DEVELOPMENT OF AN OPEN-SOURCE NEXT GENERATION FLOATING OFFSHORE WIND TURBINE

Executive summary

Text Report - Final

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Executive summary

Text Report - Final

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REVIEW OF DELIVERABLES

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Text report	70151-5-RD	Design basis
Text report	70151-6-RD	Design screening through hydrodynamic and structural analyses
Text report	70151-7-RD	Preliminary design, evaluation and validation of an open-source reference floater for industrial-scale FOWT research
Text report	70151-8-RD	Basin tests for validation of numerical model
Text report	70179-4-RD	Blade pitch control using reinforcement learning for a floating offshore wind turbine
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1 INTRODUCTION

1.1 Background

Floating offshore wind energy is rapidly developing. Current global developments and installations consist mainly of pilot and demonstration projects, with typical farm sizes of 10-100MW [1], but in recent years, a clear commitment is seen to further develop floating offshore wind turbines (FOWTs) into a cost competitive solution [2]. This is mainly done by upscaling the turbine and associated substructures, as well as upscaling the installed capacity.

Current FOWT designs have wind turbines ranging between 10-15MW and this is expected to increase further towards 20MW or larger. This is illustrated by the ongoing development of NREL and DTU of a 22MW reference wind turbine [3]. As the wind turbine generators (WTGs) used on FOWT platforms grow in size, the motion and load responses become strongly non-linear, with a strong aero-hydro-servo-elastic coupling [4]. Currently existing benchmark floaters use smaller wind turbines, which are not suited to evaluate the fully coupled response.

To assist the industry development towards larger-scale FOWT systems, MARIN is developing an open-source reference floater for a 20+MW wind turbine. The results and data are publicly disseminated to support further advances by industry and academia. Throughout the entire project, only use is made of publicly accessible data. MARIN has an extensive track record in assessing FOWT floaters, but data from this work is not included in this project, to ensure that all reports, lessons, and datasets are open to share.

The work is funded through MARIN internal resources and was performed from 2022 onwards. MARIN employees from several departments contributed directly or indirectly to this work; their contributions are gratefully acknowledged. This executive summary report will be updated when new research is available.

1.2 Aim and objectives

The focus in this work is not on the floater itself, but on the methodologies used in the design and evaluation of the floater. The floater acts merely as a tool to allow open research and communication with the industry on design challenges, and methods to overcome those design challenges.

Specific objectives within the project are:

- To gain experience in design challenges encountered by MARIN's clients, by following a design trajectory from the basics.
- To develop an automated workflow for hydrodynamic design screening and to apply this workflow to study (1) the hydrodynamic performance of FOWTs with varying sizing and (2) the sensitivity of design performance to design factors.
- To perform conceptual basin tests with good accuracy but limited scope, yielding relevant data for numerical model tuning and validation by MARIN and external partners.
- To test a wireless measurement setup for physical model tests.
- To test software in the loop (SIL) approaches for simulating wind loads in physical modelling tests whilst considering aero-hydrodynamic coupling effects.
- To investigate the performance of a reinforcement learning agent in controlling blade pitch angles of a floating wind turbine.

1.3   Organisation of supporting reports

The research objectives were addressed through different activities, that are described in detail in different MARIN reports. Table 1-1 presents a summary of the reports. All report, as well as the basin test data, are delivered through a public FTP (see Chapter 3). The graphical summary in Figure 1-1 illustrates the steps from design basis to basin tests.
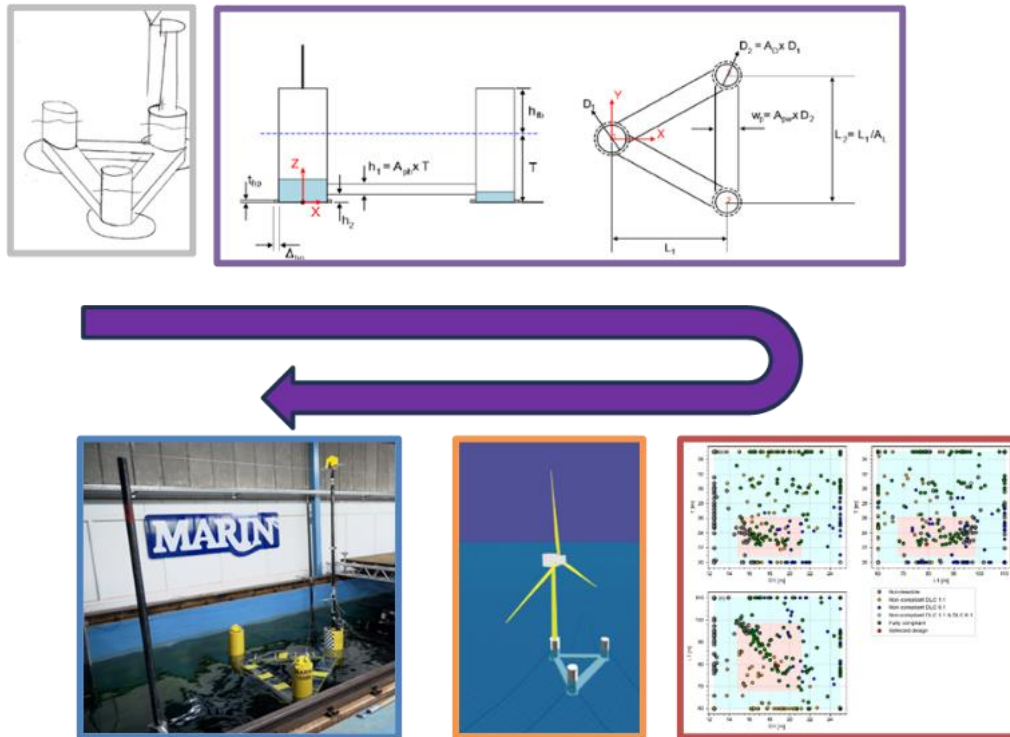
Figure 1-1:   Graphical summary of design trajectory.

