Level 29, 221 St Georges Tce
Perth, WA 6000

Contact: Dr Tim Gourlay
+61 416 328883
tim@perthhydro.com

Comparison of WAMIT and MoorMotions with Model Tests for a Tanker Moored at an Open Berth

Tim Gourlay

Perth Hydro Research Report R2019-09

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SUMMARY

This report shows a validation of WAMIT and MoorMotions software against model tests of a 200,000 DWT tanker in shallow water, a well-known test case described in van Oortmerssen (1976).

Comparisons are made with model test results for forced-oscillation hydrodynamic coefficients, fixed-ship wave loads, and moored-ship motions and mooring loads.

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1. Test case

The test case uses a 200,000 DWT tanker, tested at 1:82.5-scale in Marin's shallow-water basin (210 m x 15.75 m). The model tests are described in detail in van Oortmerssen (1976).

Particulars of the tanker and test setup are shown in Table 1. All quantities are given at full scale.

Length overall	316.8 m
Length between perpendiculars	310.0 m
Beam	47.20 m
Draught	18.90 m
Displacement	235,000 m^3
Block coefficient	0.85
Vertical Centre of Gravity	13.32 m above keel
Longitudinal Centre of Gravity	-1.1 m forward of Station 10
Transverse Metacentric Height (GM)	5.78 m
Roll Radius of Gyration	17.0 m
Pitch Radius of Gyration	77.5 m
Yaw Radius of Gyration	77.5 m
Water depth	22.68 m

Table 1: Particulars of the 200,000 DWT tanker

Added mass and damping were measured from strain gauge readings during forced oscillation tests. Wave loads were measured from strain gauge readings with the model held fixed in waves. These tests are described in van Oortmerssen (1976, Section 3.2).

Moored ship motions and loads in waves were also measured, as described in van Oortmerssen (1976, Section 5.3). The mooring arrangement used is shown in Figure 1. The wharf structure sits mainly above the water surface and is assumed transparent to waves.

Figure 1: Mooring arrangement used for model testing of 200,000 DWT tanker, from van Oortmerssen (1976, Figs. 5.2, 5.4, 5.5)

In the moored ship tests, fenders were simulated using vertical wheels, to allow free vertical movement, mounted on springs with stiffness 1575 tonnes/metre. Mooring lines were chosen to be representative of wire lines with nylon tails, and have measured force/displacement curves as given in van Oortmerssen (1976, Fig. 5.3). A pre-tension of 20 tonnes was used in all lines.

Uni-directional (long-crested) seas were used for the moored ship model tests, with measured wave spectrum shown in Figure 2.

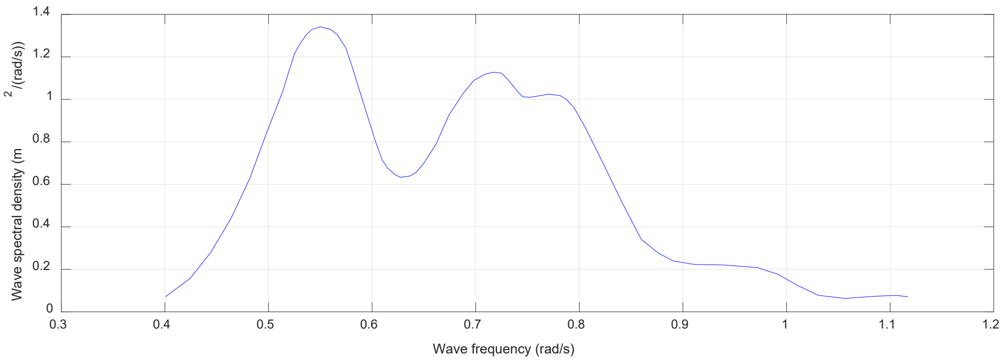


Figure 2: Wave spectrum used for moored ship model tests (van Oortmerssen 1976, Fig. 5.9). Significant wave height is 2.6 m.

2. Hull modelling

A lines plan for the ship is given in van Oortmerssen (1976, Fig. 3.1). This lines plan was used to develop a 2472-panel surface mesh using the OCTOPUS 3D Mesher. This surface mesh is shown in Figure 3.

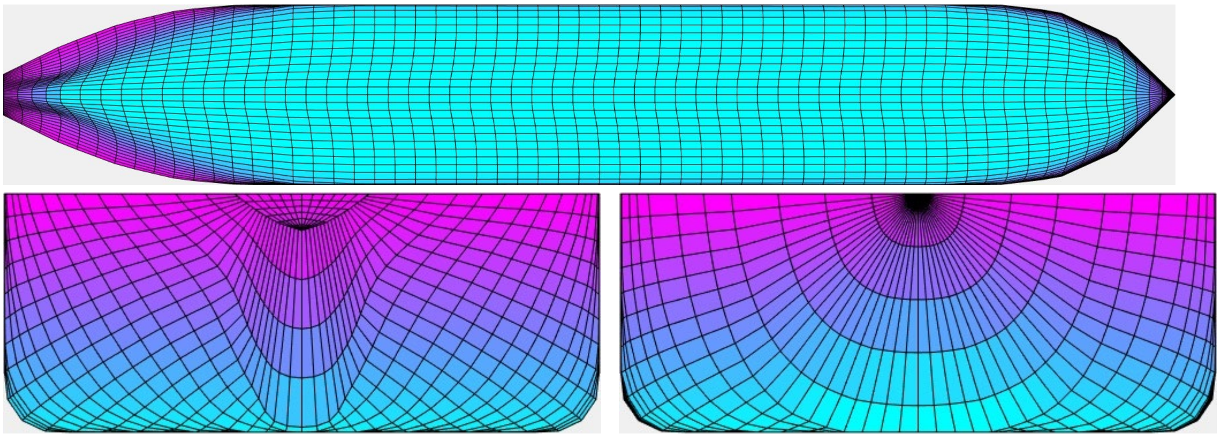


Figure 3: 200,000 DWT tanker surface mesh, up to design waterline. (Top) Plan view; (Bottom left) Stern view; (Bottom right) Bow view.

3. WAMIT calculations

WAMIT v7.3 was used for this study. Settings are described in Table 2.

WAMIT solver	Direct solver, source method
Degrees of freedom	Coupled 6-DoF
First-order wave loads method	Diffraction potential
Second-order wave loads method	Pressure integration
Frequency range for impulse response functions	0 : 0.005 : 2.5 rad/s, plus infinite frequency
Frequency range for wave loads	0 : 0.01 : 1.2 rad/s

Table 2: WAMIT solver settings used in the study

The six motion degrees of freedom are:
x_1= "surge" (fore-aft CoG motion, positive forward)
x_2 = "sway" (transverse CoG motion, positive to port)
x_3 = "heave" (vertical CoG motion, positive upwards)
x_4 = "roll" (angle, positive to starboard)
x_5 = "pitch" (angle, positive bow-down)
x_6 = "yaw" (angle, positive bow-to-port).

Diagonal impulse response functions from WAMIT for the 200,000 DWT tanker are shown in Figure 4.

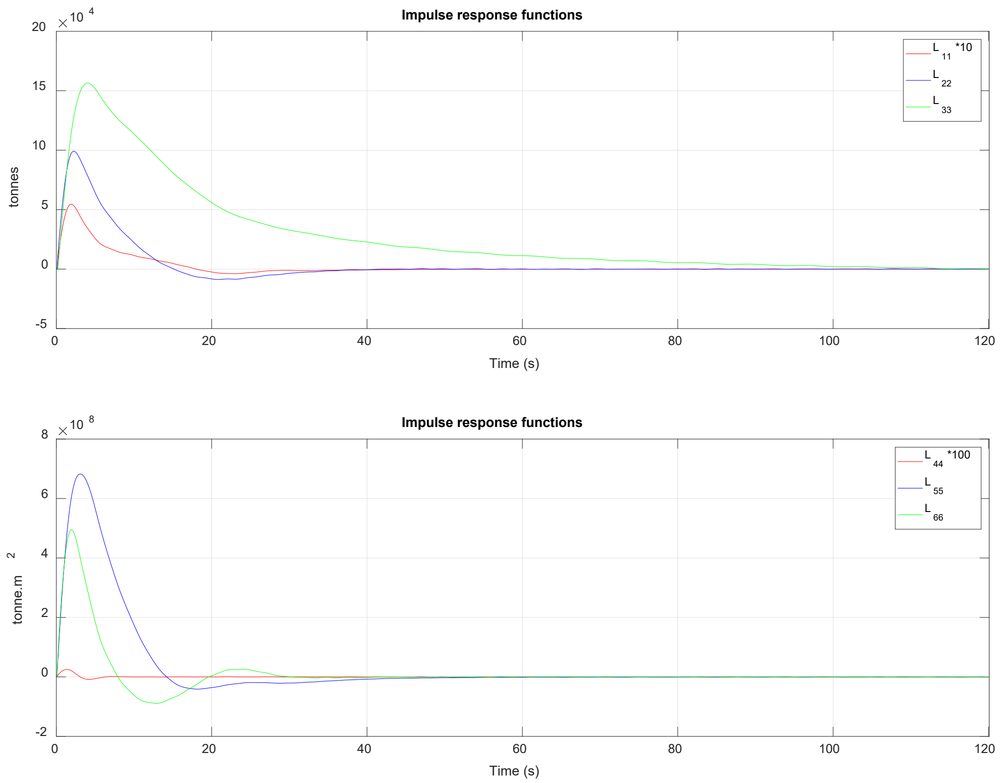


Figure 4: Diagonal impulse response functions $L_{ii}(t)$ for 200,000 DWT tanker in shallow water

4. MoorMotions calculations

MoorMotions is a nonlinear time-domain solver developed at Perth Hydro (Gourlay 2019). The software uses a fourth-order Runge-Kutta solver, with 6-DoF motion coupling for a moored ship. Wave loads, hydrodynamic coefficients and impulse response functions are calculated in WAMIT and fed into the MoorMotions software. The equation of motion is

$$\sum_{j=1}^{6}[M_{ij}+A_{ij}(\infty)]\ddot{x}_j = X_i^{(1)} + X_i^{(2)} + F_i^{(\text{lines})} + F_i^{(\text{fenders})} - \sum_{j=1}^{6} C_{ij}x_j - \int_0^{\infty}\sum_{j=1}^{6} L_{ij}(\tau)\ddot{x}_j(t-\tau)d\tau \tag{1}$$

The symbols are defined as follows:

x_j= motion in each degree of freedom, $j = 1, \ldots, 6$

M_{ij} = mass matrix (Newman 1992, p307)

$A_{ij}(\infty)$ = added mass at infinite frequency

$X_i^{(1)}$ = first-order wave load

$X_i^{(2)}$ = second-order wave load

$F_i^{(\text{lines})}$ = net force produced by mooring line tension at each instant in time

$F_i^{(\text{fenders})}$ = net force produced by fenders at each instant in time

C_{ij} = hydrostatic restoring coefficients

$L_{ij}(\tau)$ = acceleration-based impulse response functions

Equation (1) is the same as that developed by van Oortmerssen (1976, eq. 4.23), excepting the use of the impulse response functions L_{ij} based on acceleration (WAMIT 2019 eq. 13.1), rather than the impulse response functions K_{ij} based on velocity (as used by van Oortmerssen). The acceleration-based impulse response functions are calculated with WAMIT's f2t utility, using equation (13.5) from WAMIT (2019).

