BETTER SHIPS, BLUE OCEANS

WAPS Feeder (163 m): simulations for assessment of stability regulation requirements

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WAPS Feeder (163 m): simulations for assessment of stability regulation requirements

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0.9	28 Nov 2025	Draft report
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REVIEW OF REPORTS

Table i-1: Deliverables of the current project phase[1]

Deliverable	Contains
MARIN report No. 77004-3-SEA	The present report, delivered in PDF format

Table i-2: Previously delivered reports for this project[1]

MARIN report No.	Title
77001-1-SEA	Regulatory review: Stability of wind-powered vessels
MARIN report No. 77001-2-SMB Vol. 1	The present report, delivered in PDF format
MARIN report No. 77001-2-SMB Vol. 2 (Data report seakeeping tests)	All analysis and post-processing of the measured signals, delivered in PDF format
MARIN report No. 77004-1-SMB Vol. 2 (Data report weather criterion tests)	All analysis and post-processing of the measured signals of weather criterion model tests, delivered in PDF format

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[1] At the time of writing

MANAGEMENT SUMMARY

The present project was ordered by the Ministry of Infrastructure and Water Management to advance the research on the safety risks associated with wind-propelled ships. This study is part of the 'Onderzoeksprogramma Scheepvaartveiligheid Noordzee 2024'.

The main goal of this study is to assess whether current regulation is sufficient to assess and assure the stability of modern, wind propelled vessels. Stability regulation from the mandatory IMO IS 2008 code, as well as the alternative, non-mandatory assessments following IMO MSC.1/Circ.1200, and IMO SLF 53/INF.3 were considered in the presented work.

A hypothetical but realistic container feeder vessel with 6 rotor sails was chosen as the investigated vessel. For this vessel, the stability assessment by means of model tests were reported in MARIN report 77001-2-SMB. The model test's result of IMO SLF 53/INF.3 showed that a vessel with existing stability regulations assessment can exceed regulation limits in extreme but realistic conditions for wind and waves.

In present work, the stability of the vessel is assessed by means of numerical simulations using aNySIM-XMF. Ten 3-hour simulations were performed in dead ship and upper operational conditions. The dead ship simulations of IMO SLF 53/INF.3 in unsteady wind condition showed that 7 out of 10 simulations capsized within 30 min. However, no stability issue was found in the upper operational condition simulations.

Comparing the IMO SLF 53/INF.3 results with IMO IS 2008 and IMO MSC.1/Circ.1200, one would expect that lower fidelity approaches would result in conservative results. That is not the case for the present example with the wind assisted feeder with 6 Flettner rotors. Therefore, it may be concluded that the current dead ship criterion could be insufficient to assess the stability of modern, wind propelled vessels. However, further study is needed for different vessels and wind propulsion configurations.

1 INTRODUCTION

The present project was contracted by the Ministry of Infrastructure and Water Management to advance the research on the safety risk associated with wind-propelled ships. This study is part of the ‘Onderzoeksprogramma Scheepvaartveiligheid Noordzee 2024’. The associated experimental study to the present simulation work is presented in MARIN report No. 77001-2-SMB.

Background of the research

The main goal of this study is to assess whether current regulation is sufficient to assess and assure the stability of modern, wind propelled vessels. The present works applies the existing regulation and guidelines to a hypothetical vessel. Model tests and simulations of the vessel were carried out in relevant scenarios involving realistic irregular seas and wind spectra. Showing that these scenarios lead to situations where the vessel stability is at risk, could indicate that present regulations may be insufficient to assure safety for such a vessel.

Vessel selection

The intention is to simulate a realistic, worst case scenario for a vessel with wind propulsion. Based on the literature study outcome, a 163 m, 950 TEU feeder vessel with six rotor sails was chosen [Report 77001-1-SEA]. Similar concepts are in the design phase[2]. Figure 1-1 shows a visualisation of the vessel concept. Loading conditions were based on stability calculations fulfilling current regulations with little margin. The basic assumption is that in this condition, the risk on stability failure is largest.

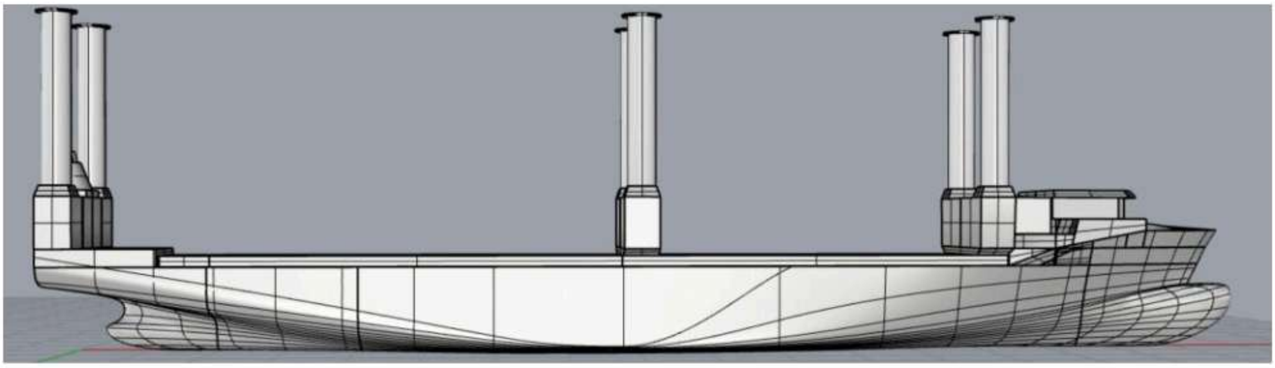

Figure 1-1: Visualisation of the investigated concept vessel.

Approach

The stability and compliance of the vessel were assessed using the existing regulations. In the previous work, [Report No. 77001-2-SMB], the following approaches to assess the dead ship condition were carried out.

1. Calculations were done following the current baseline regulation in the IMO IS 2008 code.
2. Weather criterion tests following IMO MSC.1/Circ.1200, which is an alternative assessment to prove stability compliance, were conducted because they are routinely used for this purpose despite not being mandatory.
3. Further tests following the IMO SLF 53/INF.3 were done as they are based on an experimental approach that includes both irregular seas and constant wind force tests, which represents a more realistic scenario than regular waves and calculations, modelling some of the dynamics. The IMO SLF 53/INF.3 is not a mandated assessment but is used for large cruise vessels in case of non-compliance with IMO MSC.1/Circ.1200.

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[2] https://zephyretboree.com/en/projects/mervent/ : Zephyr & Boree official website, ‘Williwaw : 5 carbon-free container ships’, last visited February 2025

These three approaches for dead ship condition provide a base line for the stability evaluation of the vessel and assure compliance with current regulations. The dead ship approaches have been compared to the upper operational condition in which the vessel is still wind assisted. In this sailing condition, tests in irregular seas and with both steady and unsteady wind were performed and compared to the results in dead ship condition.

