Definition of the OC5 DeepCwind Semisubmersible Floating System

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Contents

1 Introduction

The Offshore Code Comparison Collaboration, Continued, with Correlation (OC5) is focused on validating offshore wind modeling tools through the comparison of simulated responses of select offshore wind systems to physical test data. Phase II of OC5 involves validation using a semisubmersible floating offshore wind system as shown in Figure 1-1. This report describes the test data available for validation, and provides specifications on the structure tested. The purpose of the report is to supply the needed information to participants of the OC5 project to build and simulate the structure of interest.

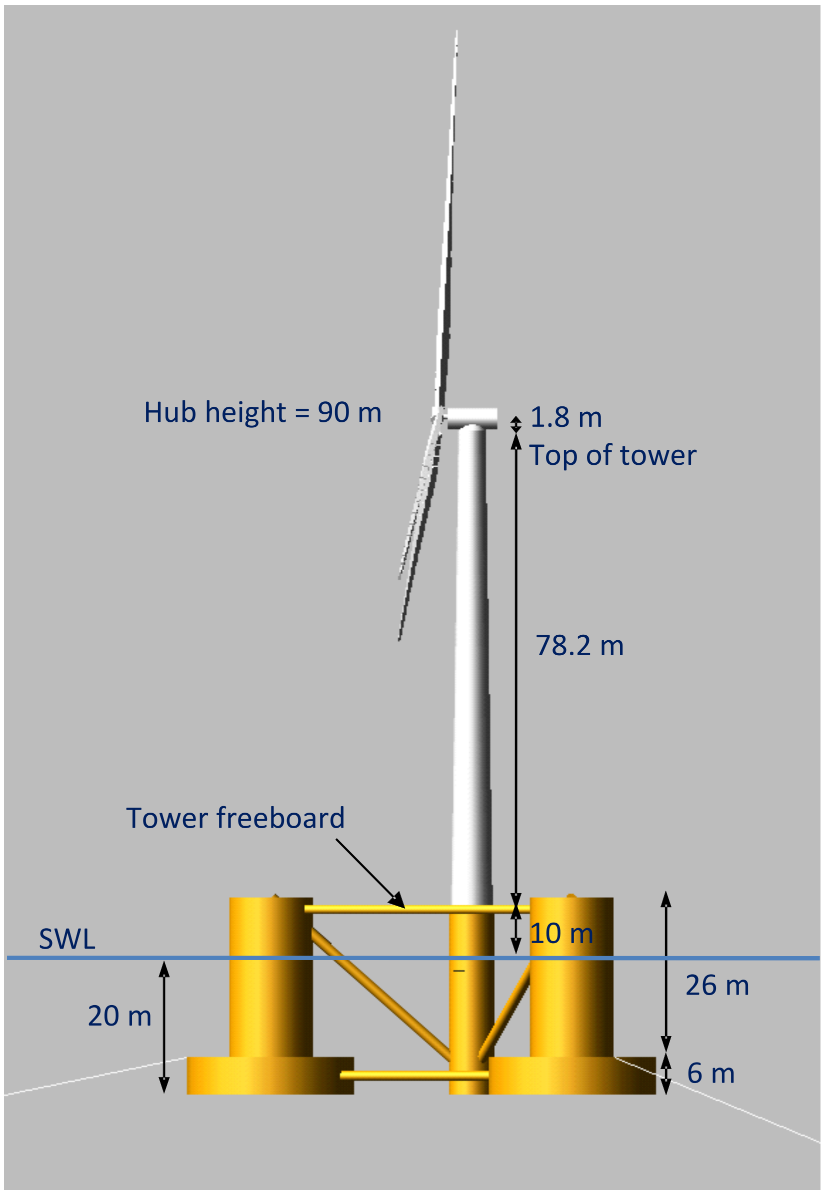


Figure 1-1: OC5 DeepCwind Floating Wind System Design

The semisubmersible design examined in this phase was tested by the DeepCwind consortium in two different test campaigns at the Maritime Research Institute Netherlands (MARIN). The first set of tests was performed in 2011 (Goupee, et al. 2013) and the second in 2013 (Goupee, et al. 2014). The same floater design was used in both test campaigns, but the wind turbine and tower were different.

- The OC5 project will model the system tested in 2013 (the **OC5-DeepCwind semisubmersible)**.
- The OC4-DeepCwind semisubmersible was similar to these two test campaigns, but was modified to use the NREL 5-MW turbine (Jonkman, et al 2009).

The turbine used in the 2013 tank tests at MARIN is a performance-scaled version of the NREL 5-MW turbine, and therefore the system examined for OC5 is similar, but not identical, to the one examined in Phase II of OC4.

This report presents the data needed to support modeling activities for Phase II of the OC5 project. The material is summarized in the following sections:

- Section 2: Model Test Description
- Section 3: Modeling Information
- Section 4: Simulations

2 Model Test Description

2.1 Overview

In 2011, the DeepCwind Consortium, led by the University of Maine (UMaine), performed an extensive series of floating wind turbine model tests at the MARIN offshore basin. These tests, which were conducted at 1/50th scale, investigated the response of three floating wind turbine concepts subjected to simultaneous wind and wave environments. During these tests, it was found that the geometrically scaled wind turbine did not perform as expected in the low-Reynolds number wind environment. A new turbine was therefore built (the MARIN Stock Wind Turbine - MSWT) that produced better scaled thrust and torque loads (see de Ridder, et al. 2014 and Kimball, et al. 2014). This turbine was mounted on the semisubmersible previously tested in 2011, and retested in 2013. This retest is what will be examined in Phase II of the OC5 project.

