to 360° in many cases, since e.g. the motion transferfunctions on locations on the centerplane will be symmetric for waves approaching from either side of the centerplane. To perform a long-term analysis of the response with equal weighting of all wave headings from 0° to 360°, one should then half the probability of occurence for wave headings 0° and 180°, as the other wave headings should count *twice*; one for waves approaching from starboard, and one for the same wave approaching from port. In this case the probabilities should be given manually, as the option “All headings have equal probability of occurrence” will give each heading the same weighting, regardless of the input being given from $0^\circ - 180^\circ$ or $0^\circ - 360^\circ$ (or any other heading combinations, for that matter).

Speed curve Speed reduction may be accounted for, implicitly, in the long term analysis by applying different vessel speeds in the different sea states. This may be done by specifying a *speed curve*, where the vessel speed is specified as a function of the wave height. The vessel speeds may then reflect the effects of voluntary and involuntary speed loss in a seaway. The speed curve also reflects the operation of the vessel in such a way that the largest H_s value in the curve is the largest applied in the calculations. For significant wave heights larger than this, the vessel is assumed to be in harbour. In this case, the response for the sea states above the speed curve range is set to zero[18]. An example of a speed curve is given in figure 47.

[18]This approach differs from truncating the scatter diagram, as this would result in an increased probability of the waves being within the speed curve, since the scatter diagram would be re-normalized, giving a sum of probabilities equal to 1.0. When the response is set to zero as done in VERES, the total probability of the sea states where the vessel has nonzero response will be less than 1.0, thus reflecting the time spent in harbour, giving more physically correct results when considering e.g. return periods of 20 years

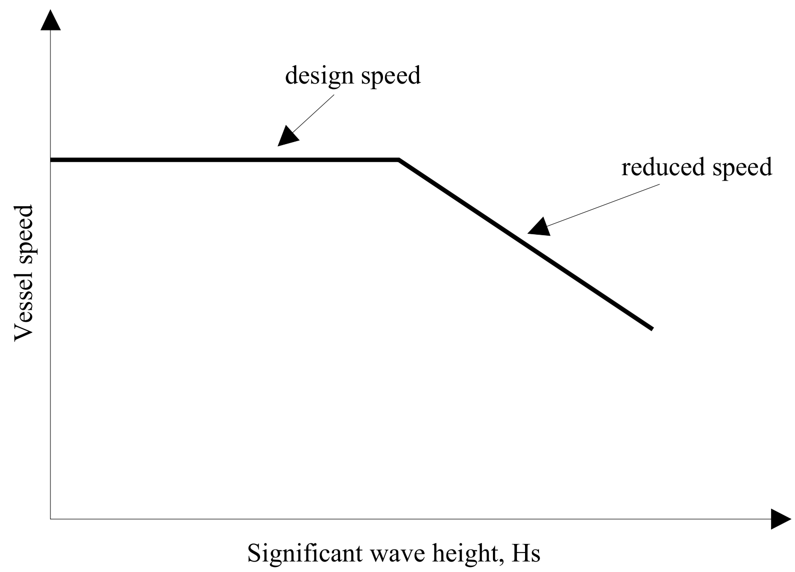

Figure 47: Example of vessel speed versus significant wave height.

4.4 Operability

This chapter describes the theory related to the calculation of operability applied in the VERES Postprocessor. In this context, *operability* refers to the degree of which the seagoing vessel is able to satisfy specified seakeeping criteria. The calculation of the operability is available in two modes:

- Operability limiting boundaries presented as limiting significant wave heights $H_s^{\lim}$ as a function of the wave period (x-y plot) or wave heading (polar plot).
- Operability diagram presenting operability contours as a function of speed and heading for a given sea state.
- Percentage operability.

4.4.1 Seakeeping criteria

To be able to assess the operational envelope of a craft, it is necessary to define limiting seakeeping criteria. The limiting criteria relate to the safety and comfort of passengers and crew, to the safety and capasity of the vessel or to operational considerations. Such limiting criteria can be found in national and international rules and guidelines, e.g. as given in [18]. In the VERES Postprocessor, the following limiting criteria may be specified for any chosen position of the vessel:

- Motions in six degrees of freedom
- Relative vertical motions
- Probability of slamming
- Probability of green water on deck
- Probability of air exposure
- Vertical accelerations according to ISO 2631/3-1985 (motion sickness)
- Forces in body-fixed coordinate system (LON, LFE and VFE)
- Motion-Induced Interruptions (MIIs)

- Motion Sickness Incidence (MSI) according to McCauley et al.
- Motion Sickness Incidence (MSI) according to ISO 2631-1:1997
- Motion Sickness Dose Value (MSDVz)
- Frequency-weighted accelerations a_w, a_{zw} and a_{yzw}
- Combined body-fixed accelerations a_{xyz} and a_{yz}
- Axial gangway motion
- Angular gangway motion (vertically)
- Angular gangway motion (slewing)

These options cover the most common limiting criteria considered for different ship subsystems, see Table 4 [8], [18].

Ship subsystem	Criteria with regard to										
	Slam	Deck wetn.	Vert. acc.	Lat. acc.	Roll	Pitch	Heave	Vert. vel.	Rel. mot.	MII	MSI
Ship hull	•	•									
Propulsion machinery									•		
Ship equipment			•	•	•	•					
Cargo		•	•	•	•	•					
Personnel effectiveness		•	•	•	•	•				•	•
Passenger comfort			•	•	•	•	•			•	•
Helicopter					•	•	•	•			
Sonar									•		
Lifting operations	•	•		•	•	•	•	•			

Table 4: Common limiting criteria for different ship subsystems

In the following paragraphs, the following main seakeeping criteria catagories are discussed:

- Comfort and safety for passengers and crew
- Safety of the craft and cargo
- Operational considerations

Passenger and crew comfort and safety The comfort and safety of the people onboard the vessel depends upon the type of imposed motion, the duration of the voyage and type of persons and activities onboard, i.e. crew, (cruise)tourist, occasional or regular passengers, sex and age distribution. Recommended limiting values for various types of motions and voyage durations are listed in Table 5.

When considering motion sickness, there are four criteria directly related to this topic in the VERES Postprocessor:

- Vertical accelerations according to ISO 2631/3-1985
- Motion Sickness Incidence (MSI) according to McCauley *et al*
- Motion Sickness Incidence (MSI) according to ISO 2631-1:1997
- Motion Sickness Dose Value ($MSDV_z$)

The ISO 2631 standard from 1985 [13] recommends boundary values for the human tolerance to vibration. The ISO 2631/3 covers vertical vibration in the frquency range of 0.1 to 0.63 Hz (periods of 1.6–10 sec). In this range, motion sickness may occur. The limits of the standard are specified in terms of:

- Vibration frequency
- Vibration magnitude
- Exposure time
- Direction of vibration relative to torso

Only the vertical acceleration (i.e head–to–toe) limits are available in the standard. However, this is considered to be the dominant direction in which severe reactions are caused. The ISO standard assumes 10% incidence of motion sickness at the boundary among infrequent travellers of the general public. Time of exposure can be chosen to be 30 minutes, 2 hours, or 8 hours. The incidence of motion sickness will of course increase with exposure time. When applying the ISO criterion, it is important to choose the most severe position(s) of the vessel, i.e. areas occupied by passengers or crew most remote from the pitch and roll center of the vessel. Designers wishing to minimize the motion sickness should avoid or reduce vibration in the range of 0.1 to 0.315 Hz (periods of 3–10 sec).

The ISO 2631 standard from 1997 (ISO 2631-1:1997) [14] utilizes frequency–weightings of the r.m.s. vertical accelerations combined with the exposure duration to calculate a motion sickness dose value, MSDV$_z$. The Motion Sickness Incidence (MSI) value can be calculated from this value by multiplication with a K$_m$ value which may vary based on the population onboard the vessel time (see Section 4.2.7 for details). The standard only propose one value (K$_m = 1/3$) which represents a mixed population of unadapted male and female adults. The K$_m$ value as well as the exposure duration may be specified by the user in addition to the limiting MSI value. The MSDV$_z$ can also be applied directly as a comfort criterion.

In addition to the ISO 2631 standard, Motion Sickness Incidence (MSI) based on the formulation by McCauley *et al* [17] can also be applied as a criterion for passenger comfort. The MSI operability criteria are specified by the percentage of crew being seasick for a given exposure time (see Section 4.2.6 for details).

Please note that the MSI values calculated by different formulations may vary significantly in some cases. Care should be given to specifying which method is applied when using MSI criteria.

DESCRIPTION	CRITERIA (RMS)	COMMENT	REFERENCE
VERTICAL ACC:			
Exposure: $\frac{1}{2}$ hour	0.10g	10% motion sickness incidence	ISO 2631/3
1 hours	0.08g	ratio (MSI) (vomiting) among	1987 & 1982
2 hours	0.05g	infrequent travellers of the	
8 hours	0.03g	general public.	
- - - - - - - - - - - - - -	- - - - - - - -	- - - - - - - - - - - - - - - - - - -	- - - - - - - - - - -
Simple light work possible	0.275g	Most of the attention devoted to keeping balance.	Connolly 1974
Light manual work possible	0.20g	Causes fatigue quickly. Not tolerable for longer periods.	Mackay 1978
Heavy manual work	0.15g	Limit in fishing vessels.	
Work of more demanding type	0.10g	Long term tolerable for crew.	Payne 1976
Passengers on a ferry	0.05g	Limit for people unused to ship motions.	Goto 1983
Passengers on a cruise liner	0.02g	Older people. Lower threshold for vomiting to take place.	Lawther 1985
ROLL:			
Light manual work	4.0°	Personnel effectiveness.	Comstock 1980
Demanding work	3.0°	Personnel effectiveness.	Hosoda 1985
Passengers on a ferry	3.0°	Short routes. Safe footing.	Karppinnen 1986
Passengers on a cruise liner	2.0°	Older people. Safe footing.	Karppinnen 1986
PITCH:			
Navy crew	3.0°	Personnel safety.	Comstock 1980
Light manual work	2.0°	Personnel effectiveness.	Hosoda 1985
Demanding work	1.5°	Personnel effectiveness.	Hosoda 1985
HORIZONTAL ACC. (LON/LFE):			
Passenger on a ferry	0.025g	1–2 Hz frequency. General public.	ISO 2631/1
Navy crew	0.050g	Non-passenger and navy ships.	ISO 2631/1
Standing passenger	0.07g (max.)	99 % will keep balance without need of holding.	Hoberock 1977
	0.08g (max.)	Elderly person will keep balance when holding.	Hoberock 1977
	0.15g (max.)	Average person will keep balance when holding.	Hoberock 1977
Seated passenger	0.15g (max.)	Nervous person will start holding.	Hoberock 1977
	0.25g (max.)	Average person max. load balance when holding.	Hoberock 1977
	0.45g (max.)	Person will fall out of seats.	Hoberock 1977

Table 5: Comfort criteria for passengers and crew [8].