MoorMotions settings used in this study are as shown in Table 3.

Total simulation time	2200 s
Wave ramp-up time	100 s
Time step	0.1 s
Degrees of freedom	All
Fender friction	No
Mooring line energy dissipation	No
Fender energy dissipation	No

Table 3: MoorMotions settings used in the study

MoorMotions is first run with hydrodynamic impulse response functions, but no incoming waves, to calculate the natural motion periods of the moored ship system. Results are shown in Table 4.

Surge	190 – 200 s
Sway	70 – 80 s
Heave	17 s
Roll	15 s
Pitch	15 s
Yaw	60 – 70 s

Table 4: Natural motion periods of the moored ship system. Natural motion periods depend on the motion amplitude, since the system is nonlinear.

For wave-induced motions and loads, the wave spectrum shown in Figure 2 is divided into 15 equal frequency bins from 0.425 to 1.125 rad/s, as done by van Oortmerssen (1976, p.99).

First-order wave loads are calculated from the WAMIT wave load RAOs on the ship, together with the spectral wave amplitude at each frequency, as described in van Oortmerssen (1976, eq. 4.26). Random phasing is used for each input wave frequency.

Second-order wave loads considered here are the “difference-frequency” and “mean-drift” wave loads. Difference-frequency wave loads use the Newman (1974, eq. 9) approximation, with the arithmetic mean of the diagonal elements. “Sum-frequency” wave loads are neglected.

5. Added mass and damping

Comparison of the model test results with WAMIT is shown below. Roll is not included, as WAMIT measures roll moments about the waterline, whereas the model tests measured roll moments about the centre of gravity.

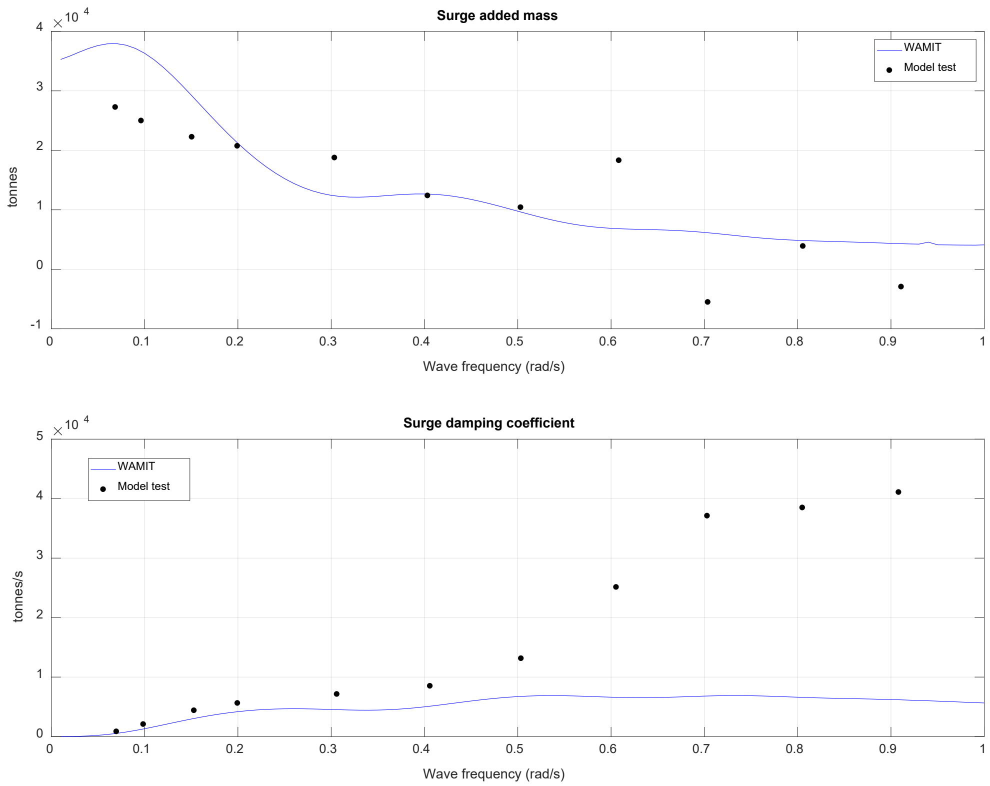


Figure 5: Surge hydrodynamic coefficient comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.13).

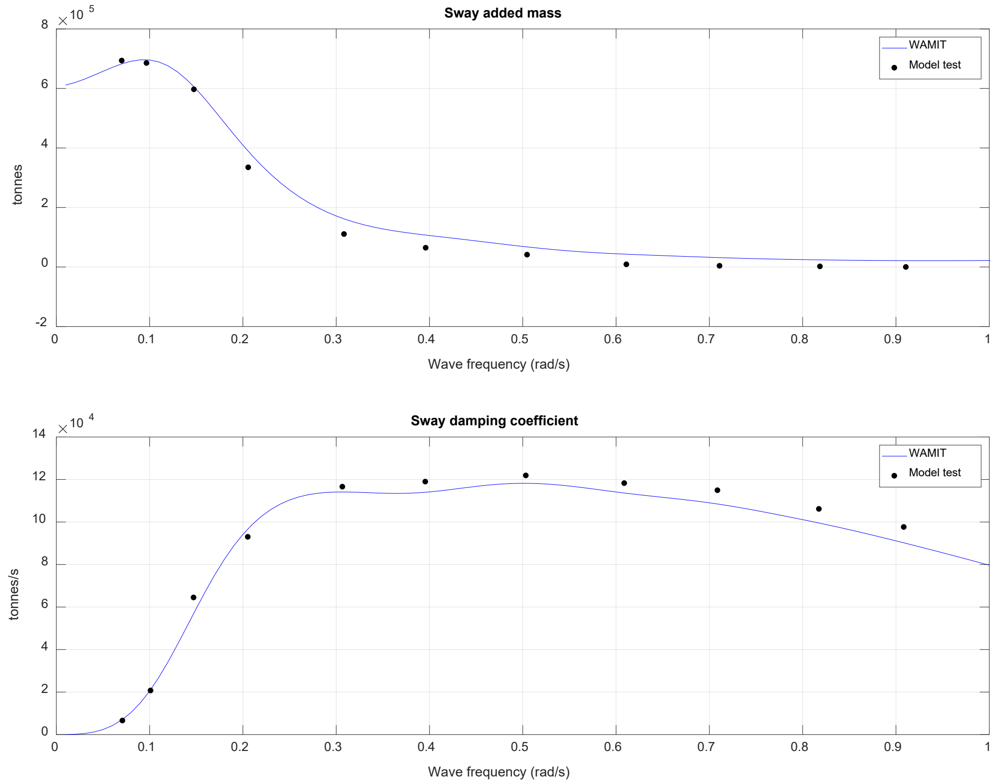


Figure 6: Sway hydrodynamic coefficient comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.14).

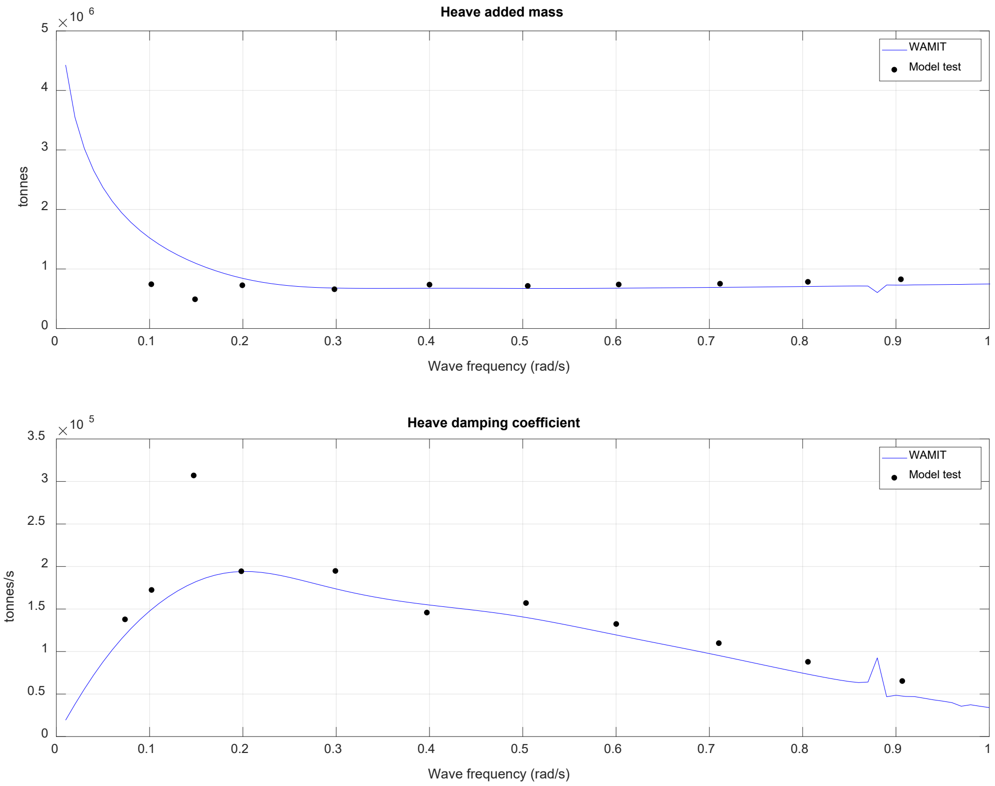


Figure 7: Heave hydrodynamic coefficient comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.15).