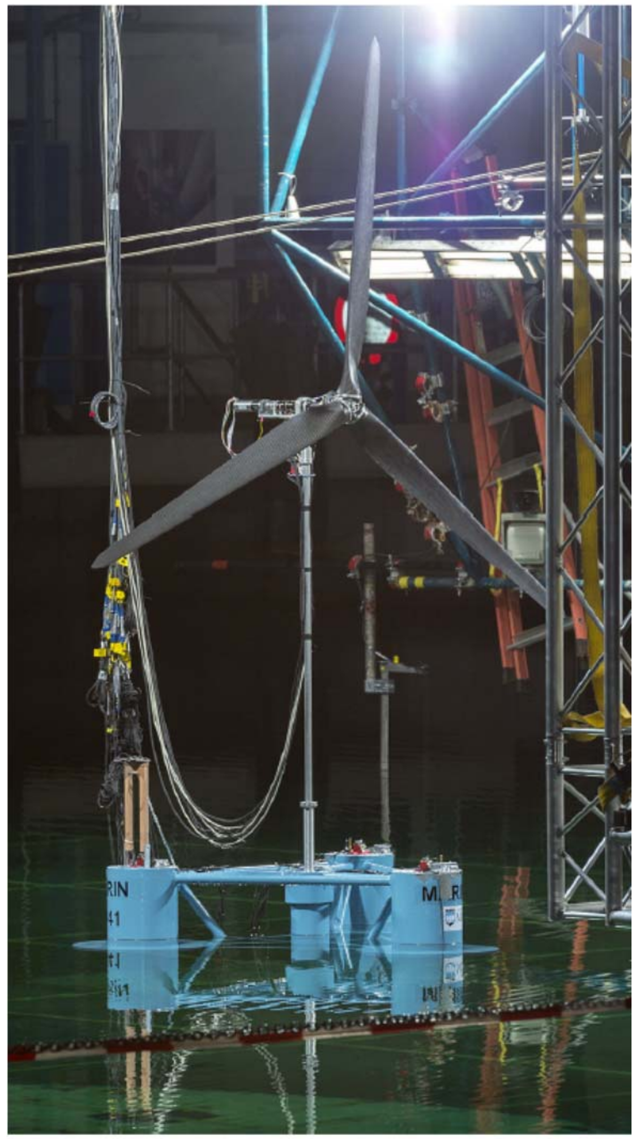


Figure 2-1: Instrumented OC5-DeepCwind model in basin (Helder, et al. 2013)

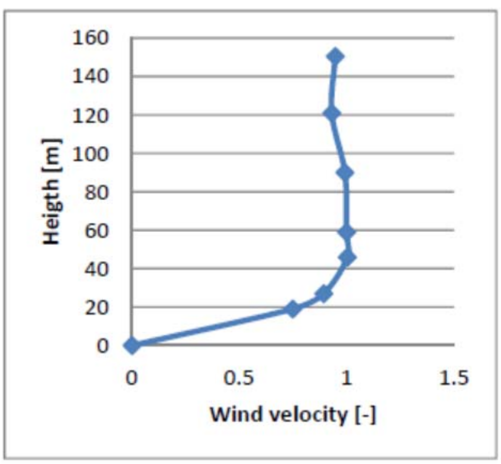
The turbine is a 1/50th-scale horizontal-axis model of the NREL 5-MW Reference Wind Turbine (Jonkman, et al 2009) with a flexible tower affixed atop a semisubmersible (semi). The system was tested under Froude-scaled wind and wave loads; see Jain (2012) for more details on the scaling process. The high quality wind environments, unique to these tests, were realized in the offshore basin via a novel wind machine that exhibits negligible swirl and low turbulence intensity in the flow field. Recorded data from the floating wind turbine models included rotor torque and position, tower-top and -base forces and moments, mooring line tensions, six-axis platform motions, and accelerations at key locations on the nacelle, tower, and platform. A large number of tests were performed ranging from simple free-decay tests to complex operating conditions with irregular sea states and dynamic winds.

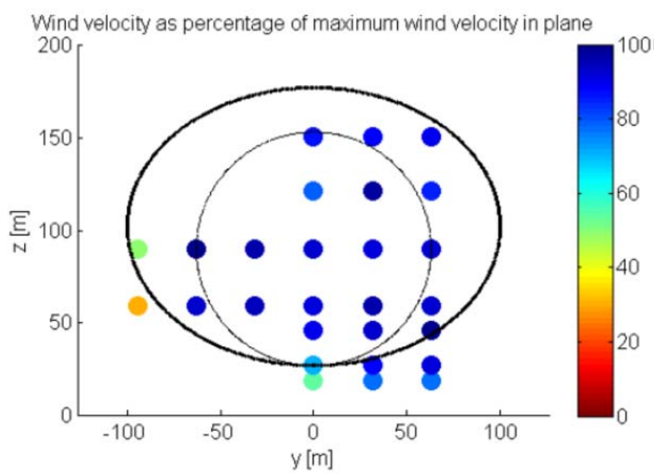
While in previous work with OC5 the systems have been modeled at model scale, all of the information in this report is presented at full (prototype) scale since MARIN provides the model and test data at full scale. Modeling for this phase will therefore be done at **full scale**.

2.1.1 Wind Generation at MARIN

The wind field in the basin was generated using a matrix of 35 fans in 5 rows. To improve the wind quality, each fan was equipped with a straightener, the fans were run in alternating directions (a checkerboard of clockwise and counter-clockwise rotation), two honeycomb screens were placed in front of the fans, and a nozzle was placed in between the screens to create an elliptical outlet. The result was a fairly homogeneous flow field with minimal swirl and low turbulence. The wind generation system is placed above the SWL to prevent interference with the passing waves. In order to cover the entire rotor with quality wind that isn't diminished in speed, the wind machine is tilted down slightly (2.5 degrees). The fetch is small enough (from machine to turbine), that wind-generated waves are not a problem. The resulting consistency of the wind field is shown in Figure 2-3. In addition, Figure 2-4 shows the resulting turbulence level of the flow field, which is approximately 5% for the majority of the turbine area. In these figures, the oval represents the first nozzle and the circle represents the rotor plane.