Ship safety and capacity Limiting values for the ship safety and capacity vary with the type of ship, and recommending limiting values is difficult. However, slamming and shipping of green water are typical problems that impose large loads on most ships. A permissible probability of occurrence of 3% for slamming and 7% for green water on deck is often recommended [18].

Operational considerations Operational considerations depend very much on the type of vessel considered. Demands from heave compensators on drilling or crane vessels, helicopter landings, use of sonar, use of fishing equipment or danger of cargo displacements are typical examples. The list is indefinite, and the critical values must be evaluated in each case.

4.4.2 Operability limiting boundaries

Operability limiting boundaries are obtained in the VERES Postprocessor by combining the results from the short term statistics with seakeeping criteria defined by the user, as discussed above (Section 4.4.1). When plotting the operability limiting boundaries in the VERES Plot program, the seakeeping criteria appear as limiting curves in a diagram with the limiting significant wave height as the ordinate and with the wave period along the abscissa (similar to a scatter diagram). The vessel meets the seakeeping criteria for the wave height–wave period combinations below (all) the boundary curves. The diagram gives information about which significant wave height is critical for the different criteria, and which criterion is the limiting one at the different wave periods.

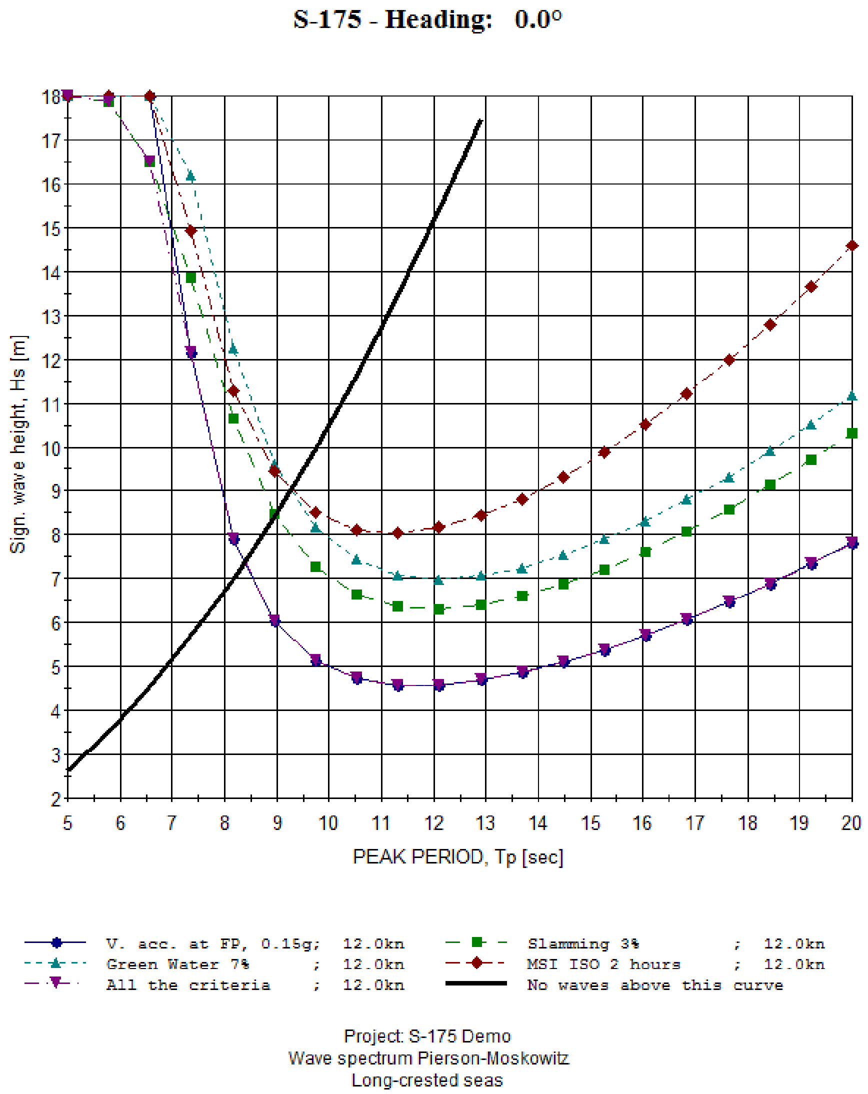

Figure 48: Operability limiting boundaries including the theoretical limit of breaking waves.

Figure 48 shows an example of operability limiting boundary curves, where the vertical accelerations at FP is the limiting criterion. Please note that the limiting significant wave heights are calculated up to a user specified maximum value[19] (=18 m in Figure 48). Exceeding limiting wave heights are set to the specified value.

There are combinations of wave heights and wave periods that cannot exist, because the waves would be too steep to be stable, i.e. they break before reaching the combination. The theoretical limit of breaking waves may be plotted together with the operability boundary limits (the thick, solid line in Figure 48). The "breaking" wave height H_s^{br} is found by (72) as a function of the peak period T_p [3]:

$$H_s^{\mathrm{br}}\left(T_p\right) = 0.105 T_p^2 \tag{72}$$

The operability limiting boundaries can either be plotted for each wave heading or for the sum over all wave headings (with equal probability of occurrence of each wave heading) in the VERES Postprocessor.

In the VERES Postprocessor, calculation of the limiting significant wave height for the different criteria is described in the following paragraphs.

Motions The limiting significant wave height H_s^{lim} due to the motion criteria is calculated directly from the results of the short term statistics. The short term statistical value of the response per meter wave height, $g_x = \sigma_x / H_s$, is known from these calculations as a function of the period with vessel speed and wave heading as parameters. Thus, the limiting significant waveheight as a function of the period for a given wave heading and ship speed is obtained by:

$$H_s^{\mathrm{lim}}\left(T_p\right) = \frac{\sigma_x^{\mathrm{lim}}}{g_x}, \tag{73}$$

where σ_x^{lim} is the limiting value of the motion criteria in question (specified by the user). If a two-parameter JONSWAP spectrum is applied (i.e. the statistical respose is not linear with respect to H_s), an iteration is performed to ensure that g_x is calculated with correct H_s and γ value. Otherwise, a unit wave height is applied.

Slamming The limiting significant wave height due to the probability of slamming is obtained as suggested by Ochi [19]:

$$H_s^{\mathrm{lim}}\left(T_p\right) = \sqrt{-\frac{1}{2\ln P_{\mathrm{s}}}\left(\frac{d^2}{g_{\mathrm{r}}^2} + \frac{V_{\mathrm{cr}}^2}{g_{\mathrm{rv}}^2}\right)} \tag{74}$$

where:

P_{s} is the permissible probability of slamming (specified by the user),
d is the local draft,
g_{r} is the RMS–value of relative vertical motion per meter significant wave height,
g_{rv} is the RMS–value of relative vertical velocity per meter significant wave height,
V_{cr} is the critical re–entry velocity.

If a relative motion calibration file (*.rmc) is specified for the motion point in question, the relative motion transfer functions will be calibrated before calculating the RMS values g_{r} and g_{rv}. See Section 4.1.3, page 49 for details.

If a two-parameter JONSWAP spectrum is applied (i.e. the statistical respose is not linear with respect to H_s), an iteration is performed to ensure that g_{r} and g_{rv} are calculated with correct H_s and γ value. Otherwise, a

[19]The user specified maximum value is introduced to avoid "infinite" limits. A typical example is a roll motion criterion, which will give infinite limiting significant wave height in head seas, since no rolling motion exist for this wave heading.

unit wave height is applied.

Equation 74 is derived from the joint probability of air exposure and the exceedance of a critical re–entry velocity, at which slamming is assumed to occur. The critical re–entry velocity V_{cr} is determined depending on the user's choice of criterion:

- Ochi [19] type: $V_{\mathrm{cr}} = 0.093\sqrt{gL}$, where g is the acceleration of gravity and L is the ship length.
- User specified critical re–entry velocity V_{cr}.
- User specified critical pressure P_{cr}, which gives $V_{\mathrm{cr}} = \sqrt{P_{\mathrm{cr}}/(\frac{1}{2}\rho k)}$, where ρ is the density of seawater and k is the pressure coefficient (85) for the point in question.

If the number of slams per hour is specified as a criterion rather than the probability of slamming, the probability of slamming can be calculated as:

$$P_{\mathrm{s}} = \frac{n_{\mathrm{s}} \cdot T_{zR}}{3600} \tag{75}$$

where:
n_{s} is the permissible number of slams per hour,
T_{zR} is the zero-crossing period of the relative motions in seconds.

Green water on deck The limiting significant wave height due to the probability of green water on deck is obtained by:

$$H_s^{\lim}(T_p) = \frac{F}{g_{\mathrm{r}}\sqrt{-2\ln P_{\mathrm{dw}}}} \tag{76}$$

where:
P_{dw} is the permissible probability of deck wetness (specified by the user). (If the user has specified the permissible number of events per hour rather than the probability, the probability can be calculated by (75)).
F is the user specified freeboard at the considered longitudal location.
g_{r} is the RMS–value of relative vertical motion per meter significant wave height,

If a relative motion calibration file (*.rmc) is specified for the motion point in question, the relative motion transfer functions will be calibrated before calculating the RMS value g_{r}. See Section 4.1.3, page 49 for details.

If a two-parameter JONSWAP spectrum is applied (i.e. the statistical respose is not linear with respect to H_s), an iteration is performed to ensure that g_{r} is calculated with correct H_s and γ value. Otherwise, a unit wave height is applied.

Air exposure The limiting significant wave height due to the probability of air exposure is obtained by:

$$H_s^{\lim}(T_p) = \frac{d}{g_{\mathrm{r}}\sqrt{-2\ln P_{\mathrm{air}}}} \tag{77}$$

where:
P_{air} is the permissible probability of air exposure (specified by the user). (If the user has specified the permissible number of events per hour rather than the probability, the probability can be calculated by (75)).

d is the draught to the user specified position at the considered longitudinal location.
g_r is the RMS–value of relative vertical motion per meter significant wave height,

If a relative motion calibration file (*.rmc) is specified for the motion point in question, the relative motion transfer functions will be calibrated before calculating the RMS value g_r. See Section 4.1.3, page 49 for details.

If a two-parameter JONSWAP spectrum is applied (i.e. the statistical respose is not linear with respect to H_s), an iteration is performed to ensure that g_r is calculated with correct H_s and γ value. Otherwise, a unit wave height is applied.