In the present report, fast-time domain simulations using aNySIM-XMF were performed for the IMO MSC.1/Circ.1200 and the IMO SLF 53/INF.3 and compared against the model tests as the validation study. The validated simulation model is allowing us to perform more simulations in more realistic scenarios. For example, ten 3-hour simulations in unsteady wind condition were performed to provide better statistic results. In addition, the stability assessment is also applied in upper operational condition.

The results of the currently approved methods and the comparison with tests and simulations in irregular seas and unsteady and steady wind are used to discuss gaps in current stability regulation concerning wind propelled vessels.

Structure of the report

Chapter 2 describes the validation material and includes an overview of the vessel and model tests setup. The simulation model is described in Chapter 3, the stability calculations and validation results in Chapter 4 and the simulations for assessing the Intact Stability criteria in Chapter 5. Chapter 6 gives the conclusions.

2 VESSEL OVERVIEW AND MODEL TEST SETUP

Table 2-1: Loading conditions and main particulars (full scale).

Designation	Symbol	Magnitude	Unit
Length between perpendiculars	L_{PP}	163.00	[m]
Length on waterline	L_{WL}	166.25	[m]
Length overall submerged	L_{OS}	172.86	[m]
Breadth moulded on WL	BWL	27.00	[m]
Draught moulded on FP (relative to baseline)	T_F	9.20	[m]
Draught moulded on AP (relative to baseline)	T_A	9.20	[m]
Displacement volume moulded	∇	28,752	[m^3]
Displacement mass in seawater	Δ_1	29,500	[t]
Wetted surface area bare hull	S	6085	[m^2]
LCG position from AP	LCG	78.21	[m]
Transverse metacentric height (incl. free surface correction) without wind	GMt_{WET}	1.50	
Transverse metacentric height (incl. free surface correction) with active wind system	GMt_{WET}	1.50	
Vertical position centre of gravity (dry)	KG	10.74	[m]
Vertical position centre of buoyancy	KB	4.98	[m]
Transverse metacentre above base	KM	12.25	[m]
Mass radius of gyration around X-axis	k_{XX}	9.99	
Mass radius of gyration around Y-axis	k_{YY}	42.41	[m]
Mass radius of gyration around Z-axis	k_{ZZ}	42.41	[m]
Natural period of roll (incl. added mass, target value provided by calculations)	T_ϕ	18.28	[s]
Block coefficient	C_B	0.71	-

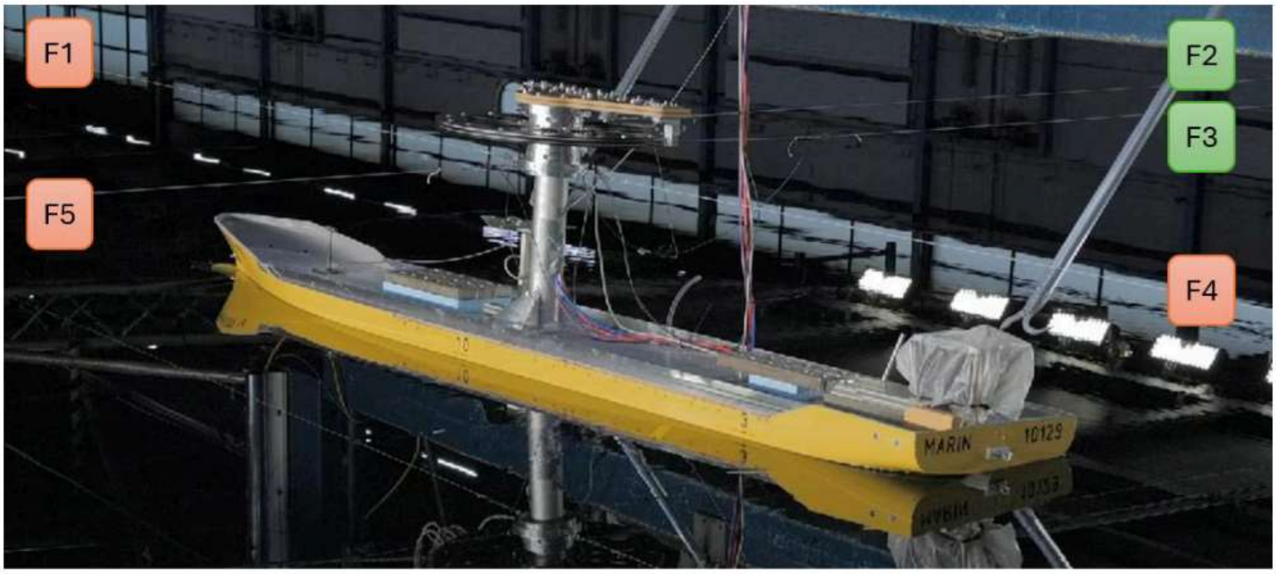


Figure 2-1: Wind winches set-up (F1-F5) used to exert wind loads on the model [Report 77001-2-SMB].

3 SIMULATION MODEL

aNySIM XMF, later called XMF, is used to perform fast-time domain simulations. Thanks to its modular architecture, XMF can simulate any ship type and any exterior loads through custom made mathematical models, including wind propulsion devices of any nature. It is of the modular type, meaning that the aerodynamic loads of the Flettner rotors sails and superstructure are modelled separately. The aerodynamic modelling of the Flettner rotors was described in the model test report [Report 77001-2-SMB].

In the model test, XMF was used to compute the aerodynamic loads, based on actual position of the model. The loads were then exerted to the model through winches. In this paper, full ship motions and loads were modelled in XMF.

In order to perform seakeeping simulations, XMF requires databases of wave excitation transfer functions and hydrodynamic coefficients. These were obtained from the frequency domain seakeeping solver, SEACAL. SEACAL solves double-body steady potentials, diffraction and radiation potentials problems with Rankine source over the hull and free surface panels. From the boundary element solutions, the source distributions, SEACAL calculates the hydrodynamic coefficients, wave-excitation forces transfer functions, and then the motions Response Amplitude Operators (RAOs) and Quadratic Transfer Functions (QTFs) of drift forces.

The hydrodynamic modelling in XMF is then as follows. Nonlinear hydrostatic and Froude-Krylov forces were computed in XMF based on instantaneous wetted hull panels. Retardation functions were computed from the SEACAL database and inputted to XMF. First and second-order diffraction forces are then computed by the superposition of the transfer functions and unperturbed wave spectrum. Manoeuvring coefficients were obtained based on the Unified Damping Model. The ship calm-water resistance was obtained from the model tests.

In XMF, roll damping can be modelled with user-specified damping coefficients, i.e. linear and quadratic damping coefficients (P and Q) from the model tests, or an user-specified sectional hull. In latter case, XMF estimates the damping coefficients based on IKEDA formulation.

In addition, the propeller, rudder, bilge keel, and anti-leeway fins were also modelled in XMF. The propeller and rudder were controlled using PID controllers for controlling ship speed and heading.