Figure 2-2: Front view of wind system (Helder, et al. 2013)





(a) Averaged vertical wind velocity profile (normalized)

(b) Wind field velocity in the rotor plane of the turbine

Figure 2-3: Wind velocity field consistency (Helder, et al. 2013)

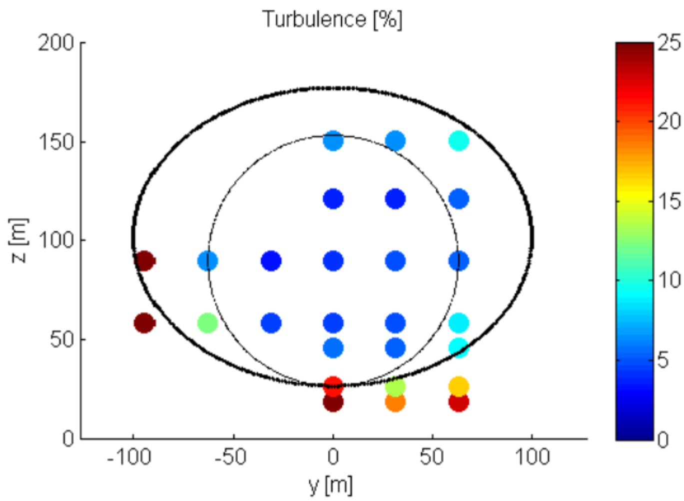


Figure 2-4: Wind velocity turbulence intensity in the rotor plane (Helder, et al. 2013)

Both steady and dynamic winds were generated. The calibrated mean wind velocities for the two steady wind velocity cases have values of 12.81 m/s (13.0 prescribed) and 21.19 (21.0 prescribed), respectively. The dynamic wind is prescribed using an NPD spectrum, which varies the mean velocity of the wind in time, but keeps the wind velocity constant across the flow field. Appendix A provides more information on the NPD spectrum.

2.1.2 Wave Generation at MARIN

Waves were generated using controlled flap-type wave makers. Waves can be generated in any direction, but for this project, we will only be looking at waves in one direction (straight at the turbine – 180 degrees).

2.2 Available Data

A large array of tests was performed at the MARIN wave basin to characterize the behavior of the systems in a variety of conditions. The tests performed include:

- Hammer tests to identify natural frequencies
- Static offset and free-decay tests
- Wave-only tests using both regular and irregular waves (operational, survival, and white noise)
- Wind-only tests with both steady and dynamic wind
- Combined wind/wave tests

A full list of the tests performed is given in Appendix B.

2.3 Measurements

The table below provides the list of measurements that were taken in the test campaign. All signals were sampled at a rate of 100 Hz model scale (14.142 Hz full scale), which results in a **time step of .0707 seconds** (full scale) for the recorded data. Analog signal measurements (wave height, motion, forces, and mooring tension) had an anti-aliasing filter applied prior to sampling the signal. A list of the output channels recorded for the tests is given in Appendix C.

Table 2-1: List of measurements

Measurement	Sensor	Location	Calibration
Wave height	Resistance-type wave probe	Neutral position of structure, and two side positions	Repeated measurements/ calibration performed without structure present
Wind velocity	Optical wind velocity meter	Reference point at HH	
Floater motion	NDI contactless optical measurement system	On column 1 (SBA), 50.75m above keel	
Loads at base of tower	Six-component strain gauge force transducer	In-line between tower and floater, 7.9 m above SWL	Before use, transducers cleaned and relationship between load and voltage assessed
Loads at top of tower	Six-component strain gauge force transducer	In-line between tower and turbine, 86.85 m above SWL	
Accelerations on columns	Piezo-type accelerometers (3-components)	Top of each offset column	
Acceleration at nacelle	Piezo-type accelerometers (3-components)	On tower, 99 m above keel	
Mooring tension	Ring-shaped strain gauge force transducers	At fairlead of each mooring line	
Turbine thrust	Strain gauge force transducer		Corrected for interaction with torque
Turbine torque	Strain gauge force transducer		Corrected for interaction with thrust
Turbine RPM	Main motor pulse signal		
Blade pitch	Potentiometer		

MARIN notes that all measured signals were zeroed prior to the tests. The recorded values are therefore with respect to their initial value at the equilibrium position of the model in still water with the mooring lines connected. One exception is that the measured still water pretensions in the mooring lines have been added to the measured values with respect to the equilibrium position in the post processing. The loads are presented as absolute values, including pretension.

In addition, analysis by NREL has shown that the initial position of the structure is not zero at the mean water level (MWL). The position at the MWL is derived from the optical measurement, which is measured on the top of column 1 (SBA), assuming no flexibility of the platform. From examination of the data, it appears that the equilibrium position changes for each test. MARIN speculates that this is due to hysteresis in the mooring lines, which can shift the equilibrium position from one test to another. To address this, we will be subtracting out initial values from the MARIN results. This value will be based on the initial recorded value for each test case prior to waves starting, but needs some further investigation.

2.3.1 Waves

The waves were calibrated prior to the model being placed in the water and are very repeatable by the wave maker. During this calibration, wave probe "WAVE CL" measured the waves at the location of the structure. This wave probe was then removed during the actual testing. However, analysis by NREL has indicated that there is some time lag between the measured values during calibration and individual tests. We therefore suggest using the WAVE 180 measurement (taken during the tests) for the wave prescription. This measurement is taken at the same distance from the wavemaker, but at a different horizontal position. Since there is no wave spreading, this measurement should be fairly similar to the waves seen at the actual structure.

The irregular waves used throughout the tests were JONSWAP spectra, and were adjusted such that the spectral density matched the theoretical value for 3-hours at full scale. A summary of the waves used in the tests, and the associated calibration test number are given in Table 2-2.