Table 1-1:   Overview of delivered reports.

Text report	70151-4-RD	**Present report – Executive summary**
Text report	70151-5-RD	Design basis
Text report	70151-6-RD	Design screening through hydrodynamic and structural analyses
Text report	70151-7-RD	Preliminary design, evaluation and validation of an open-source reference floater for industrial-scale FOWT research
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Text report	70179-4-RD	Blade pitch control using reinforcement learning for a floating offshore wind turbine

MARIN intends to continue work on their open-source 22MW FOWT in the next years. Additional reports will also be shared publicly.

When referring to the work within this project, MARIN recommends to cite the present executive summary report instead of the supporting documents.

2   SUMMARY OF ACTIVITIES

2.1   General remarks

The present section summarises the main project activities and results. Reference is made to the supporting reports for more detailed information.

It is noted that the reports on the design basis (70151-5-RD) and on the design screening methodology (70151-6-RD) assumed a 20MW turbine that was scaled up from an existing wind turbine. Following the completion of the work described in these reports, the 22MW turbine developed by NREL [5] became available. It was decided to adopt this new turbine design, leading to an updated floater design (see report 70151-7-CB) that was tested in MARIN's wave basin (report 70151-8-RD).

Throughout the reports, results are presented in metric (SI) units unless stated otherwise. The applied sign convention and coordinate system are in accordance with the OCIMF [6] standard. A right-handed coordinate system is applicable.

2.2   Applied software and facilities

The following software was used:

- DIFFRAC: MARIN wave diffraction solver [7], link
- aNySIM-XMF: MARIN time domain solver, link
- HYDRA: MARIN optimisation framework
- Rhino Grasshopper: parametric 3D modelling package, link
- Abaqus: Finite element modelling (FEM) package, link
- ROSCO: wind turbine controller [8], link

Used MARIN facilities include:

- Concept Basin
- Computational cluster Marclus5

The software and facilities are described in more detail in the supporting reports.

2.3   Design basis (report 70151-5-RD)

The design basis report describes the high-level design choices that have been made at an early start. These can be split into a decision for the floater type and the site where the floater will be deployed.

2.3.1   Platform type

A semi-submersible platform is selected as principle starting point, since this platform type is considered most representative of the current market, with 80% of the currently installed and announced FOWTs being a semi-submersible. The platform is split in multiple morphological design choices, see the left panel of Figure 2-1. This overview can be seen as a menu from which partial concepts can be chosen. Each row is a choice that has to be made, with the options shown in the columns. In total, this morphological overview gives 62,208 permutations. Such a number of permutations is infeasible for the objective of this research, and the number of permutations is reduced drastically. After selecting parameters, a general design is selected as shown in the right panel of Figure 2-1, with a simple catenary mooring system.

2.3.2 Site

The Gulf of Maine is chosen as a representative site for a large number of installations in the near future, based on water depth, wave heights, annual wind speeds and seabed conditions.

A selection of design load cases (DLC) has been made. All fault, start-up and shutdown cases are expected to depend strongly on the specific wind turbine, controller and floater, and require detailed knowledge of these components. Therefore, these DLC conditions are excluded. Two DLC conditions are considered for the actual design work, consisting of a 1-yr wind-driven condition (DLC 1.1) and a 50-yr storm condition (DLC 6.1). The corresponding wind, wave and current conditions are determined.

Parameter	Concept 1	Concept 2	Concept 3	Concept 4
No. of outer columns	3	4		
Column shape – top view	Round	Square	Triangular	
Column shape – side view	Straight	Wide bottom	Wide top	Wide top/bottom
WTG tower mount	Outer column	(+1) centre col.	Deck	Centre structure
Column connections	Bracings	Pontoons	Hybrid	
Heave plates	Yes	No		
Mooring system	Catenary	Semi taut	Taut	
Material	Steel	(Reinforced) concrete		
Weathervaning	Yes	No		
Ballast	None	Passive - during installation	Active	
Structure layout	Inner	Outer	Both	
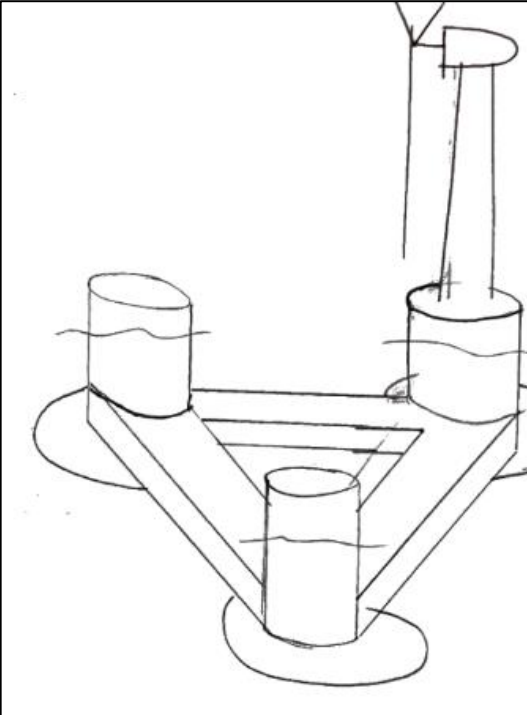
Figure 2-1:   Morphological design overview (left) and selected design concept (right).