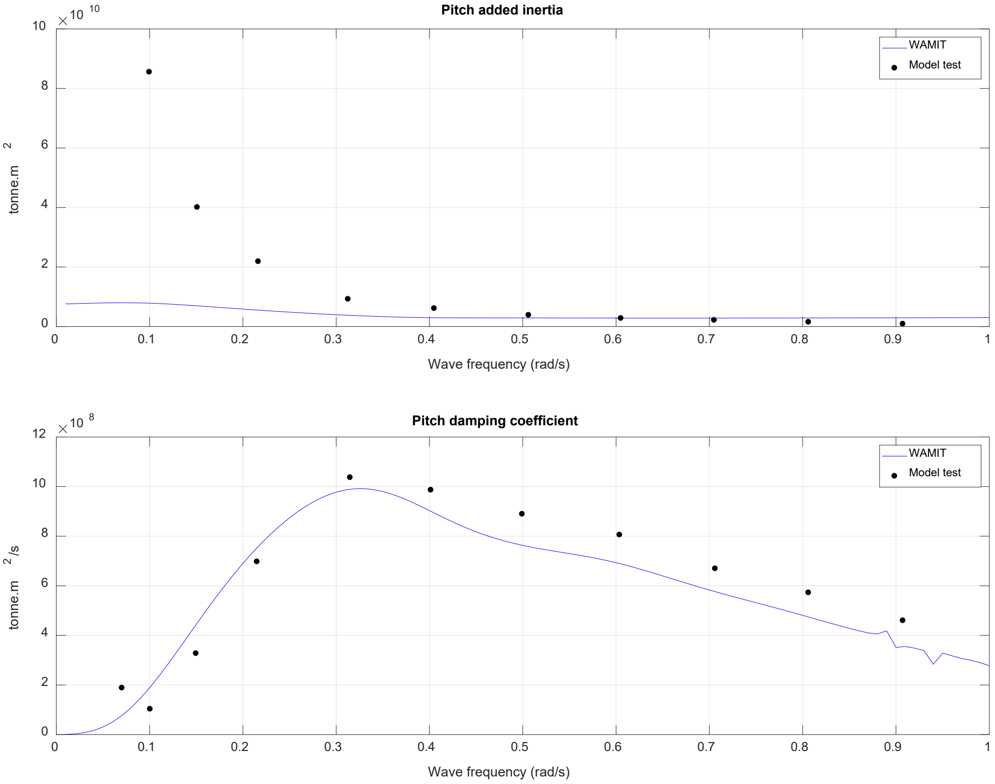


Figure 8: Pitch hydrodynamic coefficient comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.17).

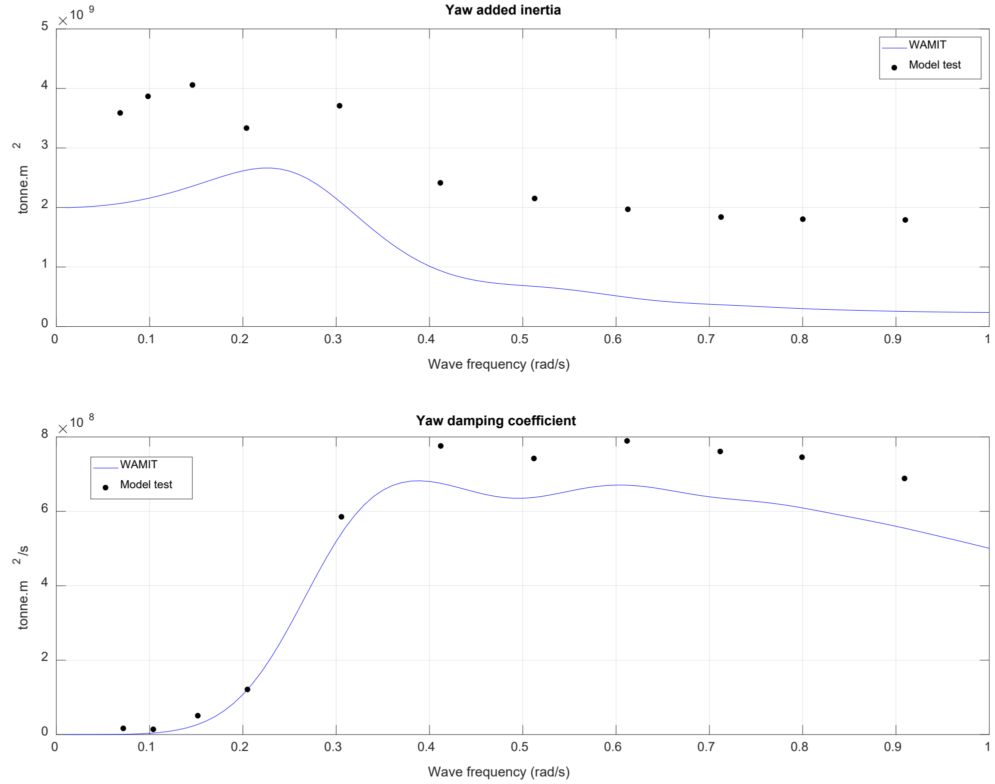


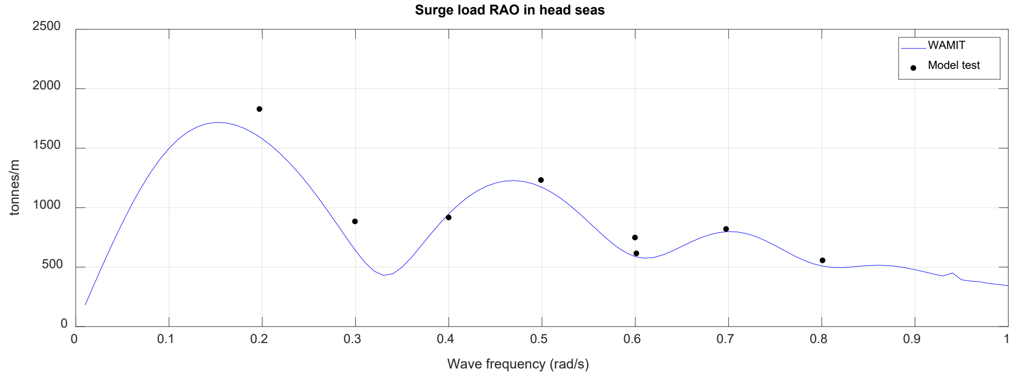
Figure 9: Yaw hydrodynamic coefficient comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.18).

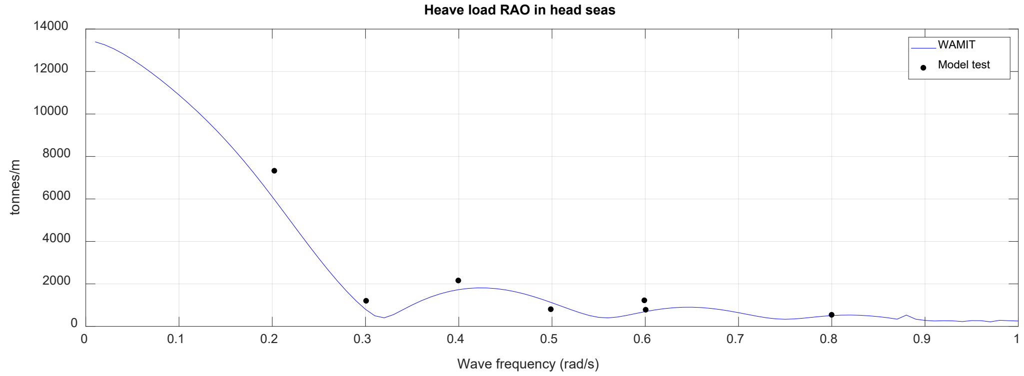
Points to note are:

- Irregular frequencies are noticeable in heave and pitch at 0.88 and 0.97 rad/s. In practice, these can be removed using WAMIT's irregular frequency option, or by interpolating between adjacent points.
- Comparison of WAMIT with model test results is good in most cases.
- Surge damping at high frequency is noticeably under-predicted by WAMIT, and was similarly under-predicted by van Oortmerssen (1976, Fig. 3.13). This may be due to viscous effects.
- Pitch added inertia at low frequency is under-predicted by WAMIT, and also by van Oortmerssen (1976, Fig. 3.17). Experimental error may be important in the low-frequency limit (van Oortmerssen 1976, p46).
- Yaw added inertia and damping are not that well predicted by WAMIT, nor by van Oortmerssen (1976, Fig. 3.18). The simplified hull surface mesh at bow and stern may be an important reason for this.

6. Wave loads

Comparisons with WAMIT first-order wave loads are shown below.





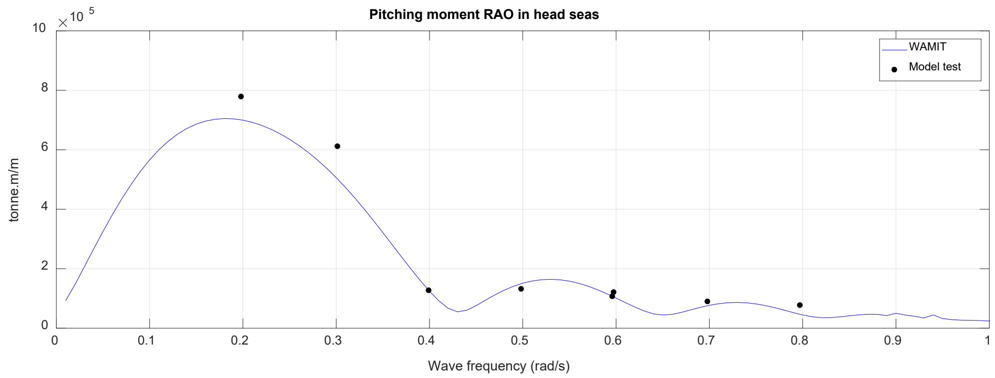


Figure 10: Wave heading 180˚ (head seas): wave load comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.10).

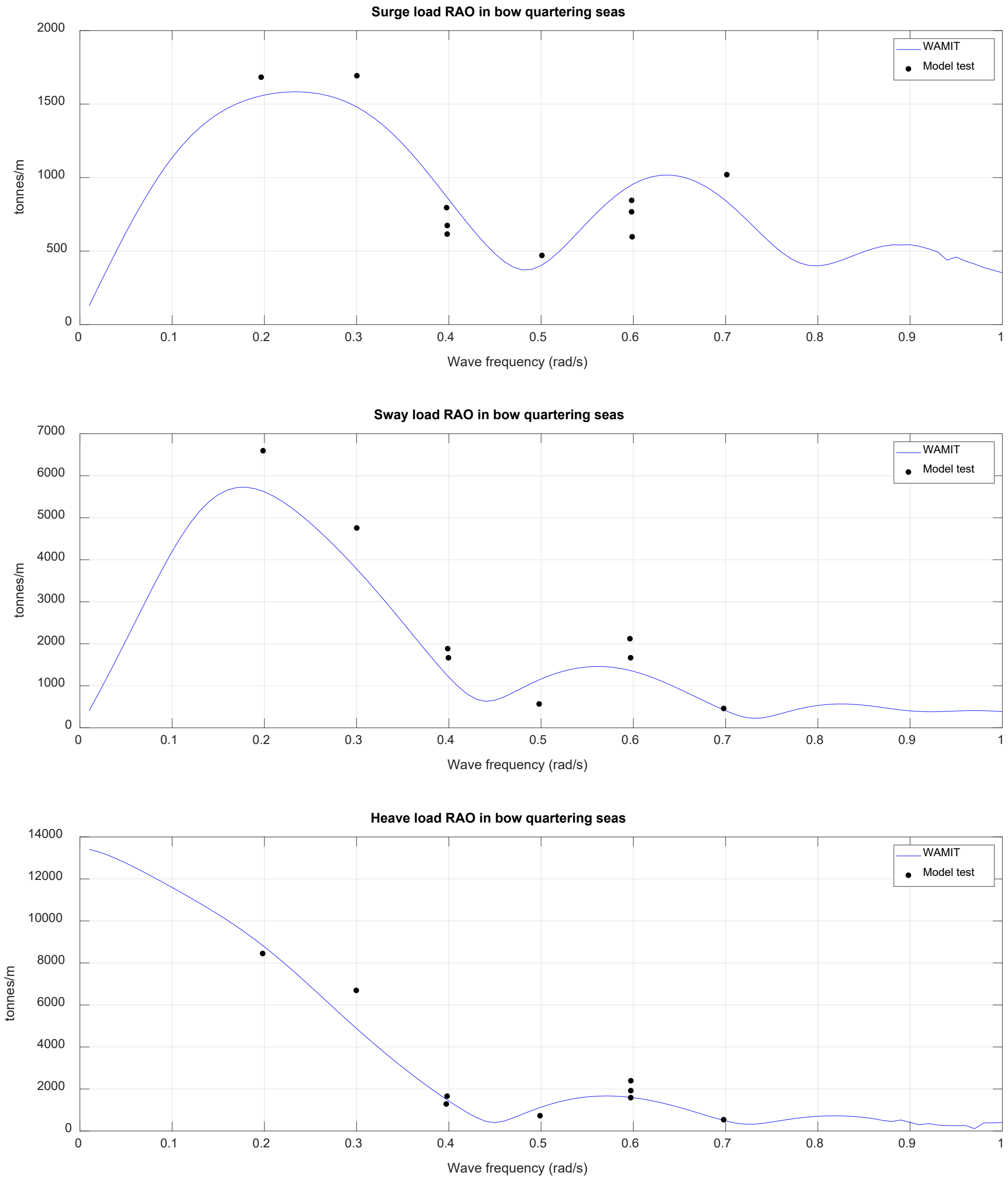


Figure 11: Wave heading 225˚ (port bow quartering seas): surge, sway and heave wave load comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.11).