4 STABILITY CALCULATIONS AND VALIDATION RESULTS

This section begins with a description of the static stability calculations. These calculations were an initial reference for the model test to determine loading condition with the minimum GM that still comply with the current stability regulation (IMO 2008, section 2.3.2).

The vessel were further assessed in the model tests for the weather criterion, the IMO MSC.1/Circ.1200 and the IMO SLF 53/INF.3, and for operational conditions [Report 77001-2-SMB] . This chapter presents simulations results aimed at reconstructing the model tests. This study was performed to enable more simulations under realistic conditions as presented in the Chapter 5.

4.1 Static stability calculations (IS 2008)

The calculations were done based on the IMO intact stability code (IMO 2008, section 2.3.2) for the considered vessel under steady wind condition. The calculation procedure was described in [Report 77001-2-SMB]. The GZ curve of the vessel is shown in Figure 4-1, with the parameters presented in Table 4-1. The calculation shows that the area *a* is smaller than the area *b* therefore the vessel was found to be complying with the weather criterion stability regulations.

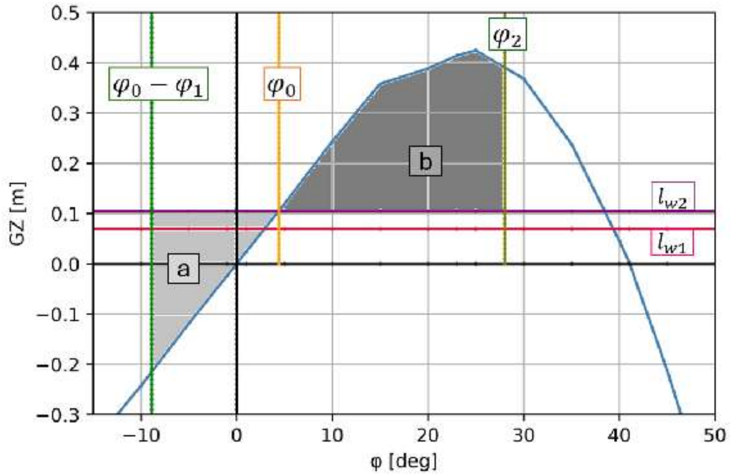


Figure 4-1: GZ curve for severe wind and rolling, calculated from hull shape of the investigated model [Report 77001-2-SMB].

Table 4-1: GZ curve and weather criterion parameters [Report 77001-2-SMB].

Item	Description	Value	Unit
T	Average Draught	9.2	[m]
Δ	Displacement	29500	[t]
KG	Vertical Centre Of Gravity	10.7	[m]
GM_{t_dry}	Metacentric height (dry)	1.5	[m]
A	Projected lateral area	2659	[m^2]
Z	Vertical distance from centre of A to the centre of the underwater lateral area at one-half of the mean draught	15.0	[m]
l_{w1}	Wind lever	0.07	[m]
l_{w2}	Wind lever including gust factor	0.10	[m]
φ_0	angle of heel under action of steady wind	4.4	[deg]
φ_1	angle of roll to windward due to wave action	13.2	[deg]
φ_2	angle of down-flooding	28.0	[deg]
a	Area a	2.1	[m*deg]
b	Area b	5.1	[m*deg]
φ_c	Capsizing angle	41	[deg]

4.2 Weather criterion

The weather criterion simulations were performed in regular and irregular waves. The tests conditions are the same as in the model tests.

4.2.1 Regular waves, MSC.1/Circ. 1200

For the regular wave cases, the wave heights were 19.1 m, with the periods varying from 14.6 s to 22 s. To keep the heading in beam waves conditions, a restoring coefficient was added to the simulation to restrain yaw angle. Several simulations were performed, each differing in the hydrostatic model and roll damping coefficients. XMF-STRIP uses sectional hull input to estimate the nonlinear hydrostatic and Froude-Krylov forces, while XMF-MESH uses three-dimensional hull panels for the force calculations. For the roll damping, IKEDA roll damping model or the P and Q damping coefficients from the model test without the winch was applied.

The results are shown in Figure 4-2. It shows that IKEDA gives slightly more damping than the PQ coefficients. The XMF-STRIP and XMF-MESH show the same results, except for the lowest and the highest periods. This shows that the models have limitations in fully predicting roll behaviour over the full range of wave periods. However, the simulation results show generally reasonably good agreement with the model tests. XMF-MESH gave slightly better results and was therefore used in further simulations presented in next sections.

From these model tests and the simulations, the regular waves roll-back angle is calculated according to MSC.1/Circ. 1200. The maximum roll angle is at the period of 19.2 s, $\phi_r = 19.8\,deg$, thus the roll-back angle $\varphi_1 = 0.7\,\phi_r = 13.9deg$. This is a slightly larger value than the calculated one in Section 4.1. Therefore, the empirical approach with the IMO 2008 intact stability calculation is slightly less conservative for the given vessel than the experimental and simulation assessment. Note that the stability calculation in Section 4.1 has already considered a constant wind load, while it is not considered in the model tests and the simulation.

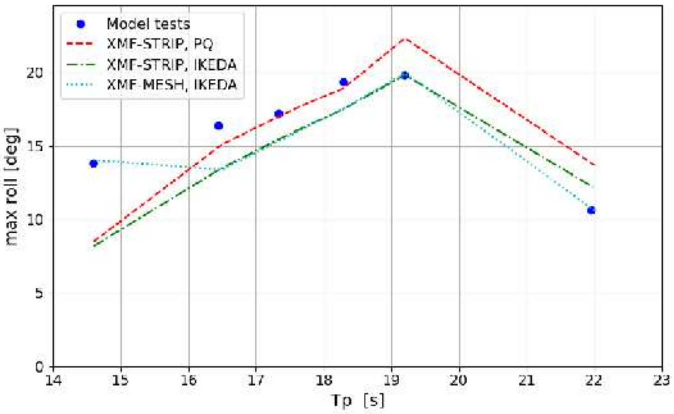


Figure 4-2: Maximum roll as obtained in the weather criterion regular wave tests and the simulations.

4.2.2 Irregular waves, SLF53/inf.3

For the irregular wave conditions, the target significant wave heights (H_s) and peak periods (T_p) were $(11.9m, 19.6s)$, $(12.6m, 18.7s)$, and $(13.2m, 17.8s)$. The waves were chosen in accordance with SLF 54-INF.3 based on the 20-year return period contour of the DNV worldwide scatter diagram, as also described in [Report 77001-2-SMB]. The tests were performed without wind loads and with steady or unsteady wind loads.

Table 4-2 shows the statistics comparison between the model tests and the simulations (see Appendix II for a more detailed comparison). It should be noted that the mean roll for the test without wind is 2.5 deg due to a slight shift of a weight in those tests, as remarked in [Report 77001-2-SMB]. That is not the case in the simulations that give a near zero mean.