2.4 Design screening methodology (report 70151-6-RD)

2.4.1 Approach

The selected three-column design concept has been used as a starting point for the actual floater design. The floater design was parameterised and an automated sizing and evaluation pipeline was set up for static bulk analysis, and feasible designs were simulated in frequency domain. The automated workflow features Rhino Grasshopper for parameterisation and meshing, DIFFRAC for wave diffraction calculations, and Python scripts for input preparation and post-processing. The workflow assumes passive ballasting through water in the pontoons and concrete in the columns.

A design of experiments approach was adopted to systematically evaluate the hydrodynamic performance of different FOWT designs. This approach was used to perform a design screening, the results of which are used to reveal the governing assessment criteria and the driving design parameters.

The screening analysis was initially performed for a 20MW turbine. At later stage (see Section 2.5), the approach was repeated for a 22MW turbine.

Figure 2-2:   Illustration of design sizing parameters.

2.4.2   DLC performance in relation do design factors

The hydrodynamic performance was assessed for the DLC conditions from the design basis and was quantified in terms of most probable maximum (MPM) values in 3-hour sea states. For the selected design space, the key hydrodynamic criteria are the tilt angle in the wind-dominated operation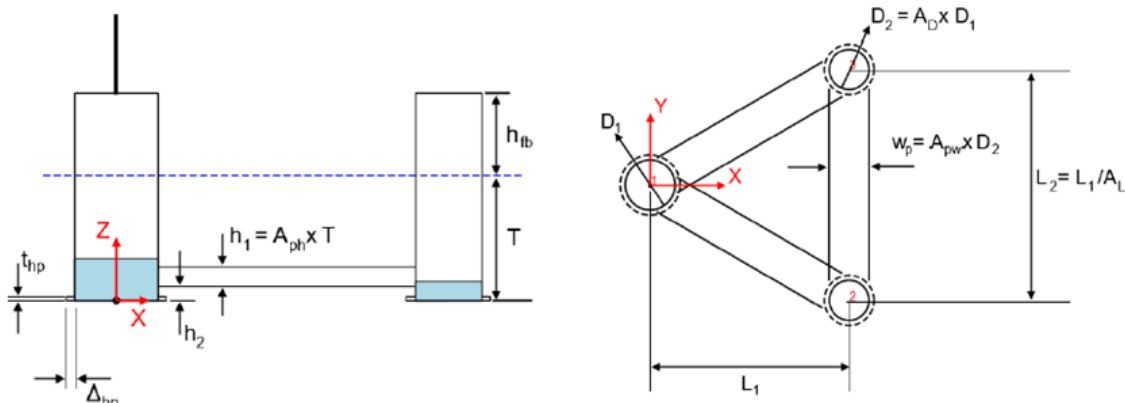al sea state (DLC1.1) and the hub acceleration in the wave-dominated survival sea states (DLC6.1). These two hydrodynamic parameters are negatively correlated through the floater's hydrodynamic stiffness, as designs with high hydrodynamic stiffness are stable in wind-dominated conditions but move more in wave-dominated conditions.

Through surrogate modelling and perturbation plots, the governing geometric factors for the floater's hydrodynamic performance were identified. These governing factors are the column diameters, floater draught, and overall length. The ballasting feasibility and maximum tolerable tilt angles impose a lower limit on draught, column diameter and length. The upper limit of these factors is governed by the nacelle accelerations in survival sea states, and likely also by aspects that were not considered in the present early stage design loop (such as structural integrity and costs). The pitch natural period is a key parameter in the design performance; all compliant designs had pitch natural periods between 20.4 and 35.6 sec.

2.4.3   FEM modelling

For one promising floater design, a finite element model (FEM) was built. The structural design was assessed in terms of local pressure loads and global (internal) stresses. The results were used to reflect on the steel mass assumptions adopted in the design screening.

2.5   Sizing and verification (report 70151-7-RD)

2.5.1   Design approach for 22MW turbine

The design methodology (Section 2.4) was initially applied to an upscaled 15MW wind turbine, based on the Heliade-X. While performing this research, a more representative 22MW reference wind turbine was made available by NREL and DTU [3]. Therefore, the design screening was repeated with updated mass, inertia, and thrust properties of the 22MW wind turbine . A total of 350 designs were evaluated.

2.5.2   22MW FOWT floater design

The hydrodynamic calculation results for the different 22MW designs were used to select the combinations of design factors that resulted in feasible (in terms of ballasting) and compliant (in terms of DLCs) designs. From there, one design that satisfied the feasibility and compliancy criteria was

selected for further study. While multiple designs satisfied these criteria, the selected design was considered promising because:

- The design has relatively low displacement, compared to other designs within the design space.
- The design has similar roll and pitch stiffness.
- The design's DLC performance shows some margin with respect to the DLC criteria.
- The overall floater length was < 80 m. Longer designs with similar displacement were slender and deemed less desirable from a structural perspective.