Vertical acceleration according to ISO 2631/3–1985 (motion sickness) The limiting RMS–value of the vertical acceleration is specified in the ISO 2631/3–1985 standard as a function of the frequency $f^{\lim} = \omega^{\lim}/2\pi$ and the exposure time t_{ex}, see Table 6. To calculate the limiting significant wave height, the response spectrum $S_{a_z}(\omega)$ is divided into freqeuncy intervals corresponding to the tabulated ISO frequencies. The RMS–values of each interval is calculated by integrating the response spectrum, see Figure 49. The limiting significant wave

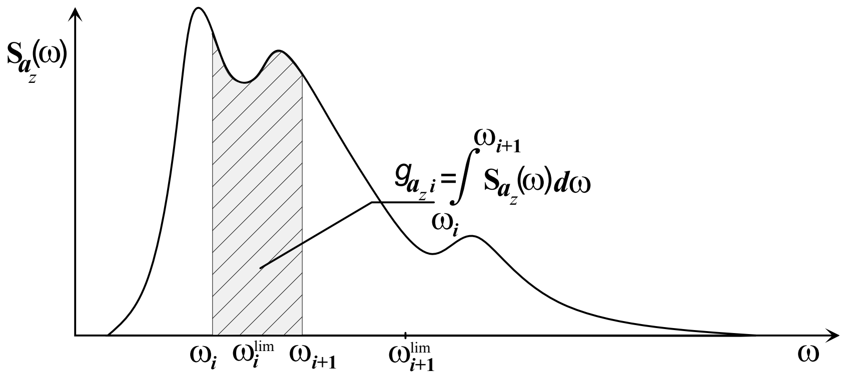

Figure 49: Dividing the response spectrum $S_{a_z}(\omega)$ corresponding to the ISO frequency intervals $\omega_i^{\lim}$, i =1–9 and integrating to find the RMS–value of the interval.

height is found by (78), as the minimum value obtained from the intervals:

$$H_s^{\lim} = \min\left(\frac{\sigma_{a_z i}^{\lim}}{g_{a_z i}}\right) \qquad i = 1, 2, 3, ..., 9 \tag{78}$$

$$g_{a_z i} = \int_{\omega_i}^{\omega_{i+1}} S_{a_z}(\omega) d\omega \qquad i = 1, 2, 3, ..., 9$$

where:
$\sigma_{a_z i}^{\lim}$ is the RMS–value of the limiting vertical acceleration tabulated in Table 6,
$g_{a_z i}$ is the RMS-value of the vertical acceleration per meter significant wave height in the ith interval,
$S_{a_z}(\omega)$ is the response spectrum for the vertical acceleration.

If a two-parameter JONSWAP spectrum is applied (i.e. the statistical respose is not linear with respect to H_s), an iteration is performed to ensure that g_r is calculated with correct H_s and γ value. Otherwise, a unit wave height is applied.

Frequency f^{lim} [Hz] (centre frequency of one–third octave band)	RMS–value of acceleration $\sigma_{a_z i}^{\text{lim}}$ [m/s^2] Exposure time t_{ex}		
	30 min	2 h	8 h (tentative)
0.100	1.00	0.50	0.250
0.125	1.00	0.50	0.250
0.160	1.00	0.50	0.250
0.200	1.00	0.50	0.250
0.250	1.00	0.50	0.250
0.315	1.00	0.50	0.250
0.400	1.50	0.75	0.375
0.500	2.15	1.08	0.540
0.630	3.15	1.60	0.800

Table 6: Numerical values of "severe discomfort boundaries" for vertical acceleration [13].

Forces and accelerations in body-fixed coordinate system The limiting significant wave height H_s^{lim} due to criteria regarding the acceleration forces and RMS accelerations in the body-fixed coordinate system[20] (e.g. LON, LFE and VFE, a_w etc.) is calculated directly from the results of the short term statistics. The short term statistical value of the response per meter wave height, $g_{\text{frc}} = \sigma_{\text{frc}}/H_s$, is known from these calculations as a function of the period with vessel speed and wave heading as parameters. Thus, the limiting significant waveheight as a function of the period for a given wave heading and ship speed is obtained by:

$$H_s^{\text{lim}}\left(T_p\right) = \frac{\sigma_{\text{frc}}^{\text{lim}}}{g_{\text{frc}}}, \tag{79}$$

where $\sigma_{\text{frc}}^{\text{lim}}$ is the limiting value of the acceleration force criteria in question (specified by the user). If a two-parameter JONSWAP spectrum is applied (i.e. the statistical respose is not linear with respect to H_s), an iteration is performed to ensure that g_{frc} is calculated with correct H_s and γ value. Otherwise, a unit wave height is applied.

Motion Induced Interruptions The limiting significant wave height H_s^{lim} due to the MII criteria is calculated by iteration on the significant wave height to find the MII value corresponding to the specified MII criterion value (MIIs per minute).

Motion Sickness Incidence and Motion Sickness Dose Value The limiting significant wave height H_s^{lim} due to the MSI and MSDV$_z$ criteria is calculated by iteration on the significant wave height to find the value corresponding to the specified criterion.

4.4.3 Operability diagram

The VERES Postprocessor can present the operability contours of a ship for different speeds and headings for a given sea state in an *operability diagram*. The operability diagram shows the combinations of vessel speeds and headings where the criterion/criteria are exceeded as shaded red areas in a plot with the vessel speed on the y-axis and heading on the x-axis.

[20] see Section 4.1.4 for details regarding the definition of LON, LFE and VFE.

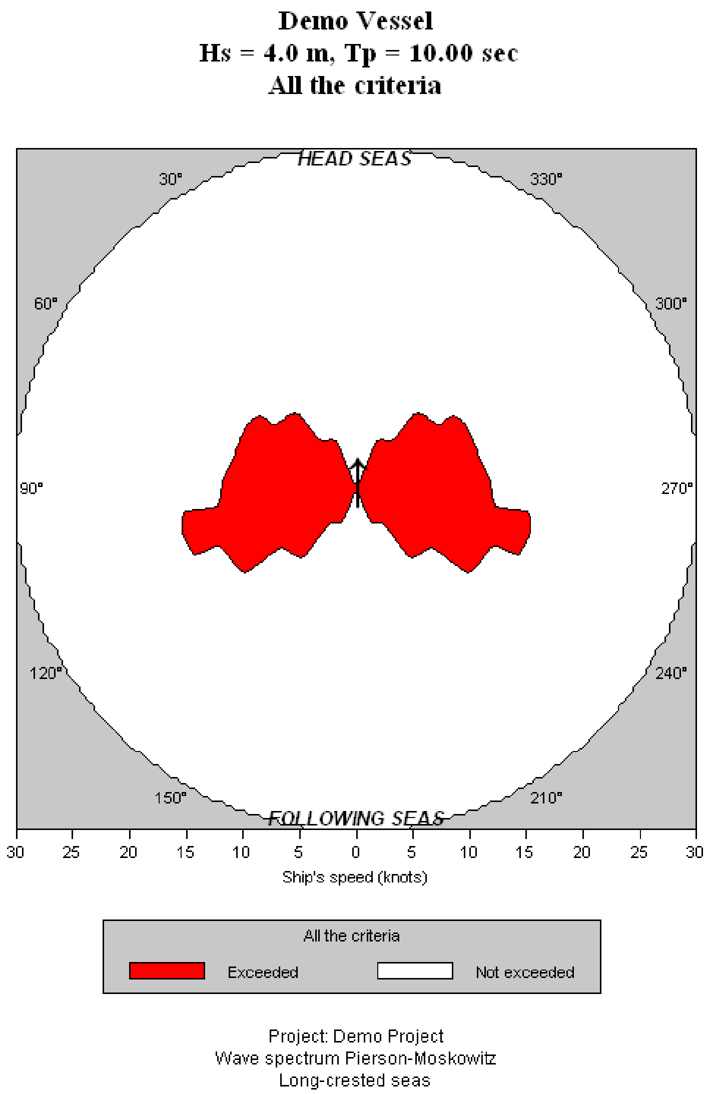

Figure 50: Example operability diagram.

Figure 50 shows the operability diagram for a container vessel with active roll stabilizing fins. The major contribution to the reduced operability at beam and following seas is due to large roll motions. The efficiency of these fins increase with higher ship speeds. Hence, no criteria are exceeded at full speed.

4.4.4 Percentage operability

The percentage operability expresses the percentage of the time period under consideration where the vessel is able to satisfy the seakeeping criteria. Figure 51 shows how the percentage operability is presented in the VERES Plot program. The percentage operability is obtained by combining the operability limiting boundaries with the probability of occurence of the sea states given in a wave scatter diagram, for a certain ship speed and wave heading, or weighted over all headings, Eqs. 80 and 81, respectively. The percentage operability for a certain seakeeping criterion, ship speed and wave heading is obtained by:

$$P_{\mathrm{Op}}^{\beta} = \sum_{j=1}^{N_{H_s}} \sum_{k=1}^{N_{T_p}} p_{jk} \left(H_{sj} < H_{s_{\mathrm{cr}}}, T_k \right) \tag{80}$$

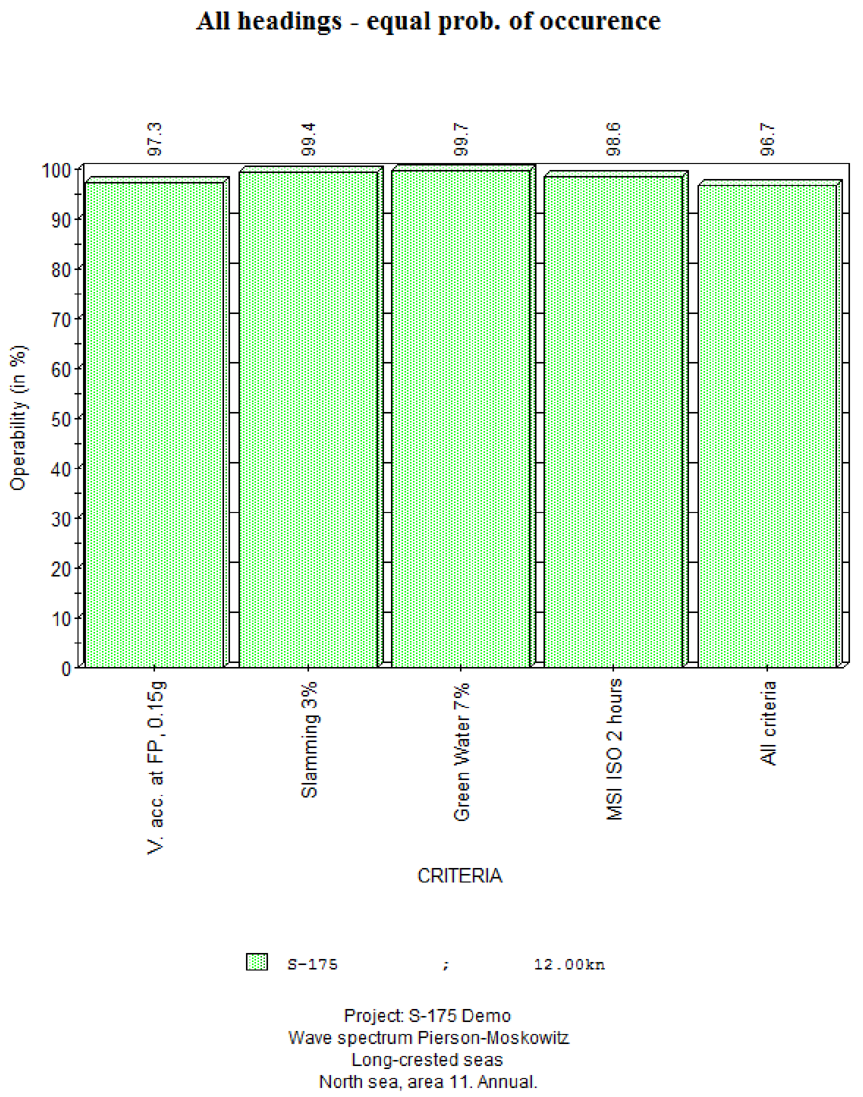

Figure 51: Example plot of percentage operability.

where P_{Op}^{β} is the percentage operability for a certain wave heading β, ship speed and seakeeping criterion and $p_{jk}\left(H_{sj} < H_s^{\text{lim}}, T_k\right)$ is the probability of occurence of a significant wave height in interval j below the limiting significant wave height with a wave period in interval k. The percentage operability for a certain seakeeping criterion and ship speed for all headings is found by:

$$P_{\text{Op}} = \sum_{i=1}^{N_\beta} P_{\text{Op}_i}^{\beta} \; P\left(\beta_i\right) \tag{81}$$

where P_{Op} is the percentage operability for all wave headings, given a certain speed and seakeeping criterion, $P_{\text{Op}_i}^{\beta}$ is the percentage operability for the ith wave heading and $P\left(\beta_i\right)$ is the probability of occurrence of the ith wave heading β_i.