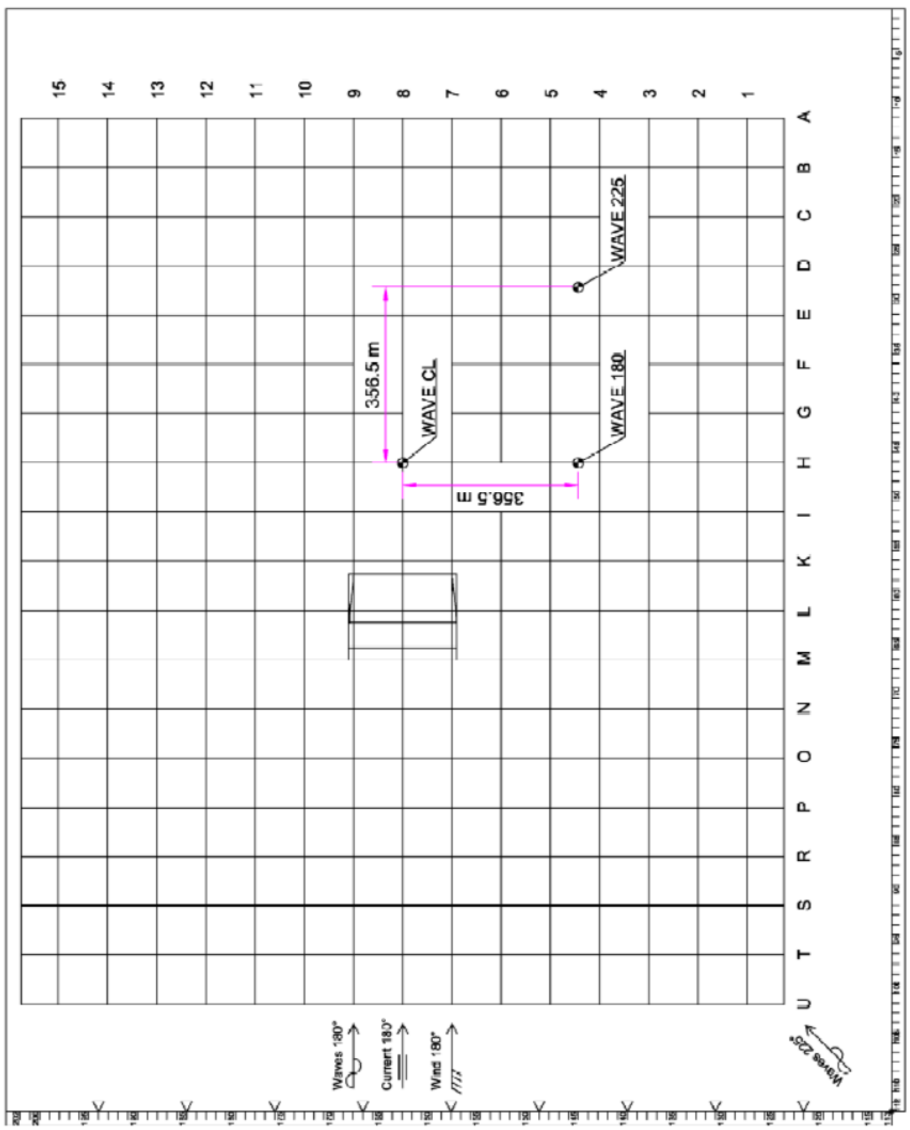


Figure 2-5: Location of wave measurements (Helder, et al. 2013)

Table 2-2: Calibration wave datasets without structure present

MARIN Test No.	Wave Condition	Duration	Wave Amp. (m) (4*√m0 for irreg.)	Tp (s)	Shape Factor
101001	Regular Wave 1	½+3 hrs	3.806	12.10	N/A
101002	Regular Wave 2	½+3 hrs	5.216	14.30	N/A
101010	Operation	½+3 hrs	7.1	12.10	2.20
101006	Design	½+3 hrs	10.5	14.30	3.00
101007	White Noise	½+3 hrs	10.5	N/A	N/A

2.3.2 Wind

During the calibration, the wind was measured at the neutral position of the nacelle (V WIND CL), which is located at the center line of the tower, 225 m downstream of the wind outlet, and 90 m above SWL. A second measurement was recorded (VWIND REF) in front of the wind turbine at 150 m downstream of the wind outlet and 134.05 m above the SWL. During the tests, only the wind probe in front of the turbine was used. For those wanting to use a direct time history of the wind field, we suggest using the measured wind values without the structure present (at the location of the turbine). The repeatability of the wind field, however, was not assessed. The wind time series at the neutral position of the nacelle is available in the following datasets, which includes the V WIND and VWIND REF measurements in the x and z-directions, as well as the wind direction (varies between 176 to 182 degrees).

Table 2-3: Reference wind datasets without structure present

MARIN Test No.	Wind Condition	Duration	Mean Wind Speed (m/s)
203010	Steady Wind 1	3 hrs	12.91
203011	Steady Wind 2	3 hrs	21.19
204006	Dynamic Wind 1	3 hrs	13.0
205003	Dynamic Wind 2	3 hrs	21.0