Simulations show slight differences in the roll statistics, the significant wave height (H_s) and the mean zero-up crossing wave period (T_z). In the steady wind conditions, the roll standard deviation (Std) decreases with respect to no wind conditions. In the unsteady wind conditions, the simulations show that the standard deviation slightly increases.

The most probable maximum roll back angle (MPM roll) is computed following SLF53/inf.3 as $\varphi_1 = \sigma\sqrt{2\ln\,(N)}$ where $N = t/T_z$, t is the time duration of the tests, represents the number of oscillations. The results in wind conditions show that the largest MPM roll back angle is 10.9 deg from the model test and 12.7 deg from the simulation.

In addition, the model tests with constant wind force were carried out in the wave condition of $(H_s, T_p) = (13.2m, 17.8s)$. The model test results the following roll statistics $[deg]$: $Mean = 5.2, std = 1.4, Min = -8.1, Max = 22.2, MPM\ roll\ back = 13.3$.

The MPM roll back angles from the model test and simulation are very close to the empirical approach with the IMO 2008 intact stability calculation. This again raises questions about the conservativeness of the current regulation.

Table 4-2: Statistics of the irregular waves model tests and simulations

Test Nr	Wind	Hs [m]		Tp [s]	Tz [s]		Std Roll [deg]		Mean Roll [deg]		Max Roll [deg]		Min Roll [deg]		MPM Roll [deg]	
		meas	simul	Target	meas	simul	meas	simul	meas	simul	meas	simul	meas	simul	meas	simul
_04_009	Unsteady	12.1	11.9	19.6	15.4	15.8	3.5	3.4	4.7	5.2	20.6	16.5	-7.1	-6.6	11.7	11.4
_04_010	No	11.9	12.4	18.7	14.0	14.7	4.3	3.5	-2.3	0.2	11.9	12.6	-14.5	-12.4	14.2	11.5
_04_003	Steady	11.5	12.7	18.7	14.3	15.3	2.9	3.5	4.8	5.1	16.0	18.5	-6.4	-4.9	9.9	11.6
_04_004	Unsteady	11.5	12.7	18.7	14.5	15.3	3.2	3.8	4.6	5.3	17.3	19.7	-6.7	-6.1	10.9	12.7
_04_011	No	12.9	13.1	17.8	13.8	14.0	4.2	3.8	-2.7	0.1	10.8	13.6	-13.0	-14.5	13.4	12.0
_04_005	Steady	12.4	13.3	17.8	13.7	14.2	3.0	3.5	5.1	5.3	15.8	18.0	-8.5	-6.7	9.9	11.5
_04_006	Unsteady	12.6	13.0	17.8	14.0	14.2	3.3	3.9	5.0	5.6	18.4	26.4	-5.6	-7.2	10.8	12.7

4.3 Operational condition

Operational condition simulations were performed for the ship sailing at 12 knots in regular waves with and without wind loads. The results are compared against the model tests as shown in Appendix II. The results show that the simulations reconstructed the transversal and lateral velocity, heave and pitch of the model tests quite well. However, the reconstruction of roll motion is less good for bow-quartering waves. This is probably due to water on deck which was not fully modelled in the simulation.

One test was performed for the ship sailing at 12 knots in bow-quartering (220 deg) irregular waves (JONSWAP, $H_s = 5m, T_p = 10s$), unsteady wind $(TWS = 24.5kn, TWA = 220deg)$. The model test results the following roll statistics $[deg]$: $Mean = 5.1, std = 1.4, Min = 1.0, Max = 11.6, MPM\ roll\ back = 5.0$.

The roll angle in the operational condition is much smaller than in the weather criterion conditions. This shows that the weather criterion condition is more conservative than the operational condition for this vessel.

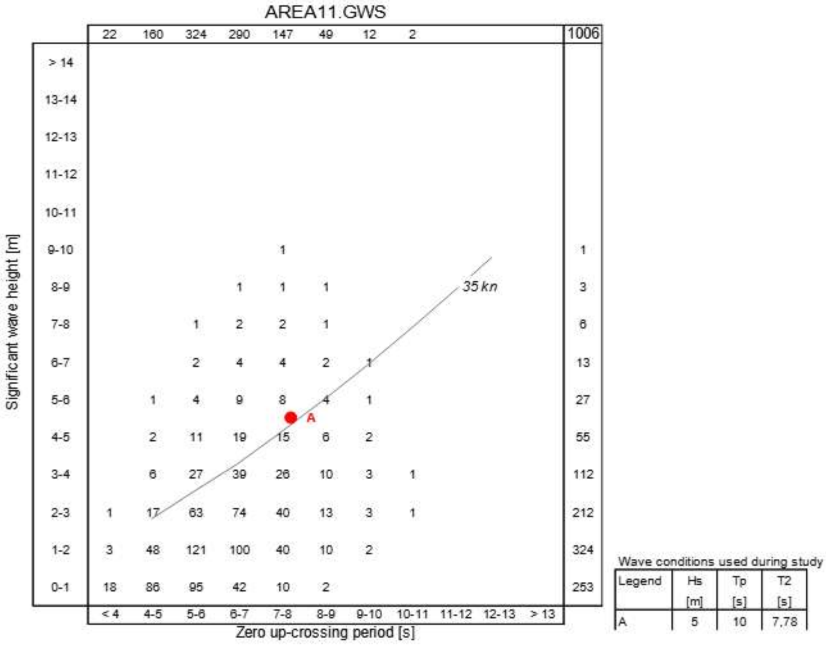
5 SIMULATIONS FOR ASSESSING THE INTACT STABILITY CRITERIA

This section presents simulations results for assessing the present IMO intact stability criteria on the wind assisted propelled vessel. The long duration simulations were performed to investigate the statistical convergence of capsize probability and exceedance of peak roll angles in irregular seas.

5.1 Simulation conditions

Simulations cover the following conditions, all in irregular waves reflecting extreme conditions for the roll period of the selected vessel:

1. Weather criterion simulations (SLF53/inf.3)
   - True wind speed (TWS) of 50.5 kn.
   - Unsteady wind (vs steady in SLF 53/inf.3).
   - The wave conditions were selected along 20-year return period contour of the DNV worldwide wave scatter diagram; with peak wave period around roll natural period (18.4 s): $H_s = 13.2m, T_p = 17.8s$. This was selected as the largest roll in the model test with the constant wind force [Report 77001-2-SMB].
   - Beam seas and wind (270 deg).
2. Operational conditions simulations
   - Selected based on Flettner rotor operation limit according to Norsepower maximum operational $TWS = 35\ kn$. This corresponds to the Beaufort wind scale of 8 that ranges between 34 to 40 kn.
   - One wave condition was selected along the 35 kn wind speed line in the North Sea wave scatter diagram: $H_s = 5m, T_p = 10s$, Figure 5-1.
   - Winds and waves from the bow quartering of 240 deg.