The selected floater design is presented in Figure 2-3. Main properties are presented in Table 2-1 and in TABLE 1 at the end of this report.
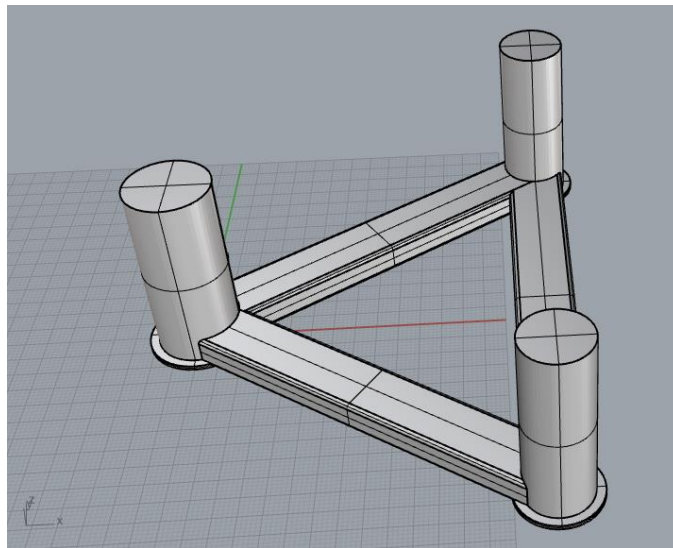
Figure 2-3:   Selected 22MW floater design.

Table 2-1:   Main characteristics of the selected floater design.

Parameter	Symbol	Value	Unit
Column 1 diameter	D1	18.8	[m]
Columns 2/3 diameter	D2/D3	15.2	[m]
Draught	T	22.4	[m]
Platform length	L1	79.2	[m]
Platform width	L2	107.2	[m]
Displacement	-	38,377	[t]
RNA/tower mass	-	1,460/1,230	
Floater steel mass	-	5,819	[t]
Mooring vertical pretension	-	1,036	[t]
Water/concrete ballast mass	-	22,849/5,983	[t]

It is noted that the floater has higher displacement than what could be expected based on upscaling of existing floaters for smaller turbines. Explanations for this are discussed in the supporting report and include:

- A major part of the displacement is formed by the water and concrete ballast.
- A conservative maximum tilt angle of 5 deg was assumed.
- The margin w.r.t. the DLC criteria shows that the design leaves room for further optimisation.
- No active ballasting was considered.
- No weathervaning was considered.

2.5.3   Verification of frequency domain calculations through time domain modelling

The hydrodynamic calculations in frequency domain oversimplify some physical processes, in order to allow for 1,000+ design evaluations in an efficient manner. These simplifications include the omission of dynamic wind loading and blade pitch controller effects, the omission of second order wave loads, the omission of non-linear hydrostatic effects, the linearisation of the total damping, and the linearisation of the mooring system stiffness. The influence of these modelling simplifications is checked by performing time domain calculations, which do include these nonlinear and physically relevant effects.

A numerical model was built in MARIN's time domain software aNySIM-XMF (details found in the supporting report). A direct comparison of the frequency and time domain results (Figure 2-4) shows that the latter results in a higher MPM platform tilt angle in DLC1.1 (wind driven condition). The computed nacelle accelerations in DLC6.1 (50-yr storm condition, wave driven condition) are similar for the two approaches.
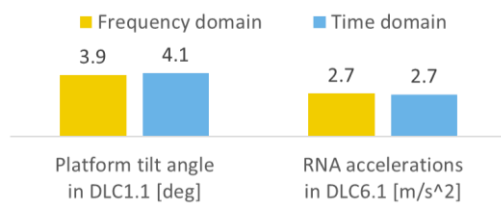

Figure 2-4:   Comparison of Most Probable Maxima (MPM) of driving criteria for DLC1.1 and DLC6.1.

2.5.4   Model tuning and validation through wave basin tests

The wave basin test data (Section 2.6, Report 70151-8-RD) were used to tune and validate the FOWT time domain model. A model-the-model approach was adopted.

Firstly, the as-built particulars, soft-mooring, and realised weight distributions were used as input to the numerical simulation. The heave and pitch damping for this "as-tested" model were tuned using decay results. Next, the tuned model was validated using the basin test outcomes, focusing on the MPM tilt angles (for DLC1.1) and RNA accelerations (for DLC6.1). Comparison between basin test and "as-tested" time domain results in Figure 2-5 show a good match (3% difference) in terms of MPM tilt angle for DLC1.1, but a significant underestimation (18%) by the numerical model in terms of RNA accelerations for DLC6.1. This difference is being further explored.