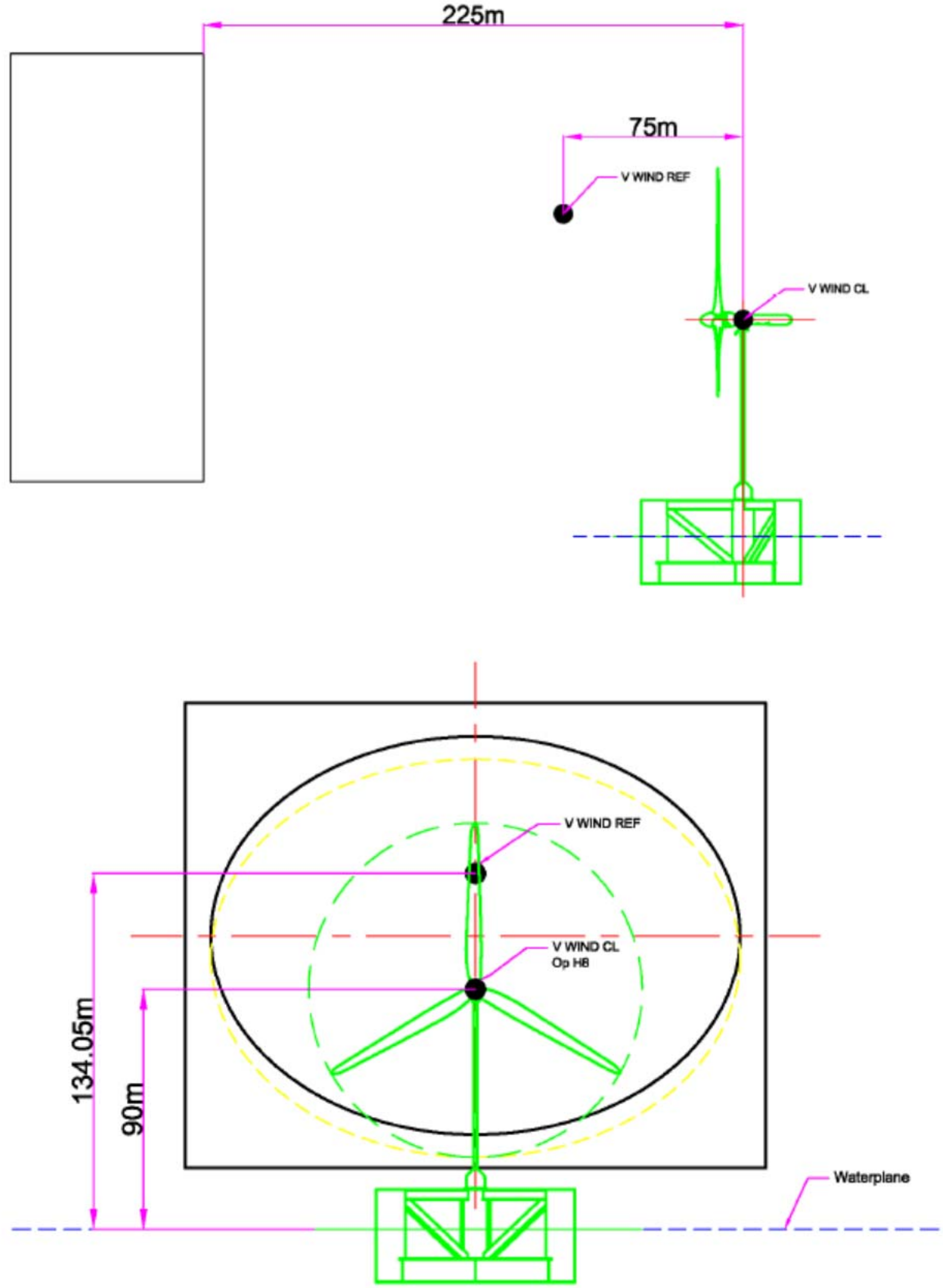


Figure 2-6: Wind measurement locations (Helder, et al. 2013)

2.3.3 System Motion

Appendix C provides a list of all the recorded outputs. The platform motion is given at the center of gravity (COG), at the mean water level (MWL), and at the location of the top accelerometer. These are derived quantities, translated from the actual measurement location of the NDI target. For this project, we will use the MWL derived values.

2.3.4 Thrust

The measured wind turbine thrust is corrected for the inertia of the nacelle as follows (Helder, et al. 2013). There is still some question about the validity of these equations, and we will need to investigate them further.

INRT T QT = M1 * AX TOP (inertia correction term)
T QT CORI = T QTTRANSD – INRT T QT (thrust corrected for inertia)

INRT FXTOP = M2 * AX TOP (inertia correction term)
FXTOP CORI = FX TOP + INRT FXTOP (thrust corrected for inertia)

where:

AX TOP	=	acceleration at the nacelle based on directly measured x-acceleration at the tower top accelerometer
M1	=	290.4 ton ; weight of the rotor (blades and rotor head) before the thrust transducer
M2	=	544.9 ton ; weight of the nacelle above the 6-component force frame

2.3.5 Coordinate System

The figures below show the location of the sensors and the coordinate system used for the measurements in the basin. In this representation, positive surge is the +X direction, positive sway is +Y, and positive heave is +Z. The MARIN coordinate system has the wind and waves traveling in the –X direction. **However, we will be modeling and simulating the system using the same coordinate system as OC4, which has the wind and waves traveling in the +X direction.** Figure 2-8 shows the coordinate system for the MARIN test data in the left image (a), and the modeling coordinate system in the right image (b). The difference is a simple rotation by 180 degrees about the Z axis. Comparisons between simulations and the measurements will be performed by rotating the MARIN results. Note, however, that the MARIN results uploaded to the website will not be altered. So, if you would like to use them, you will need to rotate the results yourself. The wind turbine is facing upwind, in the –X direction for simulations.

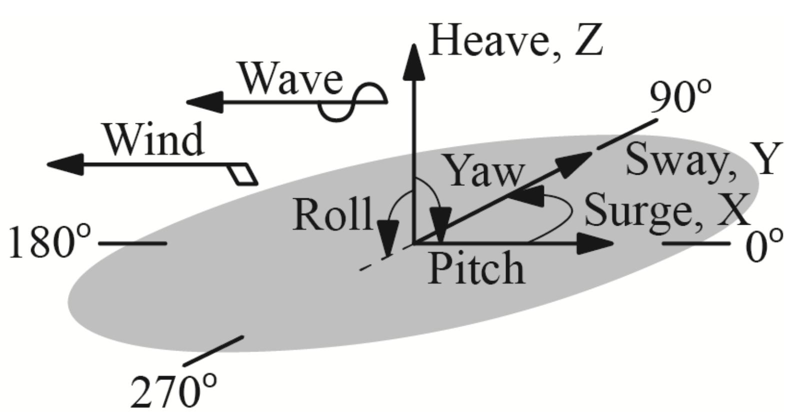
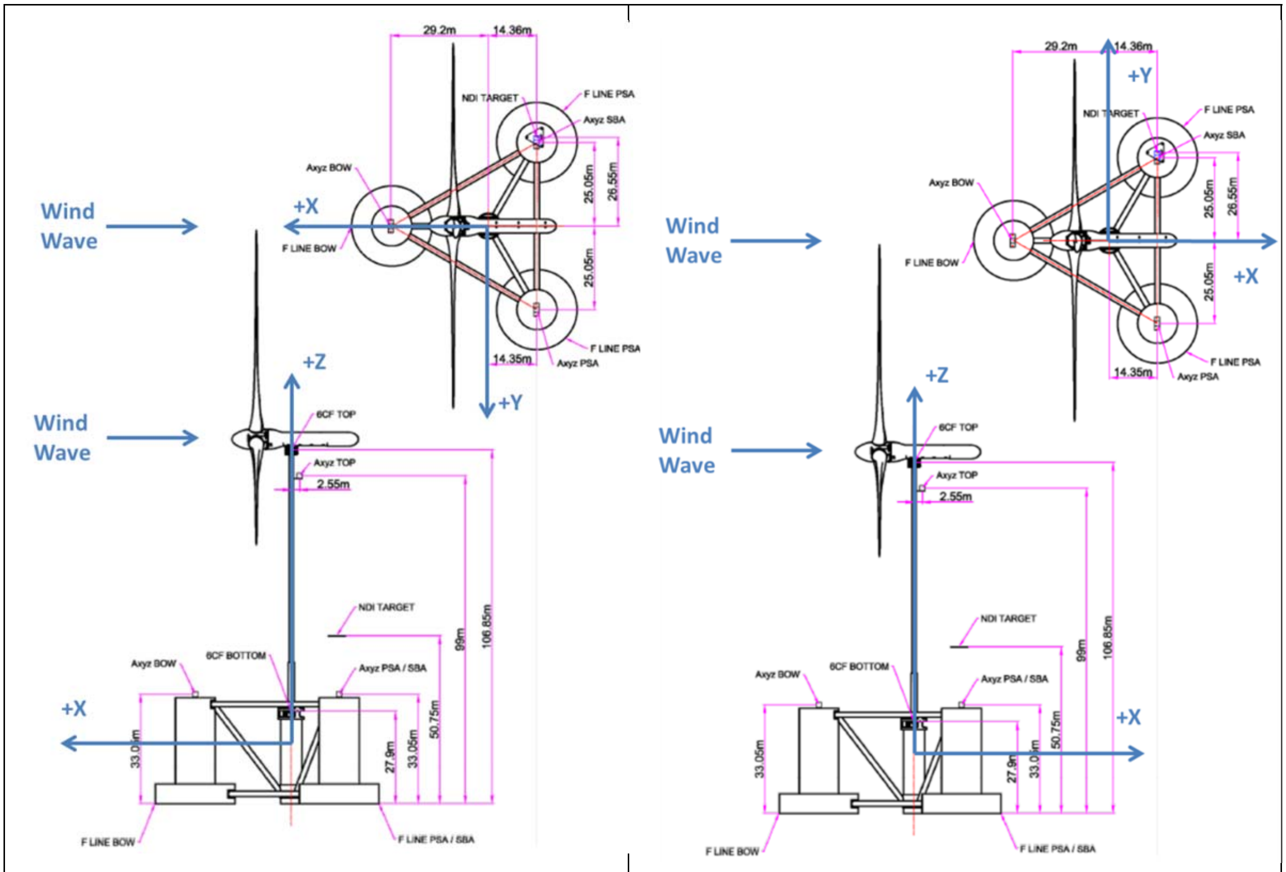