	< 4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	> 13	
	22	160	324	290	147	49	12	2				1006
> 14												
13-14												
12-13												
11-12												
10-11												
9-10					1							1
8-9				1	1	1						3
7-8			1	2	2	1						6
6-7			2	4	4	2	1					13
5-6		1	4	9	8	4	1					27
4-5		2	11	19	15	6	2					55
3-4		6	27	39	26	10	3	1				112
2-3	1	17	63	74	40	13	3	1				212
1-2	3	48	121	100	40	10	2					324
0-1	18	86	95	42	10	2						253

Wave conditions used during study

Legend	Hs [m]	Tp [s]	T2 [s]
A	5	10	7,78

Figure 5-1: North seas wave scatter diagram and the selected wave condition.

For assessing the IMO intact stability criteria, the following simulations scenarios are considered.

1. Weather criterion simulations
   a. 3-hour simulation in dead ship condition in the irregular seas and steady wind conditions.
   b. The same conditions but considering a gust factor of 1.5 with $TWS = 75.8\ kn$.
   c. If the second condition results in a stability failure (or roll angle above the downflooding angle), then ten 3-hour simulations will be done in unsteady wind ($TWS = 50.5\ kn$).

2. Operational condition simulations
    a. 3-hour simulation in upper operational condition in the irregular seas and steady wind conditions.
    b. The same conditions but considering a gust factor of 1.5 with $TWS = 52.5\ kn$.
    c. If the second condition results in a stability failure (or roll angle above the downflooding angle), then ten 3-hour simulations will be done in unsteady wind ($TWS = 35\ kn$).

5.2 Simulation results

5.2.1 Weather criterion

The simulation with steady wind, TWS = 50.5 kn, did not result in a stability failure, although a few events exceeded the downflooding angle of 28 deg, see Figure 5-2. Once a gust factor applied, the simulation with steady wind TWS = 75.8 kn, did result in a stability failure. Therefore ten 3-hour simulations in unsteady wind condition, TWS = 50.5 kn, were performed. The simulations were performed with and without Flettner rotors loads. All the simulations resulted in a stability failure, see Figure 5-3. Within 2000 s, 7 out of 10 simulations resulted in capsize, compared to 4 out 10 without the Flettner rotors. Note that the simulations could be too conservative, but it demonstrates that the capsize risk is higher with Flettner rotors than without and that IS 2008 is under-conservative with a roll back angle of 13.2 deg only.

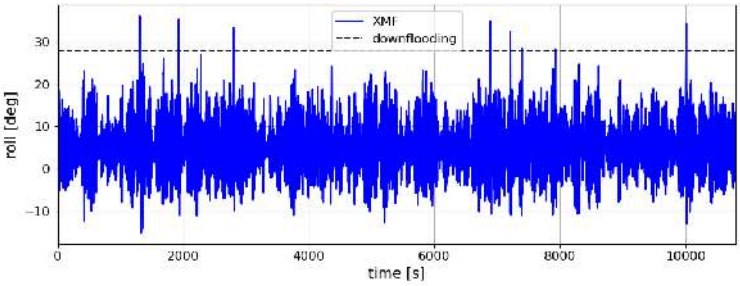


Figure 5-2: Roll time signal from the weather criterion simulation in steady wind condition, TWS = 50.5 kn.

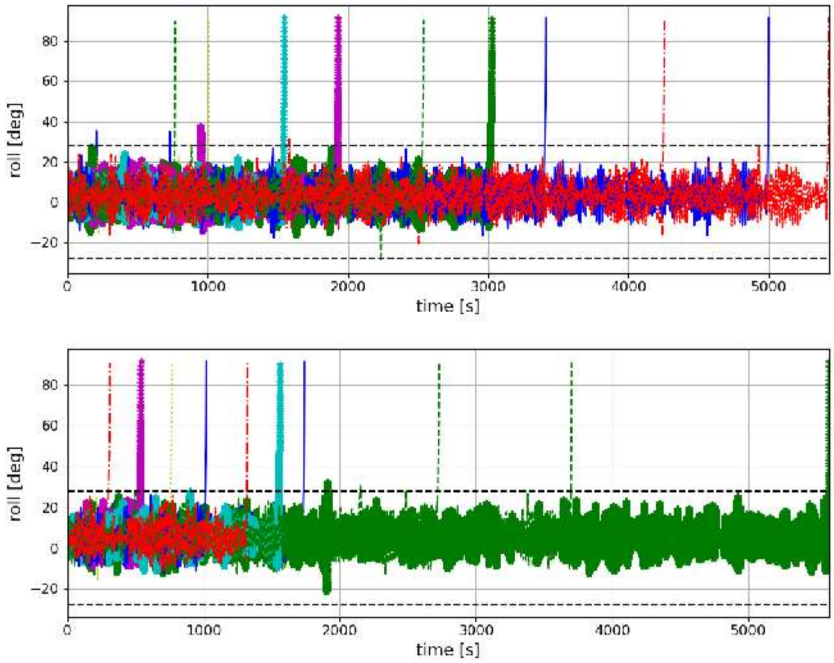


Figure 5-3: Roll time signals from the weather criterion simulations with (top) and without (bottom) Flettner rotors.

5.2.2 Operational condition simulations

Simulations for the operational condition were performed for 3-hour duration in no, steady and unsteady wind conditions with and without gust factor. The results show that no stability failure was found, see Figure 5-4. The simulation with unsteady wind of 52.5 kn results mean roll of 7.2 deg and maximum roll of 19 deg.

Although no capsizes were found in the simulations as shown in Figure 5-4, ten 3-hour simulations with and without Flettner rotors were performed for the upper operational condition, unsteady wind of 35 kn. Probability of exceedance of roll peaks and crests for all the simulations are shown in Figure 5-5. The simulations with the rotors result in a mean roll of 4.5 deg, max roll between 9 and 10 deg and MPM roll back angle around 5.2 deg. While the simulation without rotors result in a mean roll of 2 deg, max roll between 6.5 and 7.5 deg and MPM roll back angle around 4.4 deg

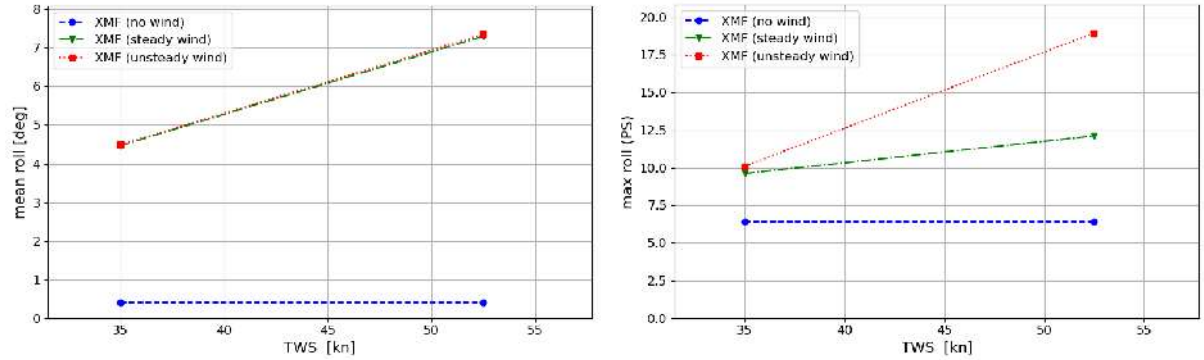


Figure 5-4: Mean and maximum roll from the upper operational condition simulations without and with the gust factor; TWS = 35 kn and 52.5 kn, respectively.