Next, the tuned and validated model was updated using the original and full particulars of the FOWT and its catenary mooring system. Simulation results for this full and tuned design predict lower MPM tilt angle in DLC1.1 but an increased RNA acceleration for DLC6.1 (Figure 2-5).
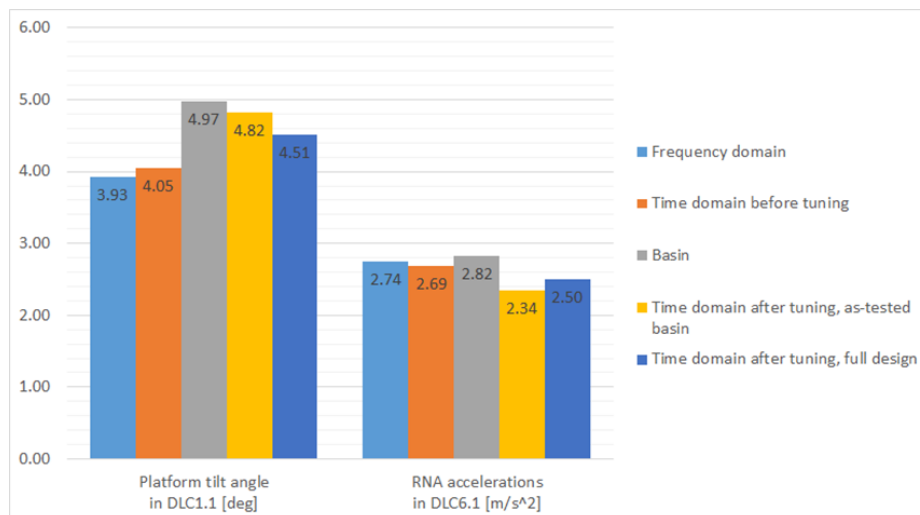

Figure 2-5:   Overview of MPM values from different modelling fidelities.

2.6 Wave basin tests (report 70151-8-RD)

2.6.1 Objectives

Basin tests were conducted in the MARIN Concept Basin. These tests serve multiple goals:

- Data gathering for numerical model validation and verification. Extensive system identification and quality assurance tests were conducted to identify the influence of (for example) the wind winch system.
- Decay tests and white noise tests, that serve as input for numerical model tuning and validation.
- Tests in wind and waves to verify the floater DLC performance and to validate the numerical modelling (frequency and time domain).

Figure 2-6 presents a summary of the performed tests, revealing a clear emphasis on decay test and system identification tests (white noise, wind only) to allow for numerical model tuning and validation.

TABLE 15   REVIEW OF TESTS IN ENVIRONMENTAL CONDITIONS

MARIN Test No. 70151_02CB_	Environment	Time [hrs]	Model heading [deg]	Hs [m]	Tp [s]	Dir. [deg]	γ [-]	Name	Wind speed [m/s]
04_003_001_01	White Noise Low	0.5 + 3.0	0.0	1.2	5-25	180	-		
04_007_001_02	White Noise High	0.5 + 3.0	0.0	4.02	5.77-28.87	180	-		
04_008_001_03	Wind only 7	0.5 + 1.0	0.0	-	-	-	-		
04_009_001_04	Wind only 8	0.5 + 1.0	0.0	-	-	-	-		
04_003_002_01	White Noise Low	0.5 + 3.0	0.0	1.2	5-25	180	-		
04_007_002_01	White Noise High	0.5 + 3.0	0.0	4.02	5.77-28.87	180	-		
04_005_001_01	Windwinch XMF 001	0.5 + 3.0	0.0	1.42	7.43	180	-	WIND 1	10.8, Kaimal
04_010_001_02	Shutdown XMF 005		0.0					WIND 5	10.8, constant
04_011_001_01	Shutdown XMF 006		0.0					WIND 5	10.8, constant
04_008_002_02	Wind only 7 - other winch setting	0.5 + 1.0	0.0	-	-	-	-	WIND 4	Force series
04_009_002_01	Wind only 8 - other winch setting	0.5 + 1.0	0.0	-	-	-	-	WIND 4	Force series
04_003_003_01	White Noise Low - other winch setting	0.5 + 3.0	0.0	1.2	5-25	180	-		
04_007_003_01	White Noise High - other winch setting	0.5 + 3.0	0.0	4.02	5.77-28.87	180	-		
04_005_001_03	Windwinch XMF 001 - other winch settings	0.5 + 3.0	0.0	1.42	7.43	180	-	WIND 1	10.8, Kaimal
04_006_001_02	Windwinch XMF 003 - other winch settings	0.5 + 3.0	0.0	4.90	15.00	180	-	WIND 2	45.5, NPD
04_008_003_02	Wind only 7 - winch setting on zero	0.5 + 1.0	0.0	-	-	-	-	WIND 4	Force series
04_009_003_01	Wind only 8 - winch setting on zero	0.5 + 1.0	0.0	-	-	-	-	WIND 4	Force series
	Model Heading 90 deg								
05_003_001_01	White Noise Low	0.5 + 3.0	90.0	1.2	5-25	180	-		
05_007_001_01	White Noise High	0.5 + 3.0	90.0	4.02	5.77-28.87	180	-		

Overview of irregular wave tests with wind, including MPM pitch, roll, RNA acceleration.

38 decay tests
6 wind only (winch) tests
8 white noise wave tests
3 DLC tests
2 (arbitrary) shutdown tests

Figure 2-6:   Overview of performed basin tests (for detailed overview, see report 70151-8-RD).

2.6.2 FOWT model, soft-mooring and instrumentation

The wave basin tests were performed at model scale 1:60, following Froude's scaling laws of similitude. The FOWT floater was represented through a PVC model (Figure 2-7). The total weight distribution of floater plus tower was calibrated prior to the tests (TABLE 1).

At the start of the campaign, heave and pitch motion decay tests were performed with different sets of heave plates. It was found that the decay tests without heave plates resulted in damping values that were closest to the values assumed in the numerical pre-study (see preceding sections). It was therefore decided to perform the model tests in waves without heave plates.

Figure 2-7:   Overview photograph of the model in the MARIN concept Basin.