Figure 2-7: Degrees of freedom and environment orientations



(a) Coordinate System of MARIN Tests | **(b) Coordinate System for Simulations**

Figure 2-8: Measurement locations and coordinate system for data

2.4 Uncertainty Assessment

When doing validation against measured data, one should keep in mind that there is some level of uncertainty in the reported experimental values. The uncertainty can come from a variety of sources, including physical model and measurement uncertainty. Then, we need to consider how this uncertainty propagates through to the measured response quantities.

Assessment of the uncertainty in this test has just begun, and below is a list of the some of the components being considered.

2.4.1 Physical Model Uncertainty

The main components of the physical model uncertainty are:

- uncertainty in the installed properties of the system (mass, distribution, geometry)
- boundary conditions of installation

In these tests, we have seen that the mooring line has some hysteresis associated with it, creating an offset in the equilibrium position of the structure that is variable from test to test. This may affect our ability to accurately assess the surge offset of the structure due to wind and waves. A range in the equilibrium position will be assessed to set uncertainty limits on this estimation.

We have also seen that the static equilibrium does not match with the provided values for the mass, displacement, and mooring properties. Uncertainty in these parameters will need to be assessed and propagated to how they will affect the response of the system.

2.4.2 Measurement Uncertainty

Below is a list of the estimated uncertainty associated with the measurement equipment used in this experiment.

Table 2-4: Estimated Uncertainty of Measurement Equipment

Measured Quantity	Device Type	Sensor Manufacturer	Estimated uncertainty Model (full) scale
Wave at CL SET UP	Resistance type wave probes		1 mm (.05 m)
Wave at -9 m aft CL SET UP	Resistance type wave probes		1 mm (.05 m)
Wave at -18 m aft CL SET UP	Resistance type wave probes		1 mm (.05 m)
Wave at -9 m beside CL SET UP	Resistance type wave probes		1 mm (.05 m)
Wave beside of CL SET UP	Resistance type wave probes		1 mm (.05 m)
Wave beside and behind SET UP	Resistance type wave probes		1 mm (.05 m)
Wave beside of CL SET UP	Resistance type wave probes		1 mm (.05 m)
Wave beside and behind CL SET UP	Resistance type wave probes		1 mm (.05 m)
Wind beside of CL TLP [longitudinal]	Anemometer		
Wind beside of CL TLP [vertical]	Anemometer		
Wind direction	Anemometer?		
Longitudinal motion	Krypton optical measuring system	In-house Marin	0.1mm (5 mm)
Transverse motion	Krypton optical measuring system	In-house Marin	0.1mm (5 mm)
Vertical motion	Krypton optical measuring system	In-house Marin	0.1mm (5 mm)
Around longitudinal axis	Krypton optical measuring system	In-house Marin	0.1 deg
Around transverse axis	Krypton optical measuring system	In-house Marin	0.1 deg
Around vertical axis	Krypton optical measuring system	In-house Marin	0.1 deg
Longitudinal (LOW Position)	Accelerometer		
Transverse (LOW Position)	Accelerometer		
Vertical (LOW Position)	Accelerometer		
Longitudinal (MID Position)	Accelerometer		
Transverse (MID Position)	Accelerometer		
Vertical (MID Position)	Accelerometer		
Longitudinal (TOP Position)	Accelerometer		
Transverse (TOP Position)	Accelerometer		
Vertical (TOP Position)	Accelerometer		

Longitudinal force	Six-component force frame	In-house Marin	0.1% full-scale
Transverse force fore	Six-component force frame	In-house Marin	0.1% full-scale
Transverse force aft	Six-component force frame	In-house Marin	0.1% full-scale
Vertical force at port side fore	Six-component force frame	In-house Marin	0.1% full-scale
Vertical force at port side aft	Six-component force frame	In-house Marin	0.1% full-scale
Vertical force at starboard centre	Six-component force frame	In-house Marin	0.1% full-scale
Forces in Tendon 1	FZ shaped force transducers	In-house Marin	0.1% full-scale
Forces in Tendon 2	FZ shaped force transducers	In-house Marin	0.1% full-scale
Forces in Tendon 3	FZ shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #1	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #2	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #3	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #4	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #5	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #6	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #7	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #8	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #9	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #1 (semi)	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #2 (semi)	Ring shaped force transducers	In-house Marin	0.1% full-scale
Forces in mooring line #3 (semi)	Ring shaped force transducers	In-house Marin	0.1% full-scale

In addition to these measurement uncertainties, we have seen potential drift in the measurement due to perhaps calibrations not being done often enough or poor installation of the sensors. For instance, the MWL for the tests have been shown to vary. This level of uncertainty will be assessed.