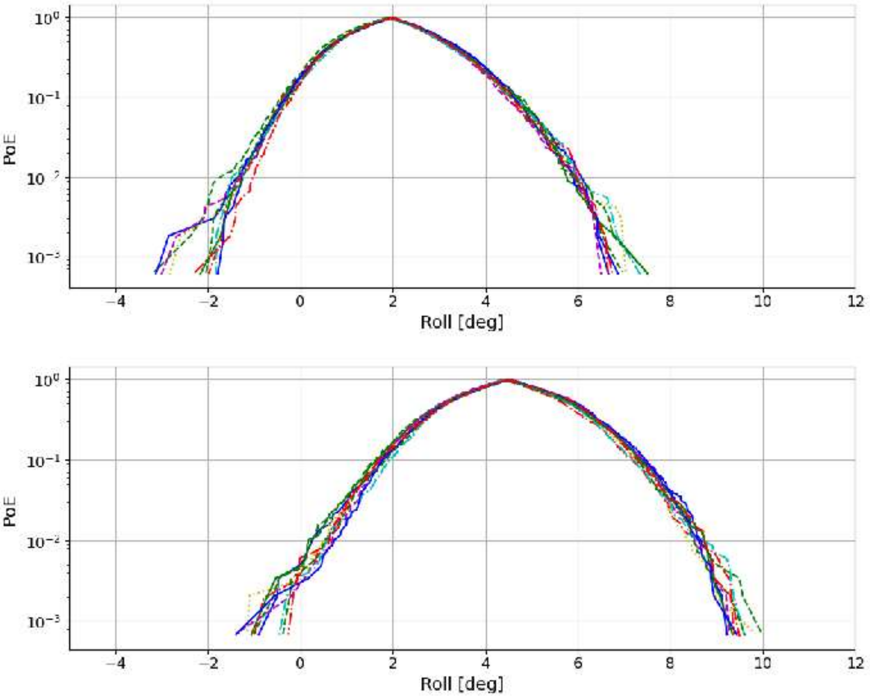


Figure 5-5: Probability of exceedance of roll crests and troughs from the upper operational condition simulations with (top) and without (bottom) Flettner rotors. Each colour or line style corresponds to a distinct wave realisation.

6 CONCLUSIONS

This report presented the calculation, model tests and simulations results for assessing the stability requirements of the wind assisted feeder vessel.

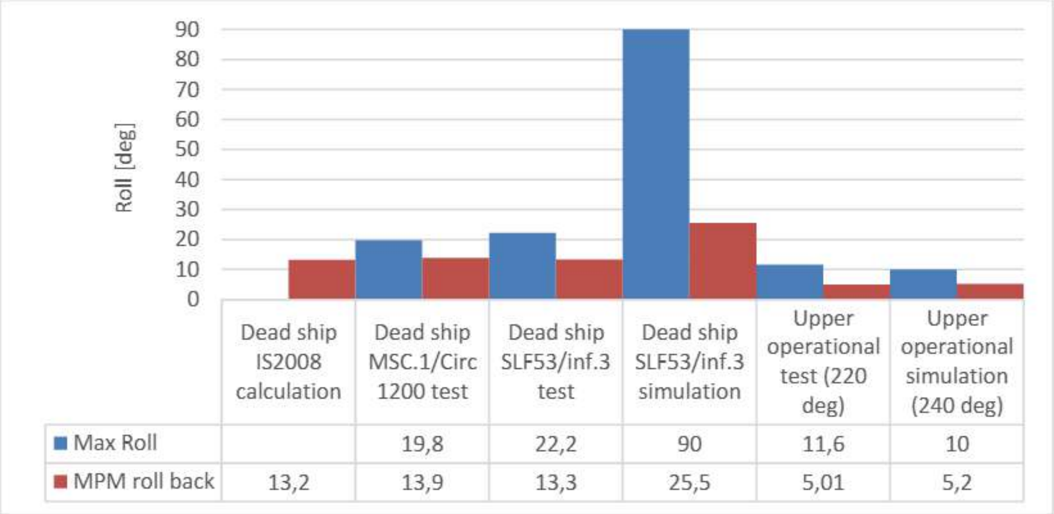
The IMO intact stability (IS) 2008 requires that the windward area under the GZ curve is smaller or larger than the leeward area. Based on the calculation, the windward area with the roll back angle of 13.2 deg is smaller than the leeward area, thus the vessel is considered stable.

The model tests of MSC.1/Circ1200 test, regular waves and no wind conditions, results a slightly higher roll back angle than the calculated one.

A higher fidelity model test of SLF53/inf.3, in irregular waves and constant wind force conditions, results a similar roll back angle as the calculated one. However, the simulation of SLF53/inf.3 in irregular waves and unsteady wind conditions indicated loss of stability. Seven out of ten simulations capsized within 30 minutes. Further investigation is recommended to determine the causes of this discrepancy. One possible explanation is that the winch system introduced additional roll damping during the tests; however, other factors cannot be ruled out.

On the other hand, the upper operational condition simulations and model tests showed that the present vessel is stable. This suggests that the current regulations for evaluating the dead ship condition may indeed represent the most critical scenario. Demonstrating compliance in that condition indicates that the vessel will also remain safe under operational conditions.

One would expect that lower fidelity approaches would result in conservative results, see Figure 6-1. That is not the case for the present example with the wind assisted feeder with six Flettner rotors. The current dead ship criteria as outlined in IS2008 and MSC.1/Circ.1200 might be insufficient to assess the stability of modern, wind propelled vessels. It is recommended to further study this for more wind assisted vessels.



	Dead ship IS2008 calculation	Dead ship MSC.1/Circ 1200 test	Dead ship SLF53/inf.3 test	Dead ship SLF53/inf.3 simulation	Upper operational test (220 deg)	Upper operational simulation (240 deg)
🟦 Max Roll		19,8	22,2	90	11,6	10
🟥 MPM roll back	13,2	13,9	13,3	25,5	5,01	5,2

Figure 6-1: Summary of maximum roll and most probable maximum roll back angle.