The model was connected to basin-fixed anchor points through a set of four linear springs. The anchor points were located below waterline such that the total vertical pretension of the soft-mooring arrangement was the same as for the catenary mooring assumed in the design basis. This ensured that the model was at the correct draught when connected to the soft-mooring lines.

The instrumentation included an optical system to measure the 6DOF (degrees of freedom) floater motions, four 3DOF accelerometers, and force transducers to measure the imposed loads by the wind winches as well as in the four soft-mooring lines. All tests were recorded on camera.

2.6.3   Wireless data acquisition

Measurement cables connected to a lightweight FOWT model can affect motion responses in the basin. To avoid influencing the model test results, use is made of a wireless data acquisition system, which has no measurement cables between the model and the basin.

2.6.4   Software in the loop modelling

The numerical model used during the verification step (Section 2.5.3) was used to model the wind turbine forces during the basin tests. The numerical model avoids the scaling issue between Froude (hydrodynamics, floater) and Reynolds (aerodynamics, wind turbine) by running at full scale. This imposed limits on the computational speed, where the numerical model must run $\sqrt{\lambda}$ times faster than the basin and must be stable at a timestep of $\Delta t_{bas} * \sqrt{\lambda}$, where Δt_{bas} is the timestep of the basin data acquisition.

Additional Quality Assurance (QA) tests were carried out, to identify the influence of the winch system:

1. <u>Winch RAO</u>: A white noise force spectrum is requested from the winch, and a wind-only test is carried out with this force spectrum. This allows to evaluate the RAO between the requested force, and the force measured on the WTG tower-top. A perfect winch would then have a force amplitude RAO of 1, and phase of 0. Two spectra with different amplitude are tested.
2. <u>Decay tests</u>: The winches are connected, and only the pretension is applied, i.e. a net zero force is applied. The resulting system should be identical to the floater without winches connected, but practically, the winch system may add mass in the lines and drums, and damping due to the response time of the force controller. The decay tests in roll and pitch are repeated to identify how the natural periods and damping ratios of the floater are changed due to the addition of the winch hardware.
3. <u>White noise test</u>: analogously to the decay tests, one white noise wave test is repeated with a net zero force allocated. This can show how the floater RAOs change due to the winch hardware.
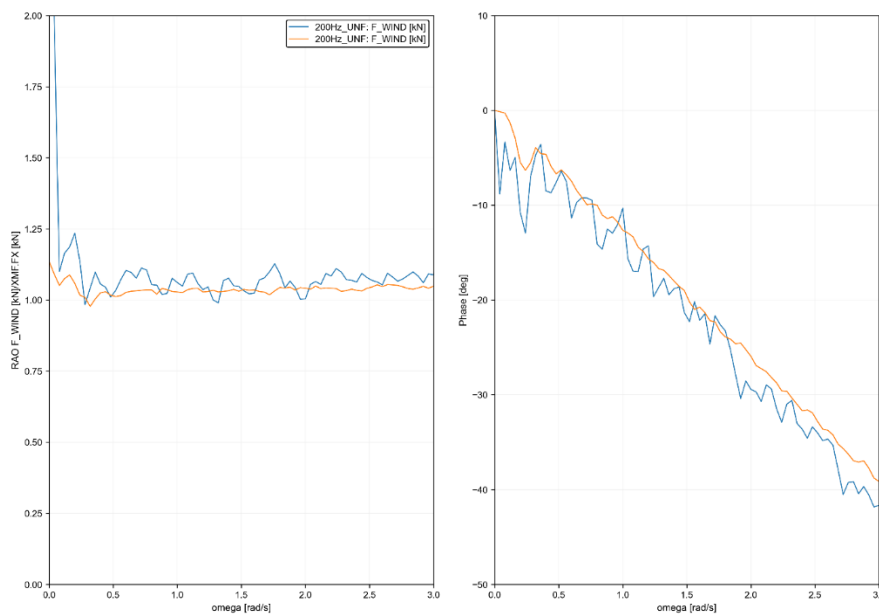

Figure 2-8:   *Winch RAO – measured net force divided by the requested net force.*

2.6.5 MPM values for tests in wind and waves

Tests in wind and waves were performed for the design load cases 1.1 and 6.1. Maximum probable maximum (MPM) tilt angles and nacelle accelerations were computed for these tests based on Weibull fits. The results were used to validate the time domain model (see Section 2.5.4).

2.7 Blade pitch control using reinforcement learning (report 70179-4-RD)

2.7.1 Objectives

The hydrodynamics of a FOWT are strongly coupled with the aerodynamics of the wind turbine (wind turbine generator, WTG). The most important aerodynamic force is the rotor thrust, which provides a strong pitching moment on the floater and mooring system. In order to optimise the power production and regulate the thrust, a controller is used.