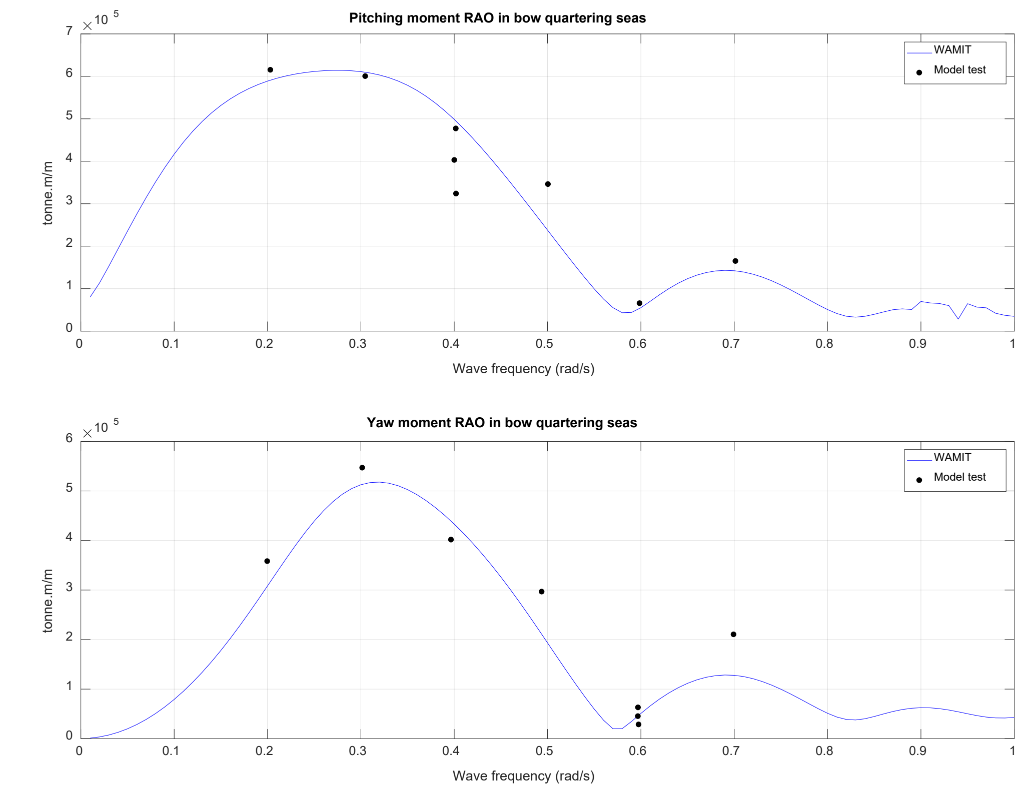


Figure 12: Wave heading 225° (port bow quartering seas): pitch and yaw wave-induced moment comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.11).

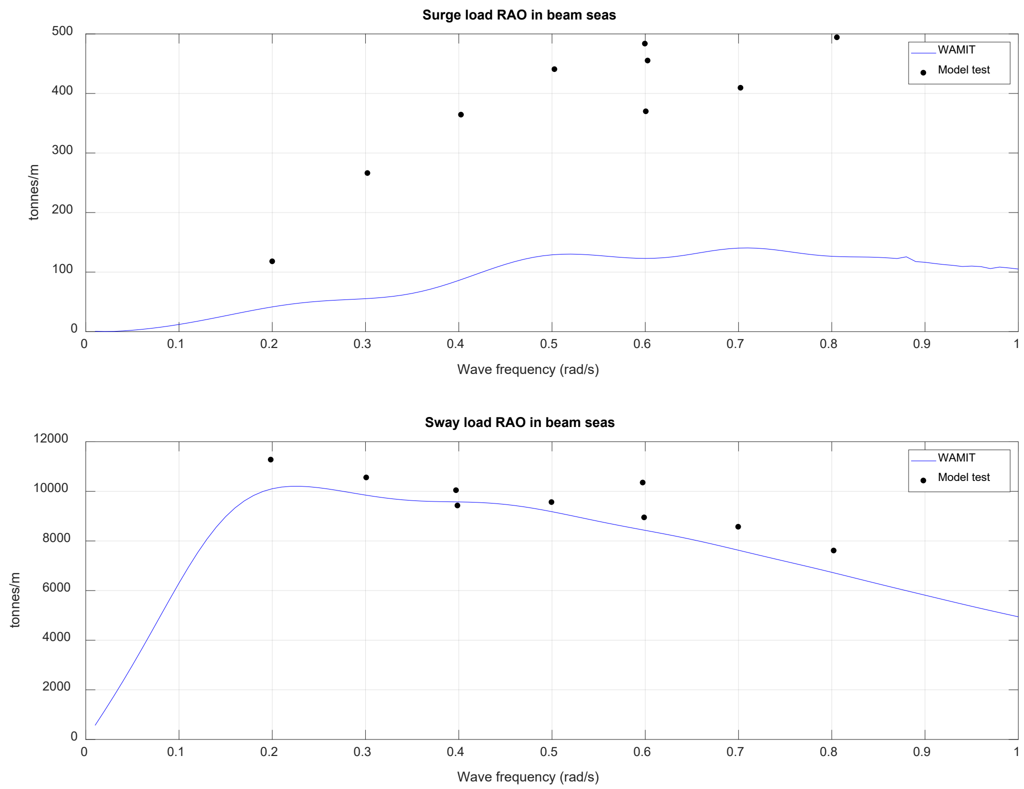


Figure 13: Wave heading 270° (port beam seas): surge and sway wave load comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.12).

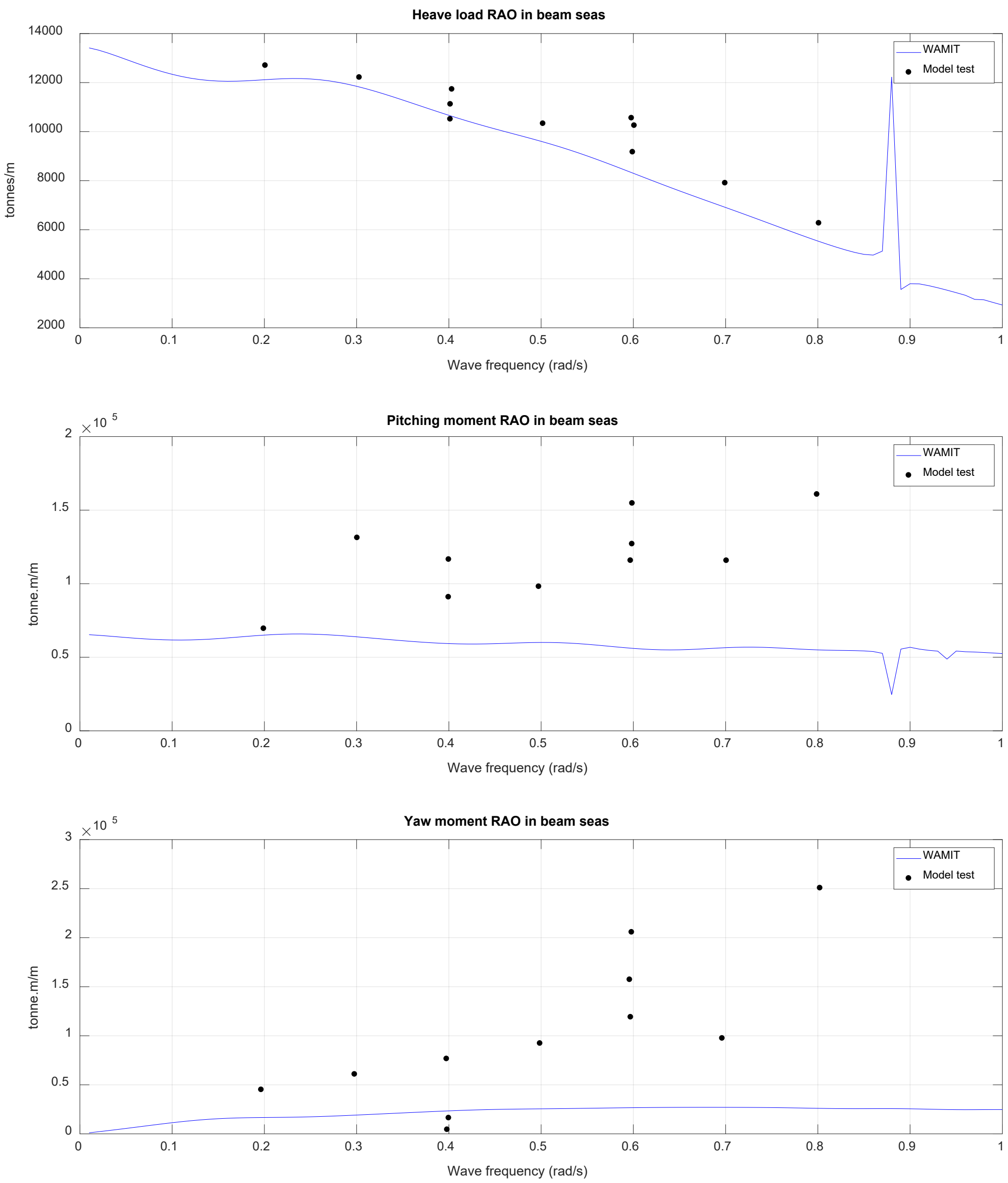


Figure 14: Wave heading 270˚ (port beam seas): heave, pitch and yaw wave load comparisons between WAMIT and model tests (van Oortmerssen 1976, Fig. 3.12).