Wageningen, December 20205
MARITIME RESEARCH INSTITUTE NETHERLANDS

APPENDICES

APPENDIX I HEADING AND COORDINATES

The coordinate system and related sign conventions follow ITTC standards. The heading (μ) of the vessel is given in a ship co-ordinate system; it is defined as the angle between the direction of wave propagation and the direction of the vessel's bow. The following sign convention for the heading and reference system for positions applies:

Table A1-1: Heading convention and reference system.

Ship heading convention		**Reference system**	
180 deg	Head seas	X=0	at aft perpendicular and positive forward
135 deg	Bow quartering seas over starboard	Y=0	at centreline and positive to portside
90 deg	Beam seas over starboard	Z=0	at base line and positive upward
45 deg	Stern quartering seas over starboard		
0 deg	Following seas		

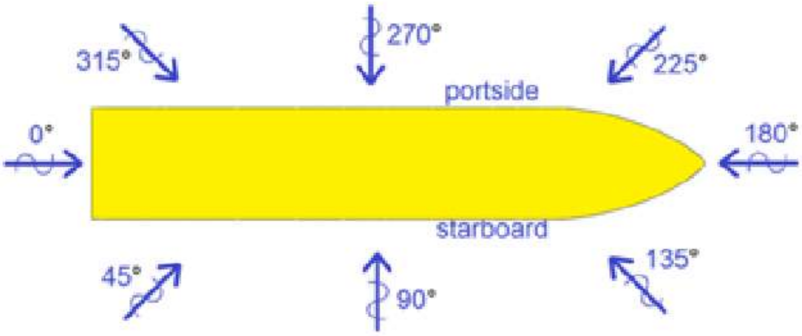


Figure A1-2: Heading convention.

APPENDIX II WEATHER CRITERION IRREGULAR WAVES TESTS

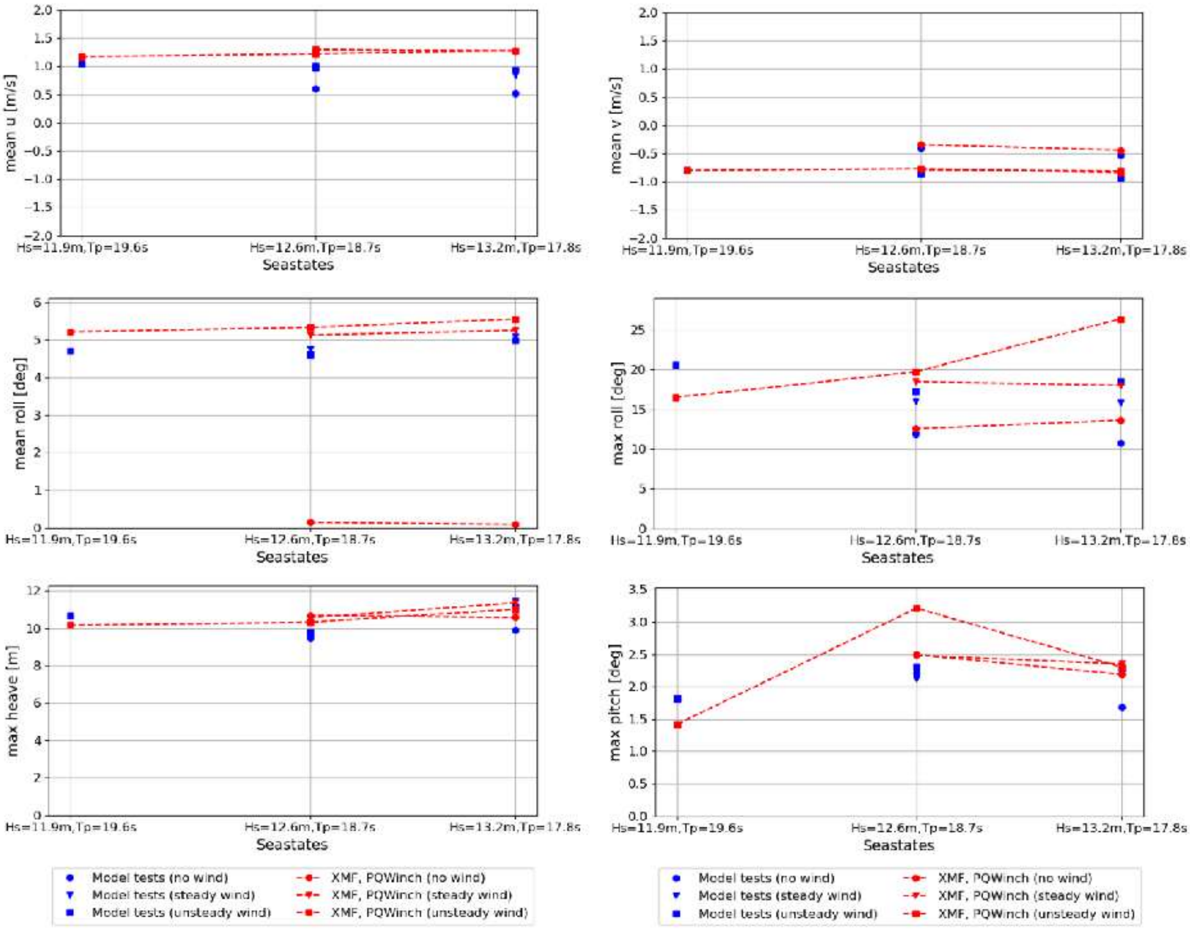


Figure A2-1: *Comparison of the statistics of velocities (top), roll (middle) and heave and pitch (bottom) between the model tests and the simulation of the weather criterion tests in irregular waves.*