The figure below shows the generator power and thrust of a generic 15MW turbine. A 'standard' land-based controller has been used here, which works as follows:

- The maximum achievable power is generated in the area $u_{wind} < u_{rated} = 11\,\text{m/s}$. The aerodynamic efficiency is maximum, and the blades are at a fixed pitch angle. Control is done by means of a pre-programmed relationship between rotor RPM and generator torque.
- In the area $u_{wind} \geq u_{rated} = 11\,\text{m/s}$ the generator has reached its maximum RPM, torque and power. These three are therefore constant in this area. Control is done by means of a PID controller at the blade pitch angle.
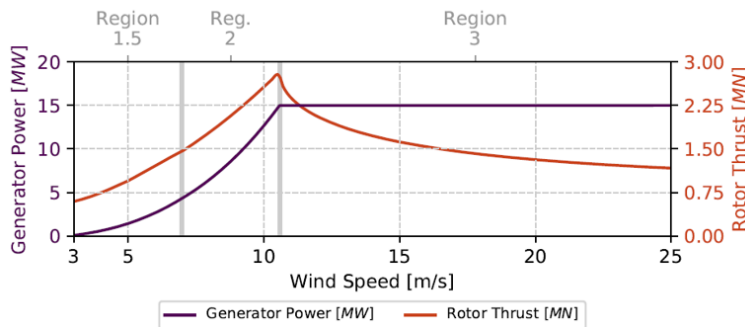

Figure 2-9:   General working principle of a traditional controller.

The goal in this project was to investigate the performance of a Reinforcement Learning agent in controlling the blade pitch angle, where the wind speed was larger than the rated wind speed (Region 3). We investigated multiple designs along with the chosen design to investigate how the blade pitch control affects the optimal design choice.

2.7.2 Approach and results

The RL agent, the Soft Actor-Critic (SAC), was trained in aNySIM. We used ROSCO 2.8.0 [8] as baseline, but ROSCO was not tuned for the environmental condition whereas the RL agent was separately trained for each design. Therefore, the comparison is far from being fair.

Figure 2-10 shows a comparison for the shaft power and tilt angle. The RL agent succeeds in keeping the tilt angle below 5° (a requirement for the design). Though the produced shaft power is about 1.5MW lower with SAC, we observe that the SAC agent does not allow large peaks in the shaft power compared to the baseline. The actuator usage demonstrates a complex picture; we observe that the sac agent tends to use high-frequency variations more the ROSCO does.
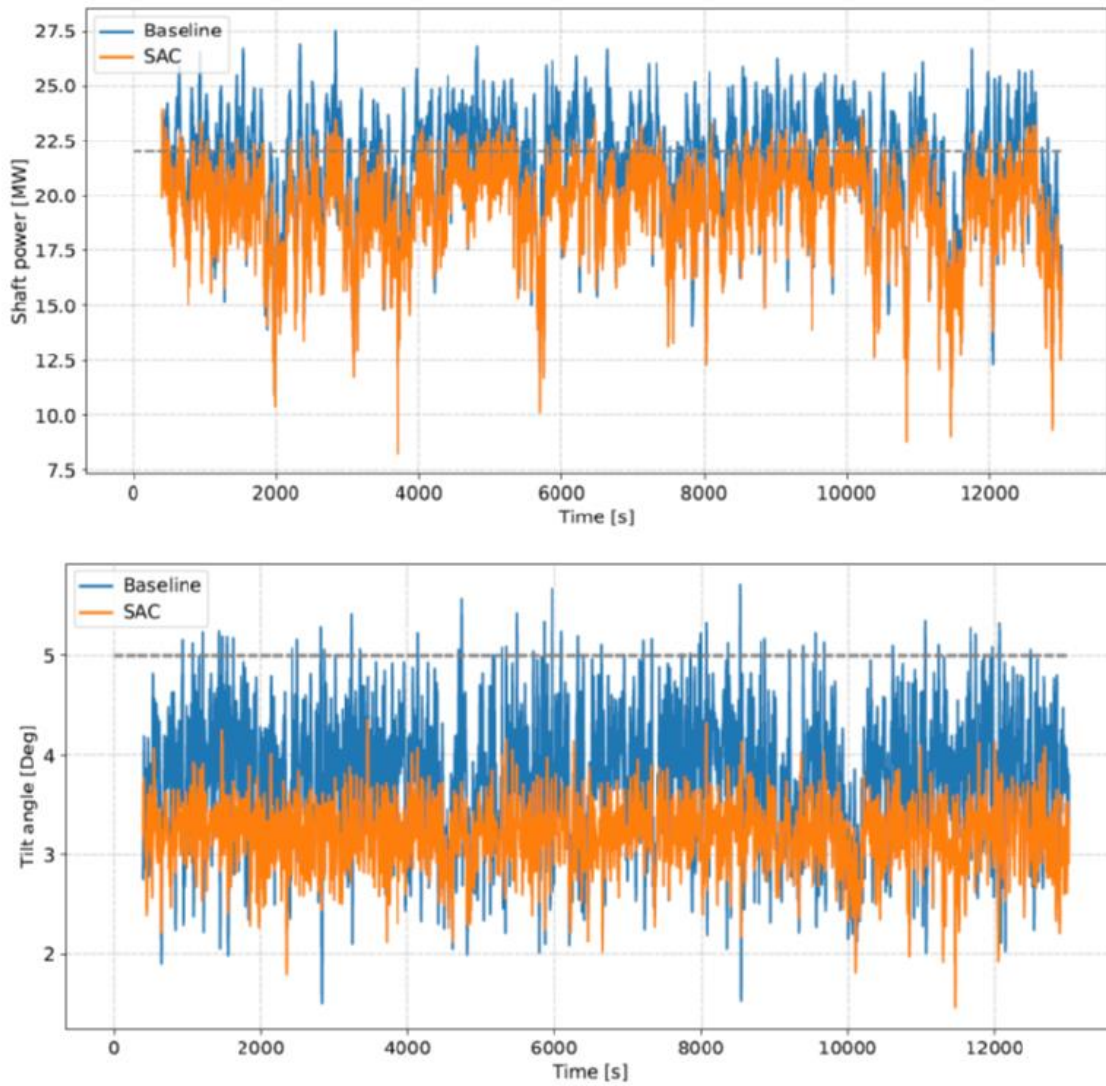
Figure 2-10: Overview of results for ROSCO controller (blue) and RL agent (orange).