Figure 52 shows the principal calculations performed by VERES to obtain the percentage operability:

1. The VERES Main Program calculates the motion transfer functions in six degrees of freedom.

2. The VERES Postprocessor combines the motion transfer functions with the specified wave spectra to obtain the response spectra (short term statistics).
3. The response spectra are combined with the specified seakeeping criteria to obtain operability limiting boundaries.
4. The operability limiting boundaries combined with the specified wave scatter diagram are summed up over the sea states to obtain the percentage operability.

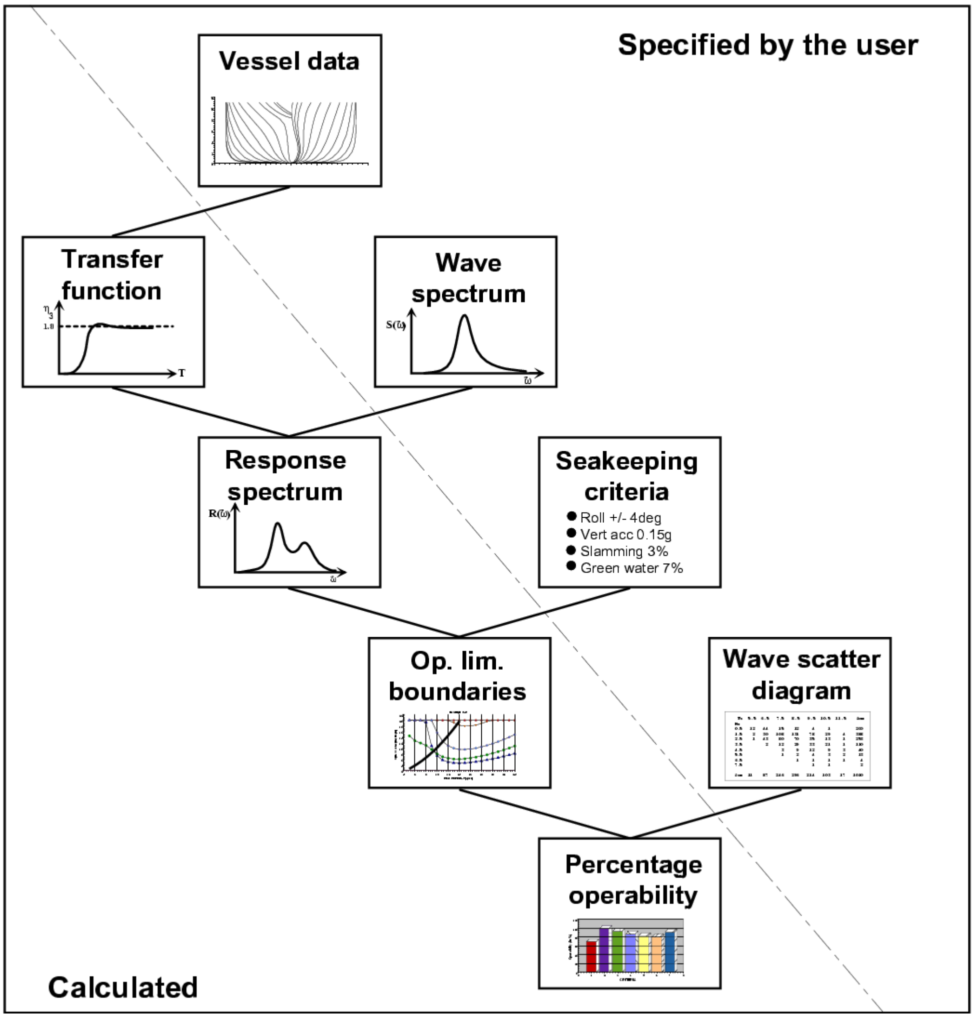

Figure 52: The principal calculations performed by VERES to obtain the percentage operability.

4.5 Fatigue assessment

4.5.1 Introduction

This chapter describes the theory related to the fatigue assessment part of the VERES Postprocessor. The option to calculate fatigue damage is only available when postprocessing general RAO files (*.re5) including stress transfer functions. In addition, the units applied for the stress transfer functions must be Pa, kPa or MPa. The stress transfer functions can be obtained e.g. by using VERES to calculate the ship motions and pressure distribution on the hull and subsequently using VESHIP and a finite element program to calculate the structural responses. VESHIP then generates a general RAO file (*.re5) which can be applied for long term statistics and fatigue damage calculations in the VERES Postprocessor.

When postprocessing a general RAO file, *Fatigue analysis* is given as a fourth option below the *Long term statistics* option on the bottom right in the **Transfer functions/Statistics** dialog (see e.g. Figure **??**). By choosing the *Fatigue Analysis* option, one can specify the related input by clicking the *Specify...* button next to it. The **Fatigue Analysis** dialog is very similar to the **Long Term Statistics** dialog and gives in fact access to much of the same input as given in the latter one. This includes specification of scatter diagram, speed curve and heading probabilities. Changing these settings will also influence subsequent long term statistics calculations. In addition to the input of these data, one can specify the S-N curve, the design life (in years) and the fraction of design life in the loading condition represented by the current general RAO file.

4.5.2 S-N curves

The fatigue analysis are based on S-N curves describing the fatigue properties of the material in use. The VERES Postprocessor gives you the opportunity to specify the S-N curve manually, or to choose from a list of standard S-N curves collected from [4] and [5]. The input S-N curves can be either linear, or bi-linear, where the latter can have a change in slope at a specified number of cycles[21].

The basic design S-N curve is given as:

$$\log N = \log a - m \log S \tag{82}$$

where

N	=	predicted number of cycles to failure for stress range S
S	=	stress range ($\Delta\sigma$) in [MPa]
m	=	negative inverse slope of S-N curve
$\log a$	=	intercept of $\log N$-axis by S-N curve.

The standard curves included in the Postprocessor are:

Steel (from *Fatigue Assessment of Ship Structures* [4]):

[21] Typically for steel $N = 10^7$ and for aluminium $N = 5 \cdot 10^6$.

S-N Curve	Material	Environment
DNV S-N Curve I	Welded joint	Air/Cathodic protection
DNV S-N Curve Ib	Welded joint	Air/Cathodic prototection
DNV S-N Curve II	Welded joint	Corrosive environment
DNV S-N Curve III	Base material	Air/Cathodic protection
DNV S-N Curve IIIb	Base material	Air/Cathodic protection
DNV S-N Curve IV	Base material	Corrosive environment
The S-N curves are applicable for normal and high strength steels used in construction of hull structures.		

Aluminium (from *Fatigue Analysis of High Speed Craft* [5]):

S-N Curve	Material	Environment
DNV HSLC S-N Curve I	Base material	Non corrosive environment
DNV HSLC S-N Curve II	Welded joint	Non corrosive environment
DNV HSLC S-N Curve III	Welded joint	Non corrosive enironment
DNV HSLC S-N Curve IV	Welded joint	Corrosive environment
The S-N curves are applicable for all wrought standard aluminium alloys and temper conditions used for design of aluminium hull structures.		

4.5.3 Fatigue damage

The fatigue damage may be calculated based on the S-N fatigue approach under the asumption of linear cummulative damage, Miner-Palmgren hypothesis. When the long-term stress range distribution is expressed by a stress histogram, consisting of a convenient number of constant amplitude stress range blocks $\Delta\sigma_i$ each with a number of stress repetitions n_i, the fatigue damage can be calculated by Miner-Palmgren's equation:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{83}$$

where

D	=	accumulated fatigue damage
k	=	number of stress blocks
n_i	=	number of stress cycles in stress block i
N_i	=	number of cycles to failure in stress block i (from S-N curve)

In the VERES Postprcessor, the number of stress blocks applied is 30. The maximum stress range in each block is applied in order to be on the conservative side.

The procedure applied to calculate the fatigue damage in the VERES Postprocessor is as follows:

1. The average long term response period $\overline{T}_R$ is calculated (see Section 4.3.1 for details).
2. The total number of response cycles N^{tot} during the specified design life is calculated according to (69).
3. The maximum stress range is calculated based on the probability of one occurrence during the design life period, $Q = 1/N^{tot}$.

4. The range from zero to the maximum stress range is divided into 30 equally spaced stress range blocks.
5. The long term probability of exceeding each of the stress block limits is calculated.
6. Based on the 30 calculated values, 600 new stress range blocks are generated by interpolation on the stress range versus the logarithm of the probability of exceedance $\log Q$ (which should form a nearly straight line). This is done to ensure that the final sum will converge.
7. Based on this, the number of stress cycles in each of the stress blocks n_i is calculated.
8. The number of cycles to failure in stress block N_i is calculated by means of the specified S-N curve applying the maximum stress range in each block as input.
9. The fatigue damage D is calculated by (83) and multiplied with the fraction of design life in the actual loading condition.

4.6 Slamming

This chapter describes the calculations related to slamming in VERES. Some of the material here can be found outher places in this manual, but are included here to give a complete reference on this subject.

4.6.1 Slamming pressures

The calculations of slamming pressures in VERES assumes that the pressure is related to the square of the relative vertical velocity between the ship and the wave, and the local hullform. This can be expressed as

$$p = \frac{1}{2}\rho\, C_P\, |V_R|^2, \tag{84}$$

where V_R is the relative vertical velocity and C_P is a pressure coefficient depending on the sectional shape, especially the local deadrise angle. This pressure coefficient is a function of time, and the maximum value is an important parameter for statistical analysis. We express the pressure coefficient for the maximum slamming pressure as

$$k = C_{P_{max}} = \frac{p_{max}}{\frac{1}{2}\rho|V_R|^2}. \tag{85}$$

The k-factor can e.g. be calculated for a given "pressure panel" on a section by the computer code *Slam2d*.

It should be noted that the pressure has an upper limit, namely the acoustic pressure, p_{ac}, due to compressibility effects in the water. The acoustic pressure can be calculated as

$$p_{ac} = \rho c_e |V_R| \tag{86}$$

where c_e is the velocity of sound in the water[22]. The main reason to include the acoustic pressure is to avoid unphysically large pressures, and the acoustic pressure is therefore included as an upper limit in VERES whenever slamming pressures are evaluated[23].