Points to note are:

- Irregular frequencies are again noticeable in heave and pitch at 0.88 and 0.97 rad/s. As for added mass and damping, these can be removed using WAMIT's irregular frequency option, or by interpolating between adjacent points.
- Comparison of WAMIT with model test results is generally very good, and an improvement on the numerical results presented in van Oortmerssen (1976). This is thought to be mainly due to increases in modern computing power, allowing a fine 2472-panel mesh to be used in the present calculations, compared to a coarse 160-panel mesh used in 1976.
- Beam-sea surge, pitch and yaw loads are not well predicted, as these are small and result only from fore-aft asymmetries in the hull, which are somewhat simplified in the meshing.

7. Moored ship: Peak horizontal motions and mooring loads

Calculations using MoorMotions are compared with model test results for the moored ship setup described in Section 1. An exact comparison is not possible, because we have the wave spectrum, but not the frequency spacing or phasing of waves in the model tests; moreover, peak results are sensitive to these inputs. The results given here are calculated over ten runs with different input wave phasing, to give a range of expected results. A similar method may be used to find expected maximum values, as described in Gourlay (2019).

Two wave load methods are used, which should be of increasing accuracy:

1. First-order wave loads only (no second-order loads)
2. First- and second-order wave loads

Peak motion and load results in beam seas, bow quartering seas and head seas, are shown in Table 5, Table 6 and Table 7 respectively.

	Model test	MoorMotions calculations	
		Without 2nd-order loads	With 2nd-order loads
Surge max (m)	0.47	0.08 – 0.54	0.06 – 0.91
Surge min (m)	-0.05	(-0.66) – (-0.11)	(-1.16) – (-0.14)
Sway max (m)	0.99	0.58 – 1.21	0.63 – 1.18
Sway min (m)	-2.10	(-3.33) – (-1.70)	(-2.26) – (-1.64)
Yaw max (deg)	0.28	0.06 – 0.46	0.05 – 0.48
Yaw min (deg)	-0.43	(-0.38) – (-0.03)	(-0.45) – (-0.05)
Line 1 max (t)	108	88 – 138	88 – 148
Line 2 max (t)	188	126 – 219	116 – 205
Line 3 max (t)	166	132 – 248	129 – 191
Line 4 max (t)	89	73 – 118	70 – 96
Fender 1 max (t)	1530	1129 – 2306	1413 – 2296
Fender 2 max (t)	1196	1214 – 2287	1503 – 2504

Table 5: Moored ship with wave heading 90˚ (starboard beam seas): comparison between calculations and model test results from van Oortmerssen (1976, Table 5.2)

Points to note include:

- Measured peak motions are generally within the range of predictions.
- Mooring line loads are all within the range of predictions.
- Fender loads are slightly over-predicted.

Peak motion and load results in bow quartering seas are shown in Table 6.

	Model test	MoorMotions calculations	
		Without 2nd-order loads	With 2nd-order loads
Surge max (m)	0.58	0.05 – 0.24	0.06 – 0.82
Surge min (m)	-0.83	(-0.38) – (-0.23)	(-1.77) – (-0.93)
Sway max (m)	0.14	0.08 – 0.15	0.15 – 0.28
Sway min (m)	-0.29	(-0.30) – (-0.16)	(-0.29) – (-0.18)
Yaw max (deg)	0.57	0.18 – 0.32	0.24 – 0.31
Yaw min (deg)	-0.40	(-0.21) – (-0.16)	(-0.22) – (-0.14)
Line 1 max (t)	57	33 – 42	46 – 65
Line 2 max (t)	57	35 – 43	35 – 50
Line 3 max (t)	85	42 – 59	45 – 62
Line 4 max (t)	61	36 – 47	34 – 52
Fender 1 max (t)	476	227 – 317	321 – 482
Fender 2 max (t)	536	265 – 364	364 – 685

Table 6: Moored ship with wave heading 135˚ (starboard bow quartering seas): comparison between calculations and model test results from van Oortmerssen (1976, Table 5.3)

Points to note include:

- Surge and sway are close to the prediction range, while yaw is under-predicted.
- Measured mooring line loads are slightly higher than the predicted range.
- Measured fender loads lie within the predicted range.

Peak motion and load results in head seas are shown in Table 7.

	Model test	MoorMotions calculations	
		Without 2nd-order loads	With 2nd-order loads
Surge max (m)	0.58	0.12 – 0.19	0.04 – 0.57
Surge min (m)	-1.39	(-0.28) – (-0.20)	(-1.14) – (-0.58)
Sway max (m)	0.03	0.03	0.03
Sway min (m)	-0.03	0.00	0.00
Yaw max (deg)	0.25	0.01	0.02 – 0.06
Yaw min (deg)	-0.13	0.00	(-0.02) – 0.00
Line 1 max (t)	57	24 – 26	33 – 46
Line 2 max (t)	38	20 – 21	20 – 24
Line 3 max (t)	54	21 – 22	24 – 29
Line 4 max (t)	50	23 – 25	21 – 33
Fender 1 max (t)	132	52	61 – 80
Fender 2 max (t)	139	43 – 47	43 – 61

Table 7: Moored ship with wave heading 180˚ (head seas): comparison between calculations and model test results from van Oortmerssen (1976, Table 5.4)

We see that:

- Surge motions are slightly under-predicted in head seas.
- Yaw motions, and hence line and fender loads, are noticeably under-predicted in head seas. The numerical method assumes long-crested, pure head seas; any variation in wave direction either side of head seas in the experiments may contribute to this difference.

8. Moored ship: Significant motion amplitudes

"Significant motion amplitudes" are calculated as 2σ, where σ is the timeseries standard deviation from the mean. The results are calculated over ten runs with different input wave phasing, to give a range of expected results.

For model test heave, roll and pitch, where σ is not given, significant amplitudes are calculated as $2\sqrt{m_0}$, where m_0 is the area under the spectrum.

	Model test	MoorMotions
Surge (m)	0.20	0.07 – 0.81
Sway (m)	0.94	0.84 – 1.15
Heave (m)	0.55	0.59 – 0.59
Roll (deg)	1.98	2.38 – 2.63
Pitch (deg)	0.86	0.08 – 0.08
Yaw (deg)	0.22	0.04 – 0.44

Table 8: Moored ship with wave heading 90˚ (starboard beam seas): significant motion amplitude comparison between calculations and model test results from van Oortmerssen (1976, Table 5.2 and Figure 5.10)

	Model test	MoorMotions
Surge (m)	0.44	0.46 – 1.20
Sway (m)	0.14	0.14 – 0.21
Heave (m)	0.11	0.07 – 0.08
Roll (deg)	0.34	0.42 – 0.53
Pitch (deg)	0.21	0.20 – 0.20
Yaw (deg)	0.26	0.15 – 0.20

Table 9: Moored ship with wave heading 135˚ (starboard bow quartering seas): significant motion amplitude comparison between calculations and model test results from van Oortmerssen (1976, Table 5.3 and Figure 5.11)

	Model test	MoorMotions
Surge (m)	0.76	0.27 – 0.70
Sway (m)	0.02	0.00 – 0.01
Heave (m)	0.11	0.08 – 0.08
Roll (deg)	0.34	0.00 – 0.00
Pitch (deg)	0.21	0.11 – 0.12
Yaw (deg)	0.16	0.01 – 0.03

Table 10: Moored ship with wave heading 180˚ (head seas): significant motion amplitude comparison between calculations and model test results from van Oortmerssen (1976, Table 5.4 and Figure 5.12)

Calculated results are generally close to the model test results. Exceptions are pitch in beam seas, and pitch and roll in head seas, which are under-predicted.

9. References

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Newman, J.N. 1992 Marine Hydrodynamics, 7th Edition. MIT Press.

Newman, J.N. 1974 Second-order, slowly-varying forces on vessels in irregular waves. Massachusetts Institute of Technology, Department of Ocean Engineering.

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WAMIT 2019 WAMIT v7.3 User Manual, WAMIT Inc.

Appendix A – Moored ship time series

Calculations shown include second-order wave loads.

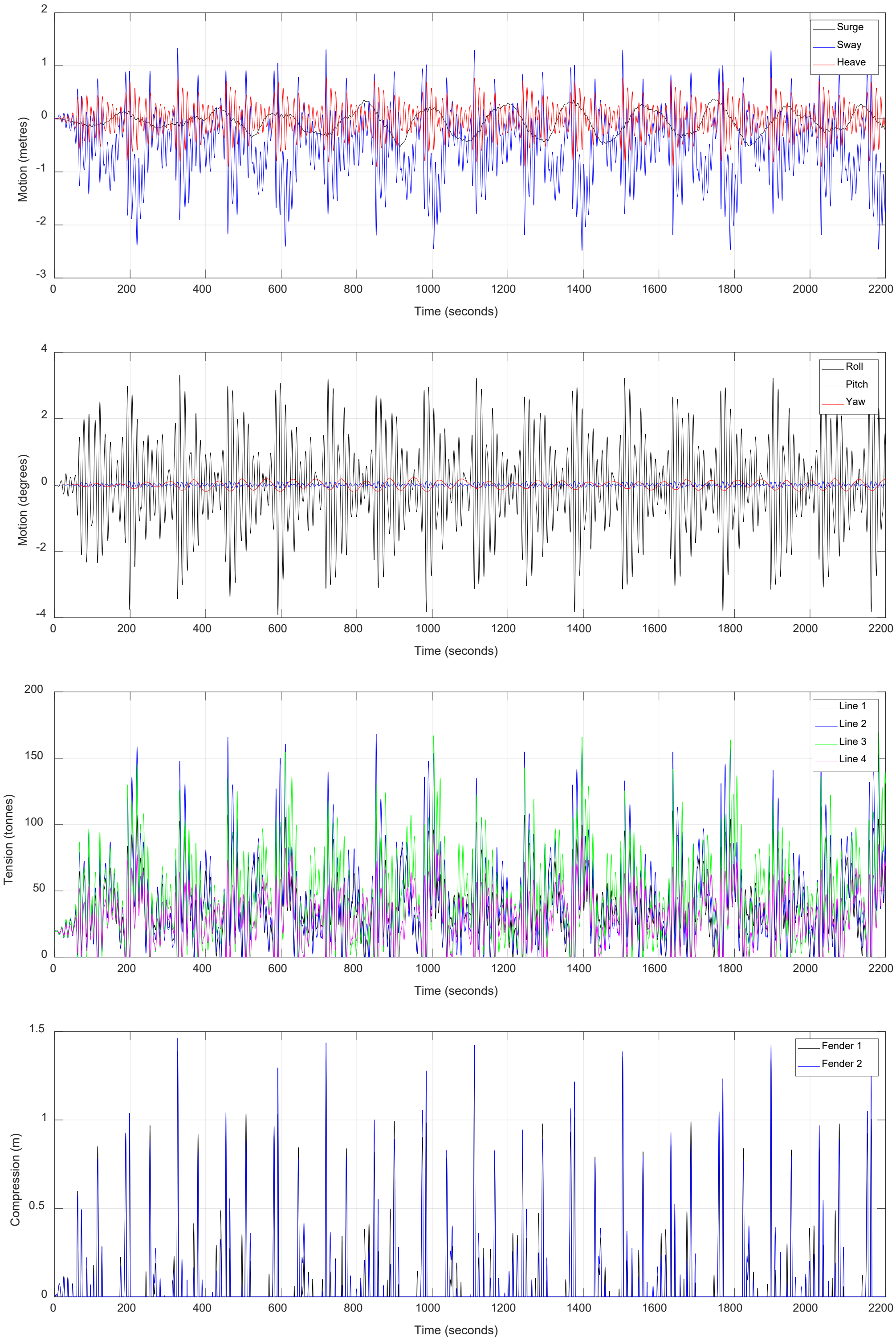

Figure 15: Motion and load timeseries for wave heading 90˚ (starboard beam seas), irregular wave spectrum with H_S=2.6 m