Another area of uncertainty is in the complexity of the measurement quantity and the inability to form a complete representation, such as the metocean characteristics (full 3D field representation). The wind field, for instance, has been shown to have variable turbulence and wind velocity across the rotor. This variability is not measured during the tests and therefore cannot be modeled. Uncertainty bounds on these values will therefore need to be assessed.

3 Modeling Information

Much of the information provided in this section comes directly from measurements performed by MARIN and summarized in a project report (Helder, et al.). However, some modifications and improvements were needed due to insufficient fidelity of the information. Notes are made in the document when changes or additional information were needed compared to the value reported by MARIN and the reason why.

3.1 System Structural Properties

This first section gives the overall system properties needed for modeling, which are summarized in Table 3-1.

During initial static simulations, NREL found that the system with these properties was not in equilibrium for the prescribed draft. Of the three components that need to be balanced (mooring tensions, buoyancy, and weight), the University of Maine suggests that the mass of the system has the most uncertainty associated with it, due to additional mass from cables/sensors. The majority of the mass is found in the platform, and it is therefore suggested that this value should be modified to obtain equilibrium. However, it is suggested that the overall system CM remain unchanged.

Table 3-1: System Structural Properties (Neglecting Moorings)

Complete system mass	1.3958E+7 kg
Draft	20 m
Displacement	1.3917E+4 m^3
CM location below SWL	8.07 m
System roll inertia about CM	1.3947E+10 kg-m^2
System pitch inertia about CM	1.5552E+10 kg-m^2
System yaw inertia about CM	1.3692E+10 kg-m^2

The CM of the system tested in 2013 is higher than the value for the OC4 semi because of a heavier turbine in the former. This results in less hydrostatic restoring in roll and pitch and higher inertias, which produces larger natural periods for these DOFs (Goupee, 2014).

Table 3-2 summarizes the hydrodynamic properties of the system. The displaced water value comes from measurements performed for the 2011 tests. The system was rebuilt for the 2013 tests, but it is assumed there was little change in the external geometry of the platform. Note that the hydrostatic restoring values in roll and pitch only represent the buoyancy term, and do not include the weight.

Table 3-2: Floating Platform Hydrodynamic Properties

Water density (ρ)	1025 kg/m^3
Water depth (h)	200 m

Displaced water in undisplaced position (V_0)	13917 m^3
Center of buoyancy below SWL	13.15 m
Buoyancy force in undisplaced position ($\rho g V_0$)	1.3989E+8 N
Hydrostatic restoring in heave ($C_{33}^{Hydrostatic}$)	3.836E+06 N/m
Hydrostatic restoring in roll ($C_{44}^{Hydrostatic}$)	-3.776E+08 N-m/rad
Hydrostatic restoring in pitch ($C_{55}^{Hydrostatic}$)	-3.776E+08 N-m/rad

Table 3-3 provides the estimated system frequencies and damping for the 6 rigid body DOFs and the 1st tower bending, based on analysis of the test data by MARIN. The methodology used to derive the damping coefficients is provided in Appendix E.

Table 3-3: System Frequencies and Damping (Extracted from Test Data)

DOF	Frequency (Hz)	Period (s)	Damping Coeff. (linear, p) (quadratic, q)	Damping (%critical) linear quadratic	Comments
Surge	0.00937	106.7	0.1095 0.1242	1.743 39.55	MARIN extracted from Test 901012– Surge free decay
Sway	0.00890	112.3	0.0795 0.1265	1.265 42.39	MARIN extracted from Test 901013– Sway free decay
Heave	0.0571	17.5	0.0094 0.2733	0.1496 14.28	MARIN extracted from Test 901014– Heave free decay
Roll	0.0305	32.8	0.0648 0.0625	1.031 6.118	MARIN extracted from Test 901015– Roll free decay
Pitch	0.0308	32.5	0.0579 0.0686	0.9215 6.653	MARIN extracted from Test 901016– Pitch free decay
Yaw	0.0124	80.8	0.1446 0.0165	2.3014 3.978	MARIN extracted from Test 901017– Yaw free decay
Tower Bending F/A	0.315	3.18			NREL extracted from hammer test 901008
Tower Bending S/S	0.325	3.08			NREL extracted from hammer test 901009

3.2 RNA Properties

The turbine used in this test is a performance-scaled version of the NREL 5-MW wind turbine developed by MARIN in 2013, called the MARIN stock wind turbine (MSWT) (de Ridder et al., 2014). This 1/50th-scale performance-matched wind turbine is capable of generating appropriately scaled aerodynamic thrust forces under low-Reynolds number, Froude-scaled winds to emulate the full-scale NREL 5-MW reference wind turbine.

The gross properties of the RNA are given in the table below. The total top weight mass reported is the value given by MARIN, but the rotor mass was calculated by the University of Maine, and the nacelle mass was assigned as the difference between the total top mass and the rotor mass. The rotor mass just considers the weight of the three blades.

The CM location of the RNA reported in the table is that provided by MARIN. Examination by NREL indicates that this CM value may create a mean, static pitch offset larger than the actual system, which appears to be around 0.05 to 0.07 degrees. Andrew Goupee also notes that MARIN attempted to balance the system so that no pitch offset was present. These points would seem to indicate a smaller offset of the CM in the x-direction than the one reported here.