4.6.2 Short term statistics

For the short term sea state, the probability of the relative velocity being larger than a certain velocity υ can be expressed as (87) assuming that the maxima of the relative velocity follows the Rayleigh distribution:

$$P(|V_R| > \upsilon) = \exp\left(-\frac{\upsilon^2}{2\sigma_\upsilon^2}\right) \tag{87}$$

where

$$\sigma_\upsilon^2 = \int_0^\infty S(\omega)\left|\frac{V_R(\omega)}{\zeta_a}\right|^2 d\omega \tag{88}$$

is the variance of the relative velocity and $V_R(\omega)/\zeta_a$ is the transfer function for the relative velocity.

In order for slamming to occur at a specified location, two conditions have to be satisfied:

1. The location considered must come out of the water
2. The pressure at re-entry must exceed a certain value to be considered to be a slam

[22]With no air content, c_e varies typically between 1450 m/s and 1540 m/s. In VERES, the value of c_e is set to 1500 m/s.
[23]The acoustic pressure is not accounted for when calculating *probabilities*, only *pressures*.

For the first item, this means that the relative vertical motion at the same longitudinal position of the ship is larger than the vertical distance d from the still water surface to the location in question. The probability for the amplitude of the relative motion being larger than d can be expressed as

$$P(|\eta_{3r}| > d) = \exp\left(-\frac{d^2}{2\sigma_r^2}\right), \tag{89}$$

where

$$\sigma_r^2 = \int_0^\infty S(\omega)\left|\frac{\eta_{3r}(\omega)}{\zeta_a}\right|^2 d\omega \tag{90}$$

is the variance of the relative motion. Here, the relative motions are calculated without any influence of the ship on the waves.

Since the relative motion and relative velocity are statistically independent, we can express the probability of the slamming pressure becomes larger than a value p at a specific point on the ship hull as a joint probability of item 1) and 2), i.e.

$$P(\text{impact pressure} > p) = \exp\left[-\left(\frac{p}{\rho k\sigma_v^2} + \frac{d^2}{2\sigma_r^2}\right)\right] \tag{91}$$

From (91), the most probable largest slamming pressure p_{max} encountered in N waves can be expressed as

$$p_{max} = \rho k\sigma_v^2\left(\log N - \frac{d^2}{2\sigma_r^2}\right) \tag{92}$$

where N can be calculated by dividing the time duration of the N encountered waves by the mean zero up-crossing period of the vertical motions.

Similarily, the most probable largest acoustic pressure can be calculated as

$$p_{max}^A = \rho c_e\sigma_v\left(\log N - \frac{d^2}{2\sigma_r^2}\right) \tag{93}$$

where c_e is the velocity of sound in water, set to 1500 m/s in VERES. The most probable largest acoustic pressure can be used to find the upper physical limit of the slamming pressure. If p_{max} acceeds this limit, the acoustic pressure is applied in the calculations.

In a given sea state, Equation (91) can also be applied to calculate the probability of slamming to occur. In this case, a threshold pressure must be specified to define the miniumun pressure that can be characterized as a slam. The probability of slamming to occur can also be calculated by specifying a limiting relative velocity V_{cr}, often referred to as the threshold velocity for slamming. Equation (91) can then be rewritten as

$$P(\text{slamming}) = \exp\left[-\left(\frac{V_{cr}^2}{2\sigma_v^2} + \frac{d^2}{2\sigma_r^2}\right)\right]. \tag{94}$$

For the threshold velocity, Ochi [19] has suggested to use

$$V_{cr} = 0.093\sqrt{gL} \tag{95}$$

where L is the ship length.

4.6.3 Long term statistics

Long term predictions of the slamming pressure can be calculated in the same manner as described in Chapter 4.3 by combining Equation (91) with the joint probability of each sea state in a scatter diagram. To account for the acoustic pressure, the probability that the acoustic pressure becomes larer than a given value p^A at a specific point can be expressed as

$$P(\text{impact pressure} > p^A) = \exp\left[-\left(\frac{(p^A)^2}{\rho^2 c_e^2 \sigma_v^2} + \frac{d^2}{2\sigma_r^2}\right)\right] \tag{96}$$

The long term slamming pressures are evaluated by calculating the pressure using the k-factor (91) and the acoustic pressure (96) for each probability level. The lowest value is selected at each level.

4.6.4 Summary of input

The following table summarizes which input is required for the different slamming calculations in the VERES postprocessor:

Required result	Required input		
	k-factor	Threshold velocity V_{crit}	Threshold pressure P_{crit}
Probability of slamming: - Ochi - Threshold velocity - Threshold pressure	$\surd$ (Threshold pressure)	$\surd$ (Threshold velocity)	$\surd$ (Threshold pressure)
Pressure statistics: - Short term - Long term	$\surd$ (Short term) $\surd$ (Long term)		

Table 7: Required input for different slamming calculations.

If a relative motion calibration file (*.rmc) is specified for the motion point in question, the relative motion transfer functions will be calibrated before calculating any statistical values. See Section 4.1.3, page 49 for details.

5 APPENDIX

5.1 Output file formats

5.1.1 Motion transfer functions (*.re1)

This section describes the file that contains data of predicted motions from the VERES program.

The format of this file is:

```
OPEN( ...,ACCESS='SEQUENTIAL',FORM='FORMATTED')


'MOTION TRANSFER FUNCTIONS.'
CARDID(1)
CARDID(2)
CARDID(3)
CARDID(4)
CARDID(5)
RHOSW   GRAV
LPP     BREADTH   DRAUGHT
LCG     VCG
NOVEL   NOHEAD    NOFREQ   NDOF
do ivel=1,NOVEL
   VEL(ivel)   SINK(ivel)   TRIM(ivel)   XMTN(ivel)  ZMTN(ivel)
   do ihead=1,NOHEAD
      HEAD(ihead)
      do ifreq=1,NOFREQ
         FREQ(ifreq)
         do l=1,NDOF
            DOF(l)   RETRANS(l,ifreq,ihead,ivel)  IMTRANS(l,ifreq,ihead,ivel)
         enddo
      enddo
   enddo
enddo
```

The definitions of the different quantities are given on the next page.

Here:

Variable	Description	Type	Unit
CARDID(1:5)	Vessel identifying text	Char.	
RHOSW	Density of water	R	kg/m^3
GRAV	Acceleration of gravity	R	m/s^2
LPP	Length between the perpendiculars	R	m
BREADTH	Vessel breadth	R	m
DRAUGHT	Vessel draught	R	m
LCG	Longitudinal center of gravity (rel. $L_{pp}/2$)	R	m
VCG	Vertical center of gravity (rel. BL)	R	m
NOVEL	Number of vessel velocities	I	–
NOHEAD	Number of wave headings	I	–
NOFREQ	Number of wave frequencies	I	–
NDOF	Number of degrees of freedom	I	–
VEL	Vessel velocity	R	m/s
SINK	Sinkage at a given velocity	R	m
TRIM	Trim at a given velocity	R	deg
XMTN	X-pos. of the motion coordinate system (rel. $L_{pp}/2$)	R	m
ZMTN	Z-pos. of the motion coordinate system (relative to BL)	R	m
HEAD	Wave heading	R	deg
FREQ	Wave frequency	R	rad/s
DOF	Degree of freedom	I	–
RETRANS	Real part of complex motion RAO	R	–
IMTRANS	Imaginary part of complex motion RAO	R	–

The following definitions apply:

- The motion transfer functions (RAO's) are defined as the motion amplitude divided by wave amplitude for all degrees of freedom.
- The rotational motions are given in radians, hence the motion RAO's will be in rad/m.
- The motion transfer functions are given in the defined motion coordinate system, i.e. vertically in the waterline or CG depending on calculation options settings, with the z–axis pointing through center of gravity. When the file is generated from other sources than VERES, XMTN and ZMTN can be used to specify the motion coordinate system at any location on the centerplane.
- The real and imaginary parts of the complex motion transfer functions are related to the wave elevation at the center of gravity. (i.e. the phase angle gives the phase lead relative to a wave crest at the longitudinal center of gravity).

Changes in this file format: No changes have been made since version 3.00. Please note that this file format is slightly changed in versions after VERES Version 2.10. For versions *before* version 2.10, VCG is given relative to the waterline WL (the motion coordinate system), while for versions *after* 2.10 VCG is given relative to the base line BL. In addition, the position of the motion coordinate system is given separately, by the values XMTN and ZMTN, for each velocity. This gives two advantages:

1. The **position of the center of gravity** can be specified relative to the hull geometry (independent of the waterline).
2. The **motion coordinate system** can be specified separately for each velocity (and does not need to have any connections to the waterline and LCG).

The old format is still supported by the VERES Postprocessor. To check if a new or old *.re1 file format is read, it simply checks to see if XMTN and ZMTN are specified. If they are not specified, the old file format is assumed. We hope this makes the *.re1 file format more flexible for general ship motion calculations.

5.1.2 Added resistance output file format (*.re2)

This section describes the file that contains data of predicted added resistance in waves from the VERES program. The file includes drift forces/moments in sway and yaw.

The format of this file is:

```
OPEN( ...,ACCESS='SEQUENTIAL',FORM='FORMATTED')
```

```
'ADDED RESISTANCE.'
CARDID(1)
CARDID(2)
CARDID(3)
CARDID(4)
CARDID(5)
RHOSW   GRAV    [WATERDEPTH]
LPP     BREADTH   DRAUGHT
NOVEL   NOHEAD    NOFREQ    [NOCURVEL]    [NOCURDIR]

[do icurvel=1,NOCURVEL]
 [do icurdir=1,NOCURDIR]
   do ivel=1,NOVEL
    do ihead=1,NOHEAD
     VEL(ivel)   HEAD(ihead)   [CURVEL(icurvel)]   [CURDIR(icurdir)]
     do ifreq=1,NOFREQ
      FREQ(ifreq) ADDEDR(ivel,ihead,ifreq) SWFRCE(ivel,ihead,ifreq) YAWMOM(ivel,ihead,ifreq)
     enddo
    enddo
   enddo
 [enddo]
[enddo]
```

The data enclosed in brackets [] are part of the new file format and are optional. These data may not be supported by all software.