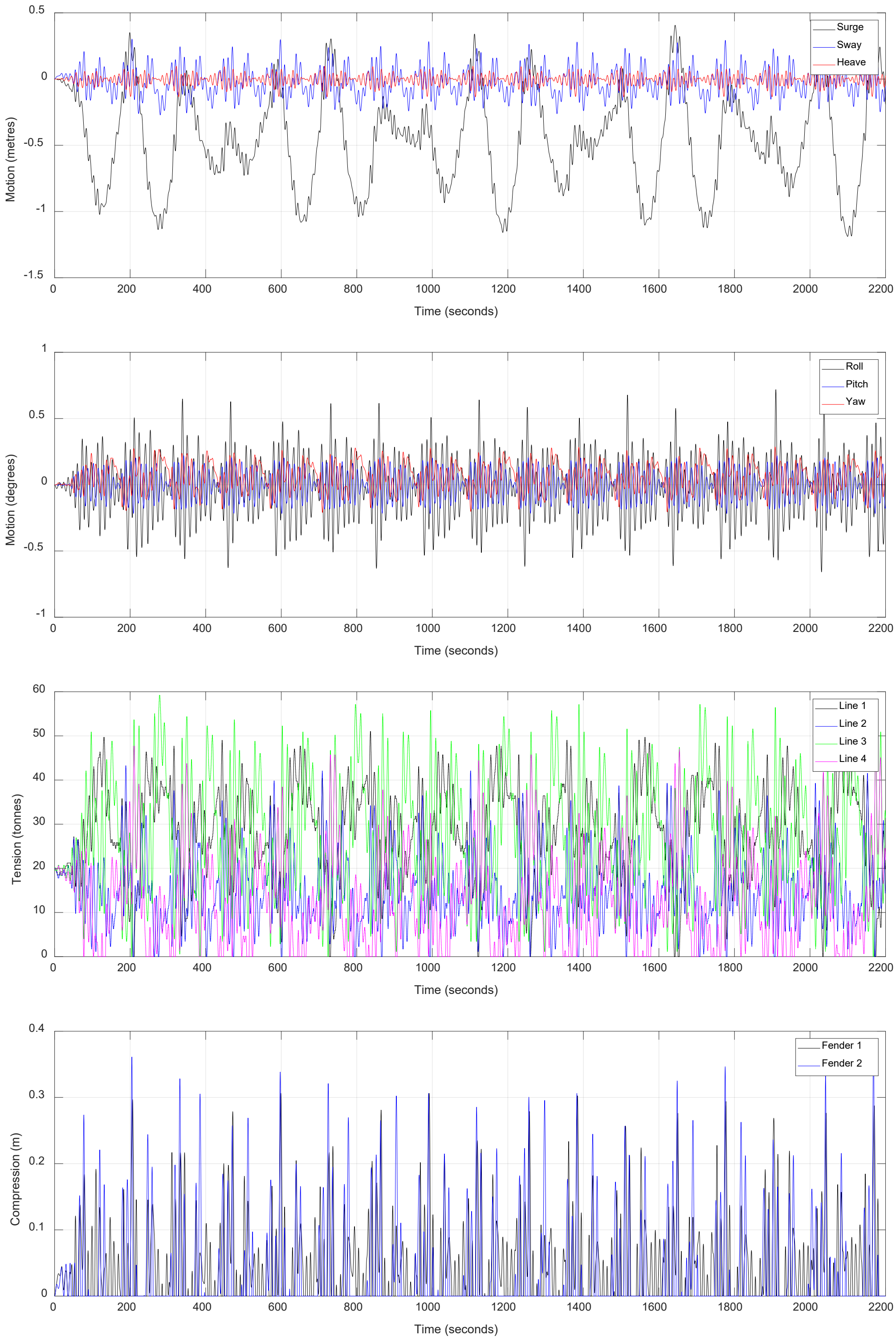

Figure 16: Motion and load timeseries for wave heading 135˚ (starboard bow quartering seas), irregular wave spectrum with H_S=2.6 m

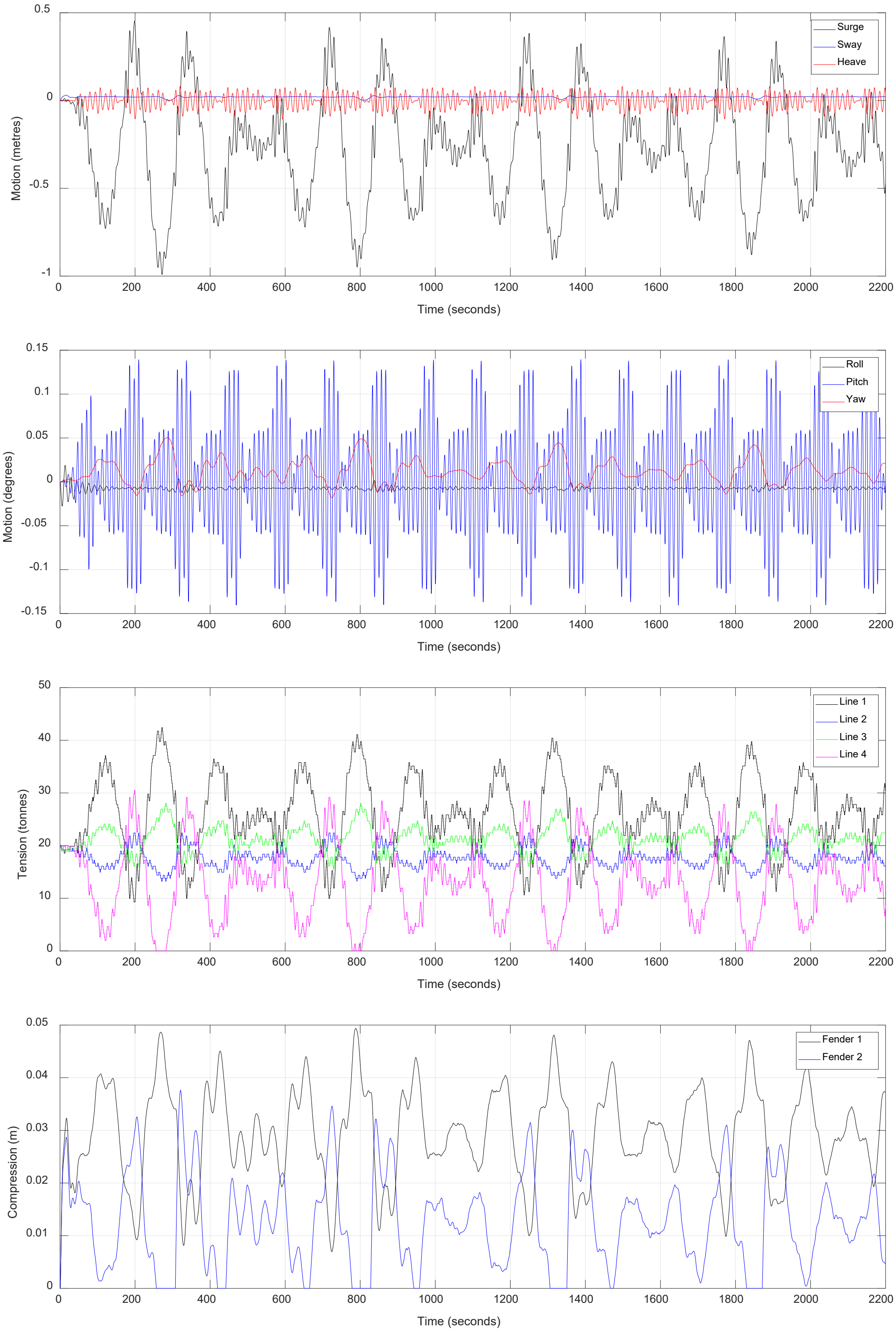

Figure 17: Motion and load timeseries for wave heading 180˚ (head seas), irregular wave spectrum with H_S=2.6 m

Appendix B – Moored ship motion spectra

Measured motion spectra are shown here, together with MoorMotions calculations including second-order wave loads. Measured spectra are taken from van Oortmerssen (1976, Figs 5.10 – 5.12). Calculated spectra are from Fast Fourier Transform of the MoorMotions results, using half-overlapped 2048-point segments with Bartlett windowing.