3   DATA ACCESS AND USAGE

3.1   Data access

Data can be accessed through a MARIN FTP using the following log-in credentials:

> https://ftp.marin.nl
> Username = MARIN_FOWT_design
> Password = TmZdDn2

It is recommended to use an FTP client such as Filezilla to download the complete dataset, including its file structure, at once.

3.2   Feedback and data updates

Feedback to the shared data is appreciated and can be shared by e-mail to p.schrijvers@marin.nl or offshore@marin.nl.

The reports and dataset may be updated in future following user feedback. Users can subscribe to an e-mail list to receive updates on the dataset. To subscribe or to unsubscribe, send an e-mail to p.schrijvers@marin.nl. Subscribers to the MARIN online webinar on 11th November 2024 are automatically subscribed to the email list.

3.3   Data format

Data are delivered in comma separated ascii format (*.csv) or in a binary HDF5 format (*.h5m). HDF5 is a generic format for data storage. HDF5 files can be read using Matlab and Python; an example script is provided in the software folder. In addition, MARIN readers to plot time trace data (TyDox) and RAOs (RAOviewer) are provided in the software folder on the FTP.

3.4   Description of files

Data are organised in the following folders:

- **02CB**: Basin test data and videos. For a full description of the delivered basin test data including test labelling, the reader is referred to report 70151-8-RD.
- **Drawings**: 3D CAD model of the floater. Note that the 3D model is without heave plates.
- **Reports**: present report and supporting documents.
- **Software**: example scripts and installation files.
- **Webinar**: recording, slides, and answers to raised questions during the online webinar on 11th Nov 2024.

3.5   Conditions for data usage

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REFERENCES

[1] W. Musial, P. Spitsen, P. Duffy, P. Beiter, M. Marquis, R. Hammond and M. Shields, "Offshore wind market report: 2022 edition," National Renewable Energy Laboratory (NREL), 2022.

[2] A. Baquet, K. Kim, J. Kim, S. Park, Y. Ha, H. Lee, Z. Shen and J. Kyoung, "Development of 15MW Floating Offshore Wind Turbine Substructure Customized to Korean Shipyard," in *Proceedings of the ASME 2022 4th International Offshore Wind Technical Conference. ASME 2022 4th International Offshore Wind Technical Conference*, Boston, Massachusetts, USA, 2022.

[3] DTU, NREL, "IEA-22-280-RWT," 04 04 2023. [Online]. Available: https://github.com/IEAWindTask37/IEA-22-280-RWT .

[4] C. E. S. de Souza and E. E. Bachynski-Polić, "Design, structural modeling, control, and performance of 20 MW spar floating wind turbines," *Marine Structures,* no. 84, 2011.

[5] NREL, DTU, "IEA-22-280-RWT turbine design repository," August 2023. [Online]. Available: https://github.com/IEAWindTask37/IEA-22-280-RWT.

[6] Oil Companies International Marine Forum (OCIMF), "Prediction of Wind and Current Loads on VLCCs," in *Companies International Marine Forum (OCIMF)*, 1994.

[7] T. Bunnik, W. H. Pauw and A. Voogt, "Hydrodynamic analysis for side-by-side offloading," in *ISOPE*, 2009.

[8] NREL, "ROSCO. Version 2.4.1," https://github.com/NREL/ROSCO, 2021.

TABLES

TABLE 1   PARTICULARS OF 22MW WIND TURBINE

Designation	Symbol	Unit	Client	MARIN		
				Theoretical	To be built	Realised
Length pontoons	L	[m]	79.20			
Width pontoon	W	[m]	107.17			
Height pontoon	H	[m]	6.73			
Draught No Mooring	T	[m]	20.96			
Draught Incl. Mooring	T	[m]	22.45			
Mass	M	[t]	37,376	37,376	37,376	37,217
Displacement mass incl mooring	D	[t]	38,377	38,344	38,344	38,218
Longitudinal position CoG	LCG	[m]	50.74	50.57	50.57	50.74
Transverse position CoG	TCG	[m]	0	0	0	0
Vertical position CoG bij GMt	KG	[m]	14.22	14.22	14.22	14.23
Transverse metacentric height	GM_t [1]	[m]	20.175	19.55	19.89	19.88
Longitudinal metacentric height	GM_l [1]	[m]	18.791	18.63	18.95	19.14
Position transverse metacentre	KM_t [2]	[m]	34.395	34.11	34.11	34.11
Position longitudinal metacentre	KM_l [2]	[m]	33.011	33.17	33.17	33.17
Roll radius of gyration	k_{xx}	[m]	49.50		49.50	50.001
Pitch radius of gyration	k_{yy}	[m]	51.50		51.50	50.534
Yaw radius of gyration	k_{zz}	[m]	46.20		46.20	50.355
Roll natural period	T_φ	[s]	27.69	-	-	-
Pitch natural period	T_Θ	[s]	26.96	-	-	-

(1) GM_t / GM_l as realised are determined by means of heeling tests in the basin.
(2) KMt / KMl as realised are derived from the measured GM and measured (Resonic) KG.