Here:

Variable	Description	Type	Unit
CARDID(1:5)	Vessel identifying text	Char.	
RHOSW	Density of water	R	kg/m^3
GRAV	Acceleration of gravity	R	m/s^2
WATERDEPTH	Water depth	R	m
LPP	Length between the perpendiculars	R	m
BREADTH	Vessel breadth	R	m
DRAUGHT	Vessel draught	R	m
NOVEL	Number of vessel velocities	I	–
NOHEAD	Number of wave headings	I	–
NOFREQ	Number of wave frequencies	I	–
NOCURVEL	Number of current velocities	I	–
NOCURDIR	Number of current directions	I	–
VEL	Vessel velocity	R	m/s
HEAD	Wave heading	R	deg
FREQ	Wave frequency	R	rad/s
CURVEL	Current velocity	R	m/s
CURDIR	Current direction	R	deg
ADDEDR	Added resistance	R	–
SWFRCE	Average sway force in waves	R	–
YAWMOM	Average yaw moment in waves	R	–

The following definitions apply:

- The added resistance is non-dimensionalized as:

$$\text{ADDEDR} = \frac{R_{\text{AW}}}{\rho g \zeta_a^2 B^2 / L_{pp}}$$

Similarily, the the sway mean force is non-dimensionalized as:

$$\text{SWFRCE} = \frac{\overline{F_2}}{\rho g \zeta_a^2 B^2 / L_{pp}}$$

Finally, the yaw mean moment is non-dimensionalized as:

$$\text{YAWMOM} = \frac{\overline{F_6}}{\rho g \zeta_a^2 B^2}$$

Where R_{AW} is the added resistance and $\overline{F_2}$ and $\overline{F_6}$ are the mean sway force and yaw moment respectively. ρ is the density of sea–water, g is the acceleration of gravity, B is the breadth L_{pp} is the vessel length between the perpendiculars and ζ_a is the wave amplitude.

5.1.3 Global wave induced loads (*.re3)

This section describes the file that contains output data from global wave induced loads calculations from the VERES program.

The format of this file is:

```
OPEN( ...,ACCESS='SEQUENTIAL',FORM='FORMATTED')


'GLOBAL WAVE INDUCED LOADS.'
CARDID(1)
CARDID(2)
CARDID(3)
CARDID(4)
CARDID(5)
RHOSW   GRAV
LPP     BREADTH   DRAUGHT
LCG     VCG
MASS    R44     R55     R66     R64
IMETH   GLMETH  IMASS
NOXCUT  NOYCUT
if (NOXCUT.gt.0) then
     (IXCALFORC(i),i=1,3),(IXCALMOM(i),i=1,3)
     XAXISGL(1)  XAXISGL(2)
     do icut=1,NOXCUT
          XCUTGL(icut)
     enddo
endif
if (NOYCUT.gt.0) then
     (IYCALFORC(i),i=1,3),(IYCALMOM(i),i=1,3)
     YAXISGL(1)  YAXISGL(2)
     do icut=1,NOYCUT
          YCUTGL(icut)
     enddo
endif
NOVEL   NOHEAD    NOFREQ
do ivel=1,NOVEL
   VEL(ivel)   SINK(ivel)   TRIM(ivel)   XMTN(ivel)  ZMTN(ivel)
enddo
do ihead=1,NOHEAD
   HEAD(ihead)
enddo
do ifreq=1,NOFREQ
   FREQ(ifreq)
enddo

do ivel=1,NOVEL
   do ihead=1,NOHEAD
      do ifreq=1,NOFREQ
         if (NOXCUT.gt.0) then
            do icut=1,NOXCUT
               (GLFCEL(j,icut,ifreq,ihead,ivel),j=1,3)
            enddo
            do icut=1,NOXCUT
               (GLMOML(j,icut,ifreq,ihead,ivel),j=1,3)
```

```
            enddo
         endif
         if (NOYCUT.gt.0) then
            do icut=1,NOYCUT
               (GLFCET(j,icut,ifreq,ihead,ivel),j=1,3)
            enddo
            do icut=1,NOYCUT
               (GLMOMT(j,icut,ifreq,ihead,ivel),j=1,3)
            enddo
         endif
      enddo
   enddo
enddo
```

Here:

Variable	Description	Type	Unit
CARDID(1:5)	Vessel identifying text	Char.	
RHOSW	Density of water	R	kg/m^3
GRAV	Acceleration of gravity	R	m/s^2
LPP	Length between the perpendiculars	R	m
BREADTH	Vessel breadth	R	m
DRAUGHT	Vessel draught	R	m
LCG	Longitudinal center of gravity (rel. $L_{pp}/2$)	R	m
VCG	Vertical center of gravity (rel. BL)	R	m
MASS	Vessel mass	R	kg
R44	Roll radius of gyration	R	m
R55	Pitch radius of gyration	R	m
R66	Yaw radius of gyration	R	m
R64	Yaw–Roll radius of gyration	R	m
IMETH	Hydrodynamic calculation method 1 – Traditional strip theory 2 – High speed theory	I	–
GLMETH	Global loads calculation method 1 – Strip theory 2 – Direct pressure integration	I	–
IMASS	Type of mass input 1 – Continuous mass distribution 2 – Discrete weights	I	–
NOXCUT	Number of transverse cuts	I	–
NOYCUT	Number of longitudinal cuts	I	–
IXCALFORC(i)	Index showing if the force in direction i is calculated for the transverse cuts	I	–
IXCALMOM(i)	Index showing if the moment about the i axis is calculated for the transverse cuts	I	–
IYCALFORC(i)	Index showing if the force in direction i is calculated for the longitudinal cuts	I	–
IYCALMOM(i)	Index showing if the moment about the i axis is	I	–

continued on next page

continued from previous page			
Variable	Description	Type	Unit
	calculated for the longitudinal cuts		
XAXISGL	Position of longitudinal moment axis (y,z)	R	m
YAXISGL	Position of transverse moment axis (x,z)	R	m
XCUTGL	x–Positions of transverse cuts	R	m
YCUTGL	y–Positions of longitudinal cuts	R	m
NOVEL	Number of vessel velocities	I	–
NOHEAD	Number of wave headings	I	–
NOFREQ	Number of wave frequencies	I	–
VEL	Vessel velocity	R	m/s
SINK	Sinkage at a given velocity	R	m
TRIM	Trim at a given velocity	R	deg
XMTN	X-pos. of the motion coordinate system (rel. $L_{pp}/2$)	R	m
ZMTN	Z-pos. of the motion coordinate system (relative to BL)	R	m
HEAD	Wave heading	R	deg
FREQ	Wave frequency	R	rad/s
GLFCEL	Longitudinal distribution of global forces on transverse cuts	C	–
GLFCET	Transverse distribution of global forces on longitudinal cuts	C	–
GLMOML	Longitudinal distribution of global moments at transverse cuts	C	–
GLMOMT	Transverse distribution of global moments at longitudinal cuts	C	–

The following definitions apply:

- The complex transfer functions for the *forces* are defined as:

$$GLFCE(i) = \frac{F_i}{\rho g L_{pp}^2 \zeta_a}. \tag{97}$$

  Further, the *moments* are defined as:

$$GLMOM(i) = \frac{M_i}{\rho g L_{pp}^3 \zeta_a}, \tag{98}$$

  where i denotes the direction, ρ is the density of sea–water, g is the acceleration of gravity, $L_p p$ is the vessel length between the perpendiculars and ζ_a is the wave amplitude.

- The real and imaginary parts of the complex transfer functions are related to the wave elevation at the center of gravity. (i.e. the phase angle gives the phase lead relative to a wave crest at the longitudinal center of gravity).

Changes in this file format: No changes have been made since version 3.00. Please note that this file format is slightly changed in VERES Version 3.00 and future versions. To be consistent with the change in the .re1 files, the variables XMTN and ZMTN are included for each velocity.

5.1.4 Generalized transfer functions file(*.re5)

This section describes the file that contains output of generalized transfer functions from the VERES program. In addition to motions, it can also be applied for other quantities that can be expressed by transfer functions

The format of version 1.0 of this file is:

```
OPEN( ...,ACCESS='SEQUENTIAL',FORM='FORMATTED')


PROGVER  FILEVER
FILETYP (=5)
CARDID(1)
CARDID(2)
CARDID(3)
CARDID(4)
CARDID(5)
RHOSW   GRAV      LSCALE
LPP     BREADTH   DRAUGHT
XCG     ZCG
NOVEL   NOHEAD    NOFREQ
NRESPS
do ires=1,NRESPS
   RESPID(ires), ISYM(ires), RESUNIT(ires), RESTXT(ires)
enddo

do ivel=1,NOVEL
  (TREHYD(ICO),ICO=1,3),(RREHYD(ICO),ICO=1,3)
  do ihead=1,NOHEAD
    do ifreq=1,NOFREQ
      VEL(ivel),HEAD(ihead),FREQ(ifreq)
      do l=1,NRESPS
        RESPID(l)  RETRANS(l,ifreq,ihead,ivel)  IMTRANS(l,ifreq,ihead,ivel)
      enddo
    enddo
  enddo
enddo
```

The definitions of the different quantities is given on the next page.

Here:

Variable	Description	Type	Unit
PROGVER	Program version	R	
FILEVER	File format version	R	
FILETYP	File type (=5 for *.re5)	I	
CARDID(1:5)	Vessel identifying text	Char.	
RHOSW	Density of water	R	kg/m^3
GRAV	Acceleration of gravity	R	m/s^2
LSCALE	Length parameter used for non-dimensionalization	R	m
LPP	Length between the perpendiculars	R	–
BREADTH	Vessel breadth	R	–
DRAUGHT	Vessel draught	R	–
XCG	Longitudinal center of gravity (rel. $L_{pp}/2$)	R	–
ZCG	Vertical center of gravity (rel. BL)	R	–
NOVEL	Number of vessel velocities	I	
NOHEAD	Number of wave headings	I	
NOFREQ	Number of wave frequencies	I	
NRESPS	Number of responses	I	
RESPID	ID number for each response (counting from 1 to NRESPS)	I	
ISYM	Symmetry property for each response (-1,0,1) for antisymmetric, no symmetry or symmetric properties regarding symmetric headings (e.g. 30° and 330°).	I	
RESUNIT	Unit for each response (must be a continuous text string)	Char.	
RESTXT	Description text for each response	Char.	
TREHYD	Components of the vector pointing from origin of the hydro-coordinate system to the intersection point between the planes formed by BL, CL and AP.	R	–
RREHYD	Rotations of the hydro-coordinate system that are needed in order to make the x-axis point towards the bow.	R	rad
VEL	Vessel velocity	R	–
HEAD	Wave heading	R	rad
FREQ	Wave frequency	R	–
RETRANS	Real part of complex response RAO	R	–
IMTRANS	Imaginary part of complex response RAO	R	–

The following definitions apply:

- The structure coordinate system is defined relative to AP and the base line, with the x-axis pointing forwards and the z-axis pointing upwards.
- Angles are given in radians.
- Lengths are non–dimensionalized with respect to LSCALE (=vessel length in VERES), L:

$$\hat{\ell} = \frac{\ell}{L}. \tag{99}$$

- Velocities are non–dimensionalized as the Froude number:

$$\hat{V} = \frac{V}{\sqrt{gL}}. \tag{100}$$

- Frequencies are non–dimensionalized as:

$$\hat{\omega} = \omega\sqrt{\frac{L}{g}}. \qquad (101)$$

- The motion transfer functions (RAO's) are defined as the motion amplitude divided by wave amplitude for all responses.
- The rotational motions are given in radians, hence the motion RAO's will be in rad/m.
- The motion transfer functions are given in the hydrodynamic coordinate system (defined by TREHYD and RREHYD).
- The real and imaginary parts of the complex motion transfer functions are related to wave elevation at the origin of the hydrodynamic coordinate system. Thus, in VERES the phase angle gives the phase lead relative to a wave crest at the longitudinal position of the origin.(i.e. the phase angle gives the phase lead relative to a wave crest at the longitudinal center of gravity.