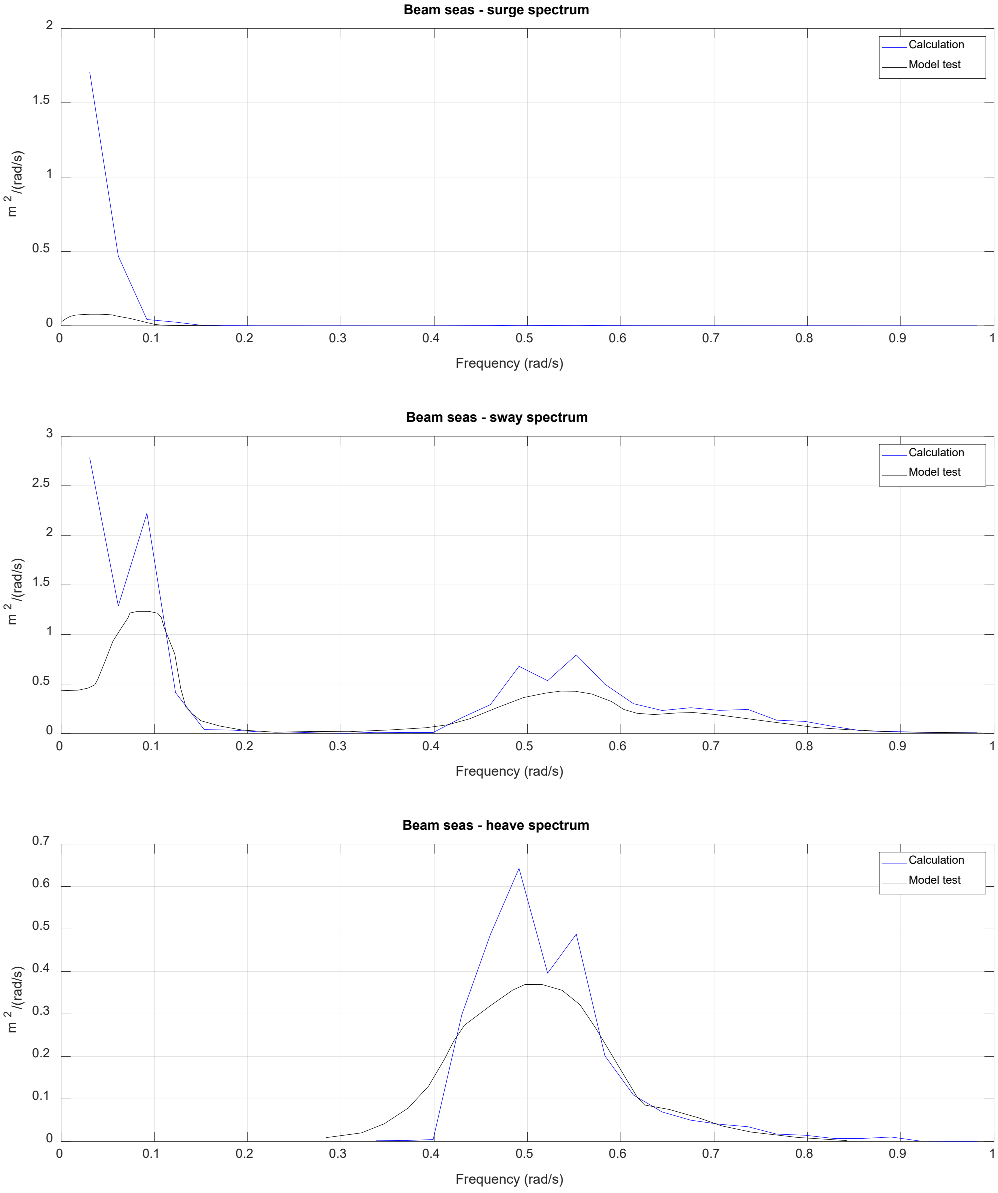

Figure 18: Wave heading 90˚ (starboard beam seas): surge, sway and heave spectra comparisons between MoorMotions and van Oortmerssen (1976, Fig. 5.10)

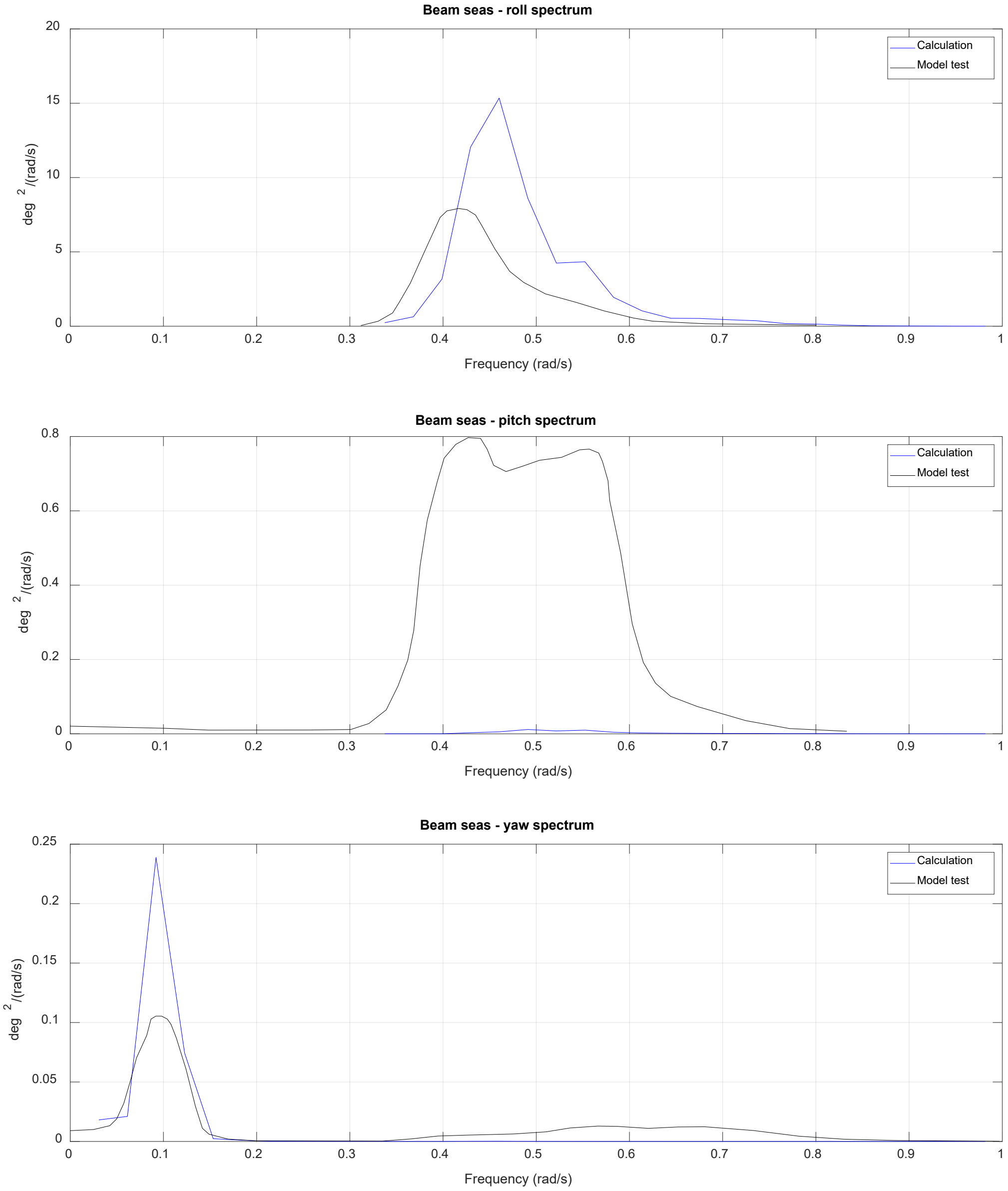

Figure 19: Wave heading 90˚ (starboard beam seas): roll, pitch and yaw spectra comparisons between MoorMotions and van Oortmerssen (1976, Fig. 5.10)

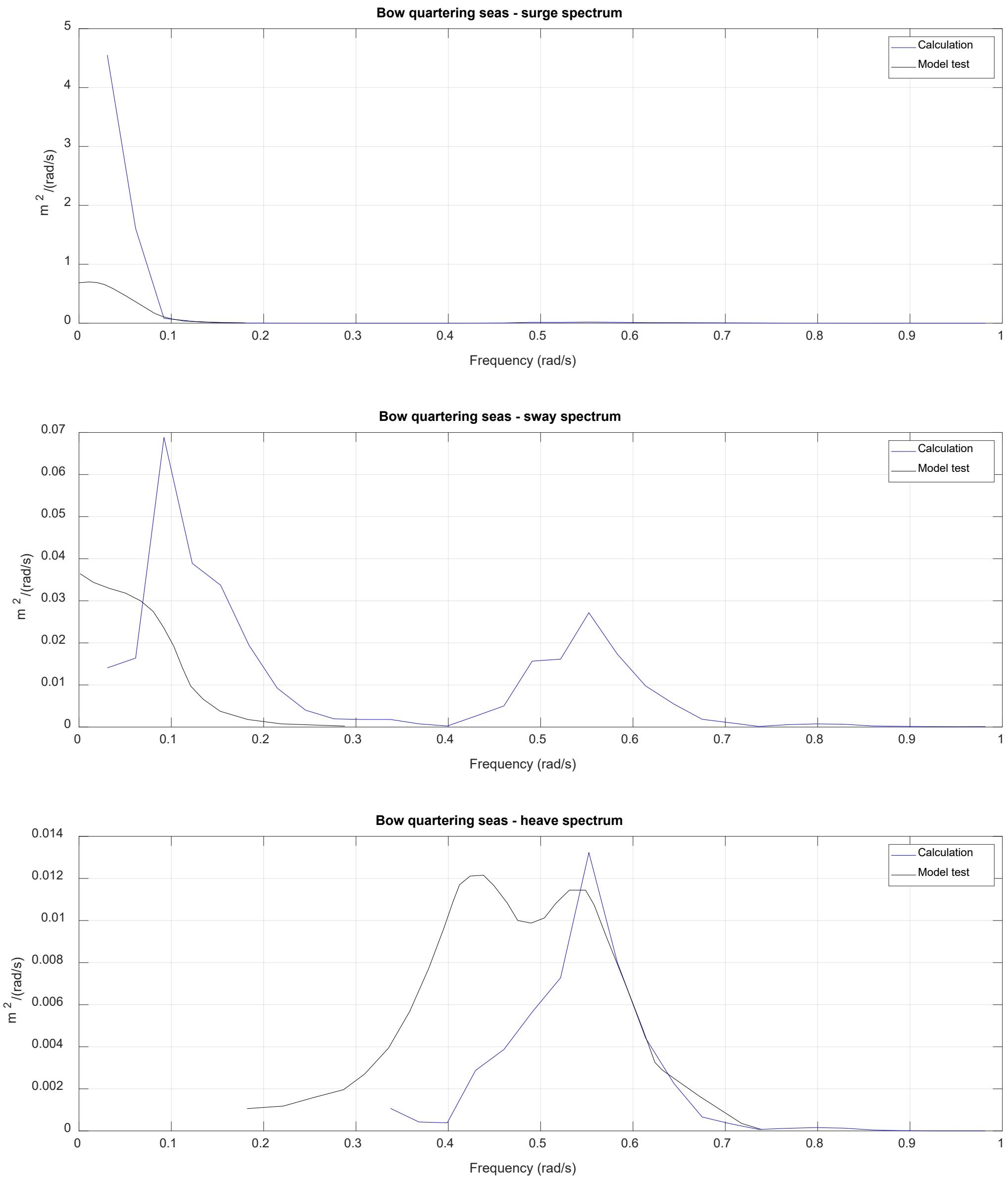

Figure 20: Wave heading 135˚ (starboard bow quartering seas): surge, sway and heave spectra comparisons between MoorMotions and van Oortmerssen (1976, Fig. 5.11)