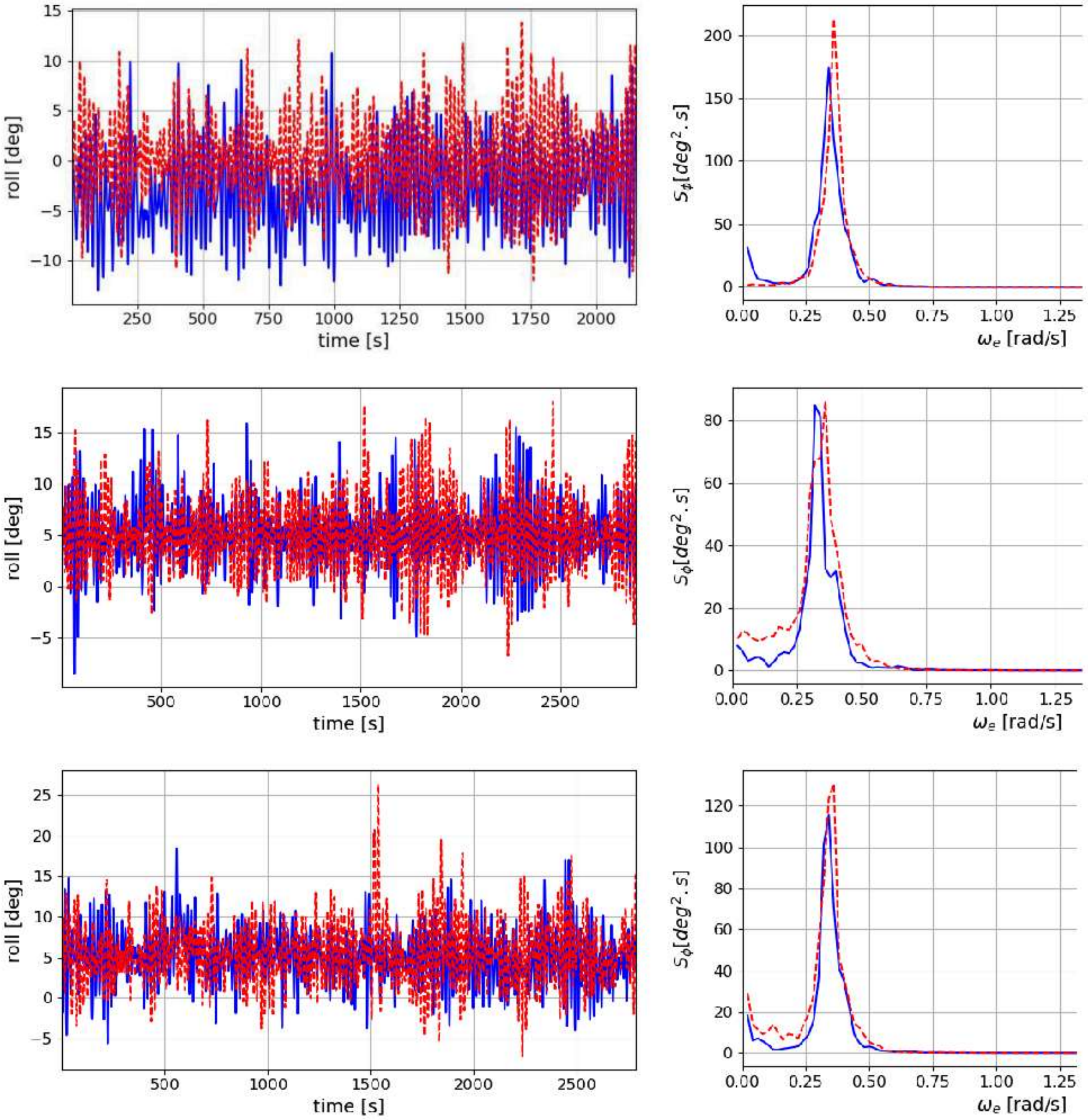


Figure A2-2: Comparison of roll time signals and spectra between the model tests and simulations for the weather criterion tests with $\left(H_s, T_p\right) = (13.2m, 17.8s)$. From top to bottom figures are for no wind, steady and unsteady wind condition, respectively.

APPENDIX III OPERATIONAL CONDITION, REGULAR WAVES TESTS

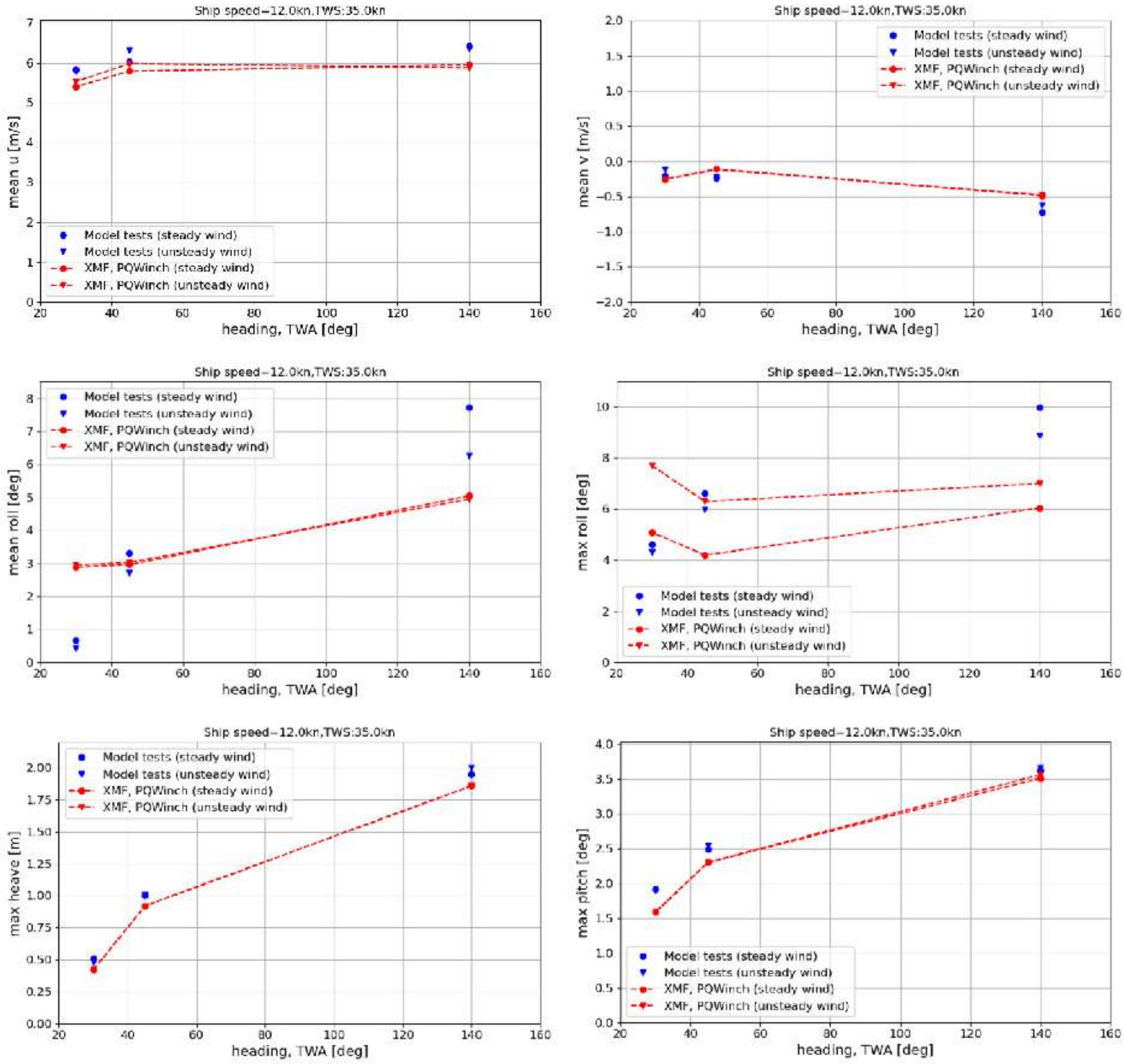


Figure A3-1: *Comparison of the statistics of velocities (top), roll (middle) and heave and pitch (bottom) between the model tests and the simulation of the upper operational condition tests in regular wave.*

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