5.1.5 Dynamic pressure distribution (*.re6)

This section describes the file that contains output of the total dynamic pressure distribution from the VERES program.

The format of version 1.0 of this file is:

```
OPEN( ...,ACCESS='SEQUENTIAL',FORM='FORMATTED')

PROGVER  FILEVER
FILETYP (=6)
CARDID(1)
CARDID(2)
CARDID(3)
CARDID(4)
CARDID(5)
RHOSW   GRAV      LSCALE
LPP     BREADTH   DRAUGHT
XCG     ZCG
NOVEL   NOHEAD    NOFREQ

do ivel=1,NOVEL
   (TREHYD(ICO)),ICO=1,3),(RREHYD(ICO),ICO=1,3)
   NHULL(ivel)
   do ihull=1,NHULL(ivel)
      NHPANS(ivel,ihull)
      do ipan=1,NHPANS(ivel,ihull)
         do ipnt=1,4
            X(ipnt)  Y(ipnt)  Z(ipnt)
         enddo
      enddo
   enddo
   NFOILS(ivel)
   do ifoil=1,NFOILS(ivel)
     XCEN(ivel,ifoil) YCEN() ZCEN() XCON() YCON() ZCON()
   enddo
   do ihead=1,NOHEAD
      do ifreq=1,NOFREQ
         VEL(ivel),HEAD(ihead),FREQ(ifreq)
         do ihull=1,NHULL(ivel)
            do ipan=1,NHPANS(ivel,ihull)
               Re(CPRESS(ivel,ihead,ifreq,ihull,ipan)) Im(CPRESS())
               Re(FORCEX()) Im() Re(FORCEY()) Im() Re(FORCEZ()) Im()
            enddo
         enddo
         do ifoil=1,NFOILS(ivel)
           Re(FCENX(ivel,ihead,ifreq,ifoil)) Im() Re(..Y()) Im() Re(..Z) Im()
         enddo
      enddo
   enddo
enddo
```

Here:

Variable	Description	Type	Unit
PROGVER	Program version	R	
FILEVER	File format version	R	
FILETYP	File type (=6 for *.re6)	I	
CARDID(1:5)	Vessel identifying text	Char.	
RHOSW	Density of water	R	kg/m^3
GRAV	Acceleration of gravity	R	m/s^2
LSCALE	Length parameter used for non-dimensionalization	R	m
LPP	Length between the perpendiculars	R	–
BREADTH	Vessel breadth	R	–
DRAUGHT	Vessel draught	R	–
XCG	Longitudinal center of gravity (rel. $L_{pp}/2$)	R	–
ZCG	Vertical center of gravity (rel. BL)	R	–
NOVEL	Number of vessel velocities	I	
NOHEAD	Number of wave headings	I	
NOFREQ	Number of wave frequencies	I	
TREHYD	Components of the vector pointing from origin of the hydro-coordinate system to the intersection point between the planes formed by BL, CL and AP.	R	–
RREHYD	Rotations of the hydro-coordinate system that are needed in order to make the x-axis point towards the bow.	R	rad
NHULL	Number of hulls on the vessel	I	
NHPANS	Number of panels on each hull	I	
NFOILS	Number of control surfaces (foils etc.)	I	
X,Y,Z	Coordinates for the corner points of the panel given in a counterclockwise direction (right-hand rule with normal vector outwards). The coordinates are given relative to the waterline for the given draught, sinkage and trim. (hydro-coordinate system)	R	–
XCEN,YCEN, ZCEN	Coordinates of the center of each foil.	R	–
XCON,YCON, ZCON	Coordinates of the point where each foils is connected to the hull.	R	–
VEL	Vessel velocity	R	–
HEAD	Wave heading	R	rad
FREQ	Wave frequency	R	–
CPRESS	Hydrodynamic pressure acting on each panel.	C	–
FORCEX,FORCEY, FORCEZ	Components of the viscous force acting on each panel.	C	–
FCENX,FCENY, FCENZ	Components of the force acting on each foil (at XCEN,YCEN,ZCEN).	C	–

The following definitions apply:

- The structure coordinate system is defined relative to AP and the base line, with the x-axis pointing forwards and the z-axis pointing upwards.

- Angles are given in radians.
- Lengths are non–dimensionalized with respect to LSCALE (=vessel length in VERES), L:

$$\hat{\ell} = \frac{\ell}{L}. \tag{102}$$

- Velocities are non–dimensionalized as the Froude number:

$$\hat{V} = \frac{V}{\sqrt{gL}}. \tag{103}$$

- Frequencies are non–dimensionalized as:

$$\hat{\omega} = \omega\sqrt{\frac{L}{g}}. \tag{104}$$

- The complex transfer functions for the pressures are defined as:

$$\hat{p} = \frac{p}{\rho g \zeta_a}. \tag{105}$$

  where p denotes the pressure, ρ is the density of sea–water, g is the acceleration of gravity and ζ_a is the wave amplitude.

- The complex transfer functions for the forces are defined as:

$$\hat{F} = \frac{F}{\rho g L^2 \zeta_a}. \tag{106}$$

- The real and imaginary parts of the complex transfer functions are related to the wave elevation at the longitudinal center of gravity (i.e. the origin of the motion and geometry coordinate system). Thus, the phase angle gives the phase lead relative to a wave crest at the longitudinal position of the origin.

5.1.6 Hydrodynamic coefficients (*.re7)

This section describes the file that contains output of the hydrodynamic coefficients from the VERES program.

The format of version 2.0 of this file is:

```
OPEN( ...,ACCESS='SEQUENTIAL',FORM='FORMATTED')

'HYDRODYNAMIC COEFFICIENTS.'
CARDID(1)
CARDID(2)
CARDID(3)
CARDID(4)
CARDID(5)
RHOSW GRAV
LPP BREADTH DRAUGHT
LCG VCG
-1 FILEVER (=2)
NOVEL NOHEAD NOFREQ NDOF
do i=1,6
  (VMASS(i,j),j=1,6)
enddo
do i=1,NOVEL
  VEL(i) SINK(i) TRIM(i) XMTN(i) ZMTN(i)
  do j=1,NOHEAD
    HEAD(j)
    do k=1,NOFREQ
      FREQ(k)
      do l=1,NDOF
        (ADDMAS(i,j,k,l,m),m=1,NDOF)
      enddo
      do l=1,6
       (ADDADDMAS(i,j,k,l,m),m=1,6)
      enddo
      do l=1,NDOF
        (DAMP(i,j,k,l,m),m=1,NDOF)
      enddo
      do l=1,6
        (ADDDAMP(i,j,k,l,m),m=1,6)
      enddo
      do l=1,NDOF
        (REST(i,j,k,l,m),m=1,NDOF)
      enddo
      do l=1,6
        (ADDREST(i,j,k,l,m),m=1,6)
      enddo
      VISCDL(i,j,k) VISCDN(i,j,k) VISCDNL(i,j,k)
    enddo
  enddo
enddo
```

Here:

Variable	Description	Type	Unit
FILEVER	File format version	R	
CARDID(1:5)	Vessel identifying text	Char.	
RHOSW	Density of water	R	kg/m^3
GRAV	Acceleration of gravity	R	m/s^2
LPP	Length between the perpendiculars	R	–
BREADTH	Vessel breadth	R	–
DRAUGHT	Vessel draught	R	–
LCG	Longitudinal center of gravity (rel. $L_{pp}/2$)	R	m
VCG	Vertical center of gravity (rel. BL)	R	m
NOVEL	Number of vessel velocities	I	
NOHEAD	Number of wave headings	I	
NOFREQ	Number of wave frequencies	I	
NDOF	Number of degrees of freedom	I	
VEL	Vessel velocity	R	m/s
SINK	Sinkage at a given velocity	R	m
TRIM	Trim at a given velocity	R	deg
XMTN	X-pos. of the motion coordinate system (rel. $L_{pp}/2$)	R	m
ZMTN	Z-pos. of the motion coordinate system (relative to BL)	R	m
HEAD	Wave heading	R	deg
FREQ	Wave frequency	R	rad/s
VMASS	Mass matrix	R	SI
ADDMAS	Hydrodynamic added mass matrix	R	SI
ADDADDMAS	Additional added mass matrix	R	SI
DAMP	Hydrodynamic damping matrix	R	SI
ADDDAMP	Additional damping matrix	R	SI
REST	Restoring matrix	R	SI
ADDREST	Additional restoring matrix	R	SI
VISCDL	Viscous roll damping, linear part	R	SI
VISCDN	Viscous roll damping, nonlinear part	R	SI
VISCDNL	Viscous roll damping, linearized	R	SI

Changes in this file format: Please note that this file format is changed in VERES Version 4.00.5 and future versions. The additional added mass, damping and stiffness matrices are written separately. These include the user input additional matrices as well as the contributions from roll stabilizing tanks etc. that are not a part of the strip-theory formulation. A new line is added in the header (line no. 10) containing -1 as first value and the file version (=2) as the second value.

5.1.7 Wave exitation forces (*.re8)

This section describes the file that contains output of the wave exitation forces from the VERES program.

The format of version 2.0 of this file is:

```
OPEN( ...,ACCESS='SEQUENTIAL',FORM='FORMATTED')

' WAVE EXCITATION FORCE TRANSFER FUNCTIONS.'
CARDID(1)
CARDID(2)
CARDID(3)
CARDID(4)
CARDID(5)
RHOSW GRAV
LPP BREADTH DRAUGHT
LCG VCG
NOVEL NOHEAD NOFREQ NDOF
do ivel=1,NOVEL
  VEL(ivel) SINK(ivel) TRIM(ivel) XMTN(ivel) ZMTN(ivel)
  do ihead=1,NOHEAD
    HEAD(ihead)
    do ifreq=1,NOFREQ
      FREQ(ifreq)
      do l=1,NDOF
        DOF(l)REFORCE(l,ifreq,ihead,ivel) IMFORCE(l,ifreq,ihead,ivel)
        REFORCE_FK(l,ifreq,ihead,ivel) IMFORCE_FK(l,ifreq,ihead,ivel)
        REFORCE_D1(l,ifreq,ihead,ivel) IMFORCE_D1(l,ifreq,ihead,ivel)
        REFORCE_D2(l,ifreq,ihead,ivel) IMFORCE_D2(l,ifreq,ihead,ivel)
      enddo
    enddo
  enddo
enddo
```

Here:

Variable	Description	Type	Unit
CARDID(1:5)	Vessel identifying text	Char.	
RHOSW	Density of water	R	kg/m^3
GRAV	Acceleration of gravity	R	m/s^2
LPP	Length between the perpendiculars	R	–
BREADTH	Vessel breadth	R	–
DRAUGHT	Vessel draught	R	–
LCG	Longitudinal center of gravity (rel. $L_{pp}/2$)	R	m
VCG	Vertical center of gravity (rel. BL)	R	m
NOVEL	Number of vessel velocities	I	
NOHEAD	Number of wave headings	I	
NOFREQ	Number of wave frequencies	I	
NDOF	Number of degrees of freedom	I	
VEL	Vessel velocity	R	m/s
SINK	Sinkage at a given velocity	R	m
TRIM	Trim at a given velocity	R	deg

continued on next page

continued from previous page			
Variable	Description	Type	Unit
XMTN	X-pos. of the motion coordinate system (rel. $L_{pp}/2$)	R	m
ZMTN	Z-pos. of the motion coordinate system (relative to BL)	R	m
HEAD	Wave heading	R	deg
FREQ	Wave frequency	R	rad/s
DOF	Degree of freedom	I	–
REFORCE	Real part of complex force transfer function	R	SI
IMFORCE	Imaginary part of complex force transfer function	R	SI
*XX*FORCE_FK	Real/Imaginary part of complex force transfer function (Froude-Krylov force)	R	SI
*XX*FORCE_D1	Real/Imaginary part of complex force transfer function (diffraction force)	R	SI
*XX*FORCE_D2	Real/Imaginary part of complex force transfer function (diffraction force without speed terms)	R	SI

The following definitions apply:

- The force transfer functions are defined as the force amplitude divided by wave amplitude for all degrees of freedom.
- The force transfer functions are given in the defined motion coordinate system, i.e. vertically in the waterline or CG depending on calculation options settings, with the z–axis pointing through center of gravity.
- The real and imaginary parts of the complex force transfer functions are related to the wave elevation at the center of gravity. (i.e. the phase angle gives the phase lead relative to a wave crest at the longitudinal center of gravity).