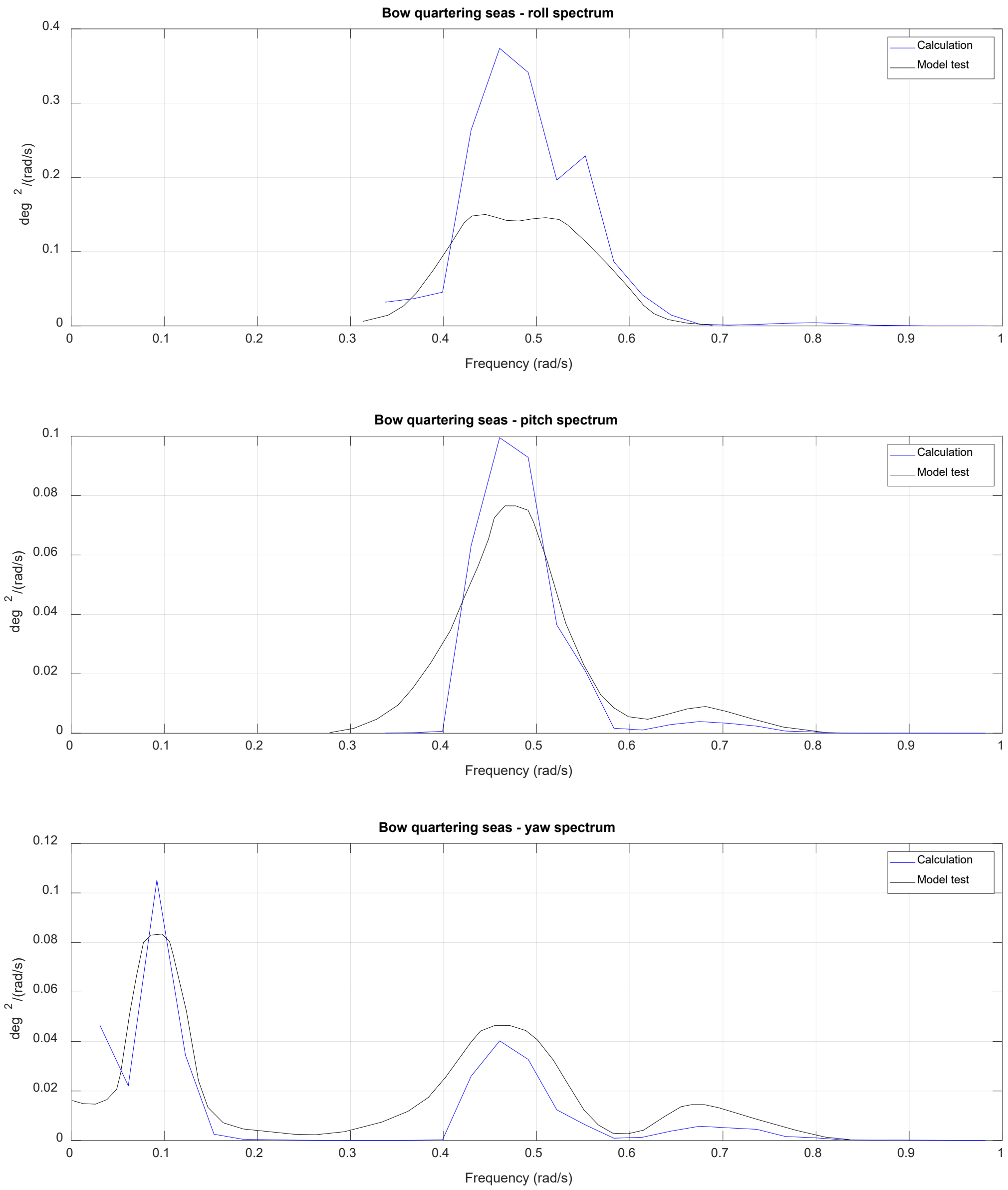

Figure 21: Wave heading 135˚ (starboard bow quartering seas): roll, pitch and yaw spectra comparisons between MoorMotions and van Oortmerssen (1976, Fig. 5.11)

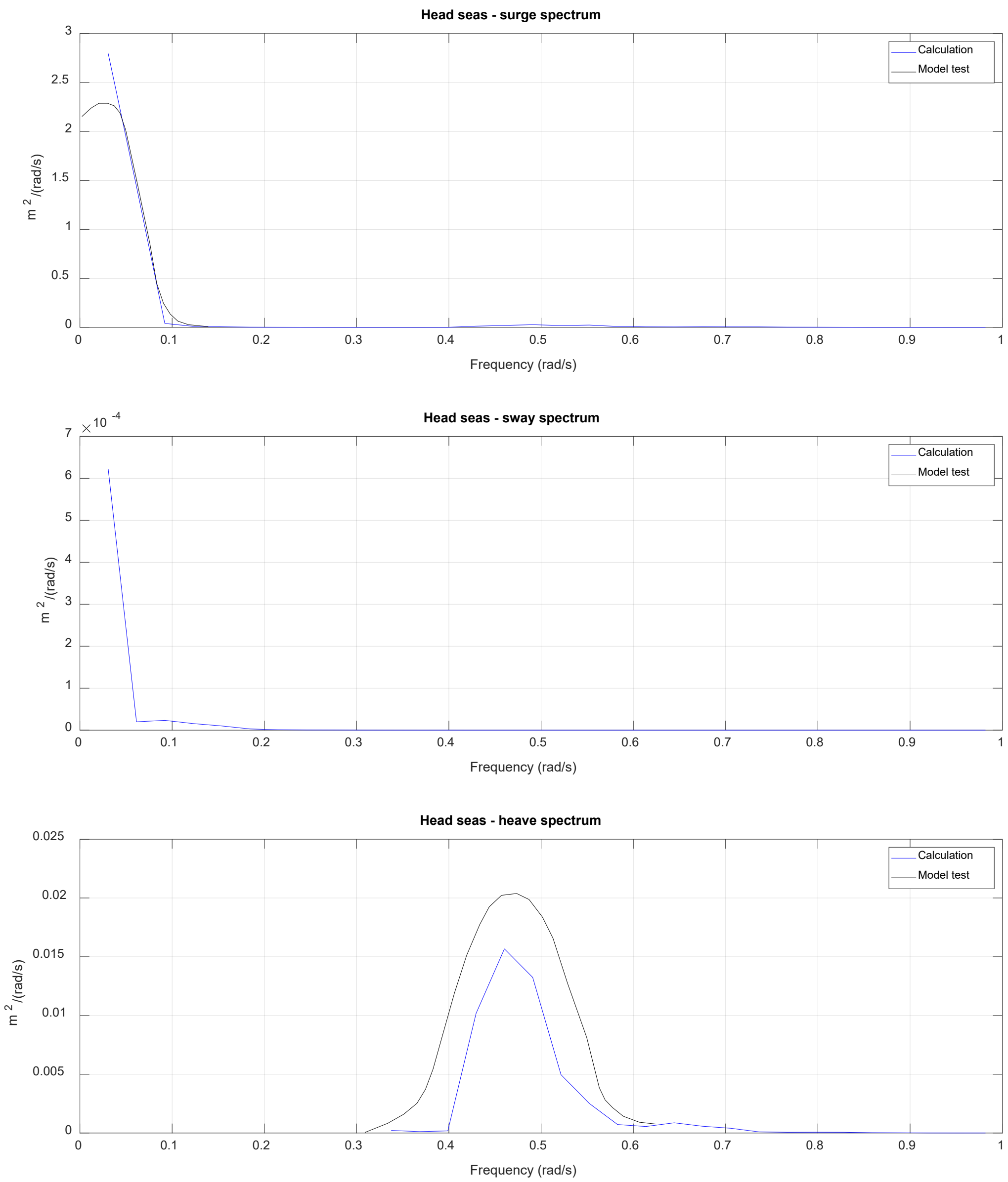

Figure 22: Wave heading 180˚ (head seas): surge, sway and heave spectra comparisons between MoorMotions and van Oortmerssen (1976, Fig. 5.12)

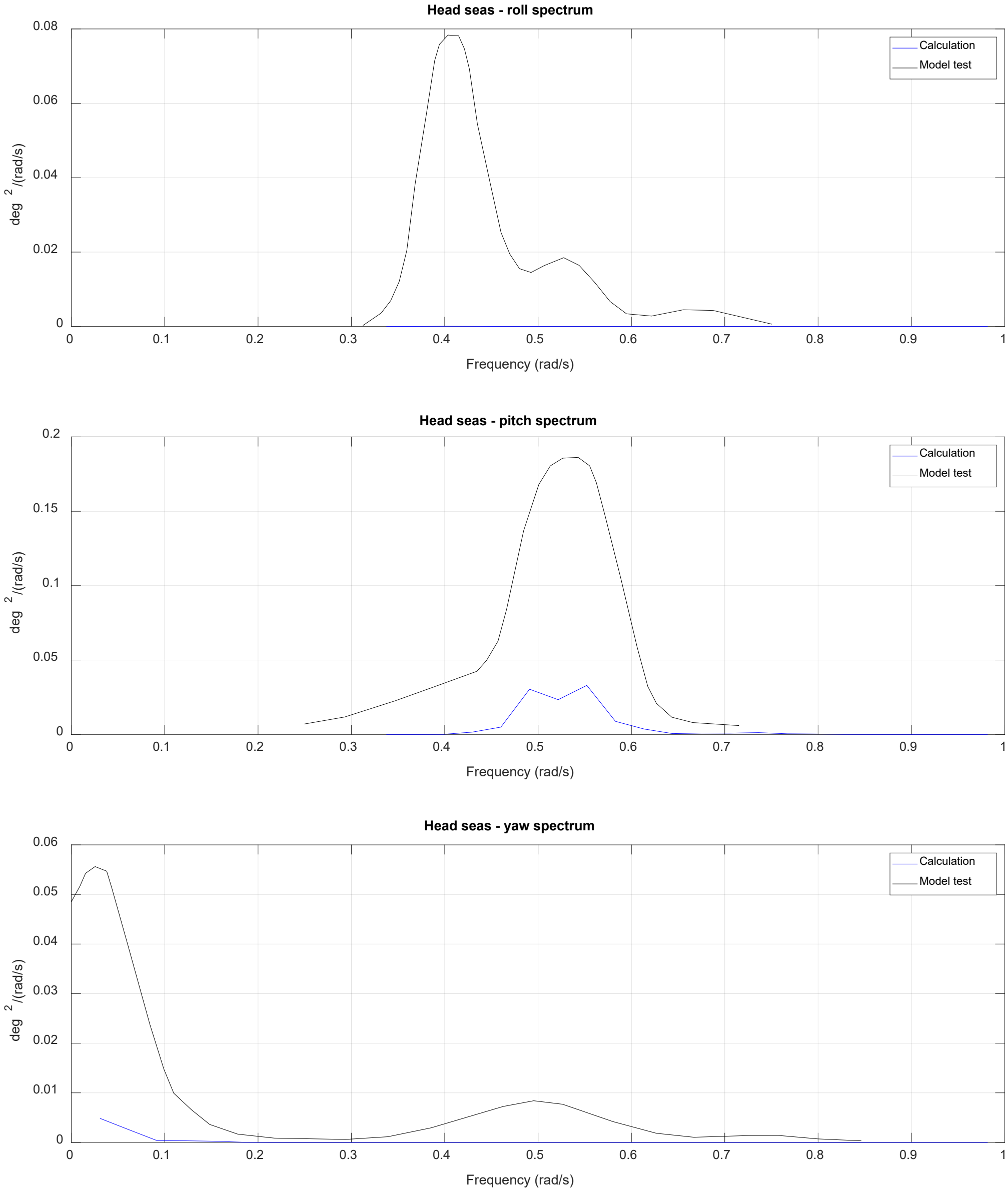

Figure 23: Wave heading 180˚ (head seas): roll, pitch and yaw spectra comparisons between MoorMotions and van Oortmerssen (1976, Fig. 5.12)