Changes in this file format: The file has been extended for VERES Version 4.08.2 and later to include separate force components if conventional strip theory or pressure integration is applied.

The force components from Froude-Krylov and diffraction are written separately for conventional strip theory and pressure integration method. No changes are done to the file header (fully backwards compatible as the new data are on the end of an existing data line), so any program using any of these new components must check that the line with force components contain more than 3 numbers.

5.2 Import/export file formats

5.2.1 Mass distribution files

Continuous mass distribution (*.m2d)

```
' 2D MASS DISTRIBUTION
' Please note the following definitions:
' X-position is the longitudinal position rel. to Lpp/2 (positive aft)
' Z-position is the vertical position of local COG above BL
' 2D moment of inertia is given about the local COG
'
' Number of mass positions:
   60
'     X-position       Z-position       2D-Mass        2D-Moment
'        (m)              (m)            (kg/m)         (kg m2/m)
' ---------------------------------------------------------------
        -62.1080          9.0000       0.000000E+00     0.000000E+00
        -60.0210          9.0000       0.247619E+04     0.000000E+00
        -57.9330          9.0000       0.705145E+04     0.000000E+00
            .               .              .                .
            .               .              .                .
```

Discrete weights (*.m3d)

```
' 3D MASS DISTRIBUTION
' Please note the following definitions:
' X-position is the longitudinal position rel. to Lpp/2 (positive aft)
' Z-position is the vertical position above BL
'
' Number of mass points:
  145
'         Mass         X-position       Y-position       Z-position
'         (kg)            (m)              (m)              (m)
' ---------------------------------------------------------------
       2893.6201        -58.0190          3.1000          12.1200
      13669.7998        -57.4390          3.1000          16.9000
       6236.2500        -56.2090          3.1000          13.4200
            .               .                .                .
            .               .                .                .
```

5.2.2 Wave scatter diagram files (*.sea)

This section describes the file format of the scatter diagram input file, which enables the user to specify any chosen wave scatter diagram for use in the long term statistics of the VERES Postprocessor.

The file format is:

```
DESCRTEXT
IFORM     HSTXTYPE     NUMHS     NUMTX
HS(IHs), IHs = 1, NUMHS
TX(ITx), ITx = 1 NUMTX
do IHs = 1, NUMHS
   (PROB(IHs,ITx), ITx = 1, NUMTX)
enddo
```

The definitions of the variables are given in Table 8.

Variable	Description	Type	Unit
DESCRTEXT	Text describing the scatter diagram	Char	
IFORM	Identifies type of wave period 1 – T_p 2 – T_z 3 – T_1	I	–
HSTXTYPE	Identifies if the H_s and T_x–values are given as: 1 – the middle value of the range 2 – the highest value of the range 3 – the lowest value of the range	I	–
NUMHS	Number of significant wave heights	I	–
NUMTX	Number of wave periods	I	–
HS	Significant wave height	R(I)	m
TX	Wave period	R(I)	s
NPROB	Number of occurence of a sea state	R(I,I)	–

Table 8: Definition of variables

An example of a wave scatter diagram input file is given below:

```
North sea, area 11 in Global Wave Statistics. Annual.
2  1  10  7
0.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8.5 9.5
3.5 4.5 5.5 6.5 7.5 8.5 10
 19  86  94  41  10   2   0
  3  49 121  99  40  10   2
  1  17  63  73  40  13   4
  0   6  27  39  26  10   4
  0   2  11  19  14   6   3
  0   1   4   9   7   4   1
  0   0   2   4   4   2   1
  0   0   1   2   2   1   1
  0   0   0   1   1   1   0
  0   0   0   1   1   0   0
```

5.2.3 Wave spectrum files (*.wsp)

This section describes the file format for user input wave spectrum, which enables the user to specify a wave spectrum for use in the short term statistics of the VERES Postprocessor as well as for time domain calculations.

The file format is:

```
DESCRTEXT
NFREQ     NDIR    IHEADTYP    IFREQTYP
IPRINCIPAL
DIR(iDir), iDir = 1, NDIR
do iFreq = 1, NFREQ
   FREQ(iFreq) , (WSPEC(iFreq,iDir), iDir = 1, NDIR)
enddo
```

The definitions of the variables are given in Table 9.

Variable	Description	Type	Unit
DESCRTEXT	Text describing the wave spectrum	Char	
NFREQ	Number of wave frequencies	I	–
NDIR	Number of wave directions (short crested if > 1)	I	–
IHEADTYP	Heading type indicator 1 – counterclockwise, +90° is from port (standard VERES definition) 2 – clockwise, +90° is from starboard (typical for compass directions)	I	–
IFREQTYP	Frequency type indicator 1 – rad/sec 2 – Hz	I	–
IPRINCIPAL	Index of principal wave direction	I	–
DIR	Wave direction	R(I)	deg
FREQ	Wave frequency	R(I)	Hz or rad/sec
WSPEC	Wave spectrum value	R(I,I)	$m^2 \cdot s$

Table 9: Definition of variables

If both IHEADTYP and IFREQTYP are not given (old file format), both of these are assumed to have a value of 1.

The wave directions and wave headings should be given in increasing order. The wave directions should be within an interval of $\pm 180°$ relative to the principal wave direction. The wave directions are converted to be relative to the principal wave direction when read by the program, so the origin of the wave directions is irrelevant.

5.2.4 Relative motion calibration file (*.rmc)

This section describes the file format of the relative motion calibration file, which enables the user to calibrate the relative vertical motions between the vessel and the waves at a specific location on the vessel. This file can be applied for a specified motion point in the VERES Postprocessor.

The file format is:

```
PROGVER   FILEVER
FILETYP (=1)
DESCRTEXT
NUMVEL    NUMHEAD    NUMFREQ
(HEAD(IHdg), IHdg = 1, NUMHEAD)
(FREQ(IFrq), IFrq = 1, NUMFREQ)
do IVel=1,NUMVEL
  VEL(IVel)
  do IFrq=1,NUMFREQ
    (FACTOR(IVel,IHdg,IFrq),IHdg=1,NUMHEAD)
  enddo
enddo
```

The definitions of the variables are given in Table 10.

Variable	Description	Type	Unit
PROGVER	Identifies program version (not used for any purpose at the moment)	I	–
FILEVER	File version (=1.0) (can be applied to preserve backwards compatibility if the file format is changed)	I	–
FILETYP	File type (=1) (can be applied to offer other ways to input calibration data later)	I	–
DESCRTEXT	Text describing the scatter diagram	Char	
NUMVEL	Number of vessel velocities	I	–
NUMHEAD	Number of wave headings	I	–
NUMFREQ	Number of wave frequencies	I	–
HEAD	Wave heading	R(I)	deg
FREQ	Non-dimensional wave frequency $= \omega\sqrt{L_{pp}/g}$	R(I)	–
VEL	Froude number, $Fn = V/\sqrt{gL_{pp}}$	R(I)	–
FACTOR	Calibration factor	R(I,I,I)	–

Table 10: Definition of variables

The relative motion transfer functions are multiplied with the calibration factor. Thus, a value of 1.0 means no calibration (undisturbed wave), a factor lower than one can be applied e.g. at the stern of a vessel in head seas to account for diffraction effects (e.g. in a shadow region behind the ship). A factor greater than one can be applied to account for water swell-up and diffraction in the bow region, e.g. to calibrate calculations related to probability of water on deck.

The calibration is a function of vessel speed, heading and frequency. Within the specified range, linear interpolation is applied to obtain values for the correct speeds/headings/frequencies of the transfer functions. Outside the specified range of values in the file, a constant calibration factor of 1.0 is applied (i.e. no calibration).

An example of a relative motion calibration file is given below:

```
3.22 1.0
1
Calibration file - stern
3 5 7
0. 15. 30. 60. 90.
1.4650 1.8312 2.1975 2.4417 2.7469 3.6626 21.975
0.0
1.00 1.00 1.00 1.00 1.0
1.00 0.90 0.80 0.71 1.0
0.97 0.75 0.85 0.74 1.0
0.84 0.77 0.83 0.84 1.0
0.62 0.68 0.69 0.95 1.0
0.41 0.40 0.39 0.67 1.0
0.00 0.00 0.00 0.00 0.0
0.150
1.00 1.00 1.00 1.00 1.0
0.68 0.69 0.70 0.63 1.0
0.87 0.76 0.66 0.67 1.0
0.80 0.76 0.73 0.63 1.0
0.62 0.70 0.77 0.59 1.0
0.07 0.10 0.13 0.27 1.0
0.00 0.00 0.00 0.00 1.0
```

5.3 Dimensions and constants

5.3.1 Array dimensions

The following dimensions apply to the arrays in the VERES program, and are therefore to be considered as maximum values in the input to the program:

Description	Max. Value
Number of vessel velocities	15
Number of wave frequencies/periods	100
Number of wave headings	36
Number of sections	150
Number of input offset-points on each section	500
Number of interpolated offset-points on each section	80
Number of hulls	7
Number of mass positions (continuous distribution)	5000
Number of mass points on half ship (discrete weights)	5000
Number of transverse cuts	50
Number of longitudinal cuts	10
Number of foil pairs	20

5.3.2 Program constants

The following constants are defined in VERES:

$$\text{Density of sea-water, } \rho = 1025 \ \ kg/m^3$$
$$\text{Acceleration of gravity, } g = 9.81 \ \ m/s^2$$
$$\pi = 4.0 \cdot \text{atan}\,(1.0)$$

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