Table 3-4: Total RNA Structural Properties (MARIN Coordinate System)

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	None for this project
Rotor, Hub Diameter	126 m, 3 m
Hub Height (HH)	90 m
Elevation of Yaw Bearing above Ground	88.2 m
Vertical Distance along Yaw Axis from Yaw Bearing to Shaft	1.8 m
Rotor overhang, Shaft Tilt, Precone (from HH)	10.6 m, 0°, 0°
Rotor Mass (just blade mass)	6.70E+4 kg
Nacelle Mass	4.779E+5 kg
Hub mass	Accounted for in nacelle
Total top weight mass	5.449E+5 kg
CM location (relative to HH, center of tower)	(1.13 m, 0 m, 0 m)
RNA roll inertia about CM	6.6413E+07 kg-m^2
RNA pitch inertia about CM	8.5004E+07 kg-m^2
RNA yaw inertia about CM	8.5004E+07 kg-m^2

3.2.1 Blade Structural Properties

The blade structural properties were calculated by the University of Maine, and are summarized in the table below. The blades are very stiff and can therefore be considered rigid.

Table 3-5: Undistributed Blade Structural Properties

Length (w.r.t. Root along Axis)	61.5 m
Overall (Integrated) Mass	2.2333E+4 kg
Second Mass Moment of Inertia (w.r.t. Root)	1.48248E+7 kg-m^2
First Mass Moment of Inertia (w.r.t. Root)	4.5727E+5 kg-m^2
CM Location (w.r.t. root along Axis)	20.475 m

3.2.2 *Blade Aerodynamic Properties*

The distributed properties of interest for performing aerodynamic calculations with a standard BEM theory method are provided in Table 3-6. It is important to note that the properties assume a hub radius of 1.5 m and a tip radius of 63 m. Further information can be found in Kimball et al. (2014) and Goupee, et al. (2015). In addition, if a CAD model is desired, people may request this from Sebastien Gueydon at MARIN (S.Gueydon@marin.nl).

Table 3-6: Distributed Blade Aerodynamic Properties

Radius (m)	Twist (°)	Chord (m)	Airfoil Type (As Built/As Modeled)	Thickness (%)
1.500	50.377	3.500	Cylinder/Cylinder	100.0
2.898	42.712	4.410	Cylinder/Cylinder	100.0
5.607	31.187	5.229	Blend 1/Cylinder	40.1
8.316	23.109	5.581	Blend 2/AG04 Mod	18.3
11.781	16.389	5.794	Blend 3/AG04 Mod	14.6
15.876	11.475	5.796	Blend 4/AG04 Mod	13.3
19.971	8.502	5.576	Blend 5/AG04 Mod	12.8
24.066	6.523	5.297	AG04 Mod	12.6
28.161	5.052	5.006	AG04 Mod	12.6
32.256	3.878	4.706	AG04 Mod	12.6
36.351	2.939	4.392	AG04 Mod	12.6
40.446	2.216	4.078	AG04 Mod	12.6
44.541	1.673	3.775	AG04 Mod	12.6
48.636	1.245	3.480	AG04 Mod	12.6
52.731	0.844	3.190	AG04 Mod	12.6
56.196	0.497	2.914	AG04 Mod	12.6
58.905	0.235	2.651	AG04 Mod	12.6
61.614	0.064	1.747	AG04 Mod	12.6
63.000	0.000	0.050	AG04 Mod	12.6

AeroDyn v14-style dynamic stall parameters, and an AeroDyn v14 airfoil data input file, can be found in Appendix C. Note that the "Blend" airfoil section is not defined here, as it was found that just using the Cylinder and AG04 airfoils could be sufficient. Further details on the blade aerodynamic properties can be found in Goupee, et al. (2015).

3.3 Tower Properties

The tower design was focused on obtaining an appropriately scaled length, mass, center of gravity, and first natural bending frequency and mode shape. The original 2011 tower was made of two sections of standard 2024 hollow aluminum rods with the following geometry:

- The bottom section had an outer diameter (OD) of 33.66 mm (1.683 m full scale) and inner diameter (ID) of 25.4 mm (1.27 m full scale) and was 24.13 cm long (12.065 m full scale).
- The top rod had an OD of 25.4 mm at model scale (1.27 m full scale) and ID of 20.57 (1.0285 m full scale), and was 129.9 cm long (64.95 m full scale).
- 6.62 cm (3.31 m full scale) of the top rod length fit inside the bottom tower section such that the total length of the tower was 77.6 m long.

Figure 3-1 shows a schematic of the 2011 tower design. The 2013 tower design (used here for OC5) is the same, except that the top tower section was truncated to a total tower length of 75.5 m rather than 77.6 m, and the force gauge at the top was placed on top of the tower rather than through it. The force gauge for the 2013 design is 2.7 m long, thus the total length from tower base to the yaw bearing is 78.2 m (75.5 + 2.7). The top force gauge can be included as part of the tower, or as part of the nacelle. In the properties provided below, the force gauges at both the top and bottom of the tower have been included in the total tower properties. The bottom force gauge can be included with the rigid platform properties if preferred.

Table 3-7 provides the global properties of the tower, both with and without instrumentation included. Table 3-8 then provides some information about the location and mass of the instrumentation that is adding the additional weight. No information has been provided on the distributed stiffness, since this was not measured.

Table 3-7: Tower Properties

Elevation to Tower Base (Platform Top) Above SWL	10 m
Elevation to Tower Top (Yaw Bearing) Above SWL	88.2 m
Tower Mass	1.778E+5 kg
Total Tower Mass including Additional Instrumentation	4.935E+5 kg
CM Location of Tower Above SWL Along Tower Centerline (All Mass Included)	43.85 m

Table 3-8: Tower Distributed Mass Information

Designation	Symbol	Unit	Magnitude	
			Specified	As-built
Tower mass	M	ton	N/A	177.8
Tower Centre of Gravity above keel	KG	m	N/A	63.85
6-component frame top mass	M	ton	N/A	19.85
6-component frame top Centre of Gravity above keel	KG	m	N/A	106.85
6-component frame bottom mass	M	ton	N/A	139.9
6-component frame bottom Centre of Gravity above keel	KG	m	N/A	27.9
Accelerometer top mass	M	ton	N/A	15.63
Accelerometer top Centre of Gravity above keel	KG	m	N/A	99.0
Turbine measurement cables mass	M	ton	N/A	140.3
Turbine measurement cables Centre of Gravity above keel *)	KG	m	N/A	76.2

*) Value is tuned in technical drawing using results of inclination tests from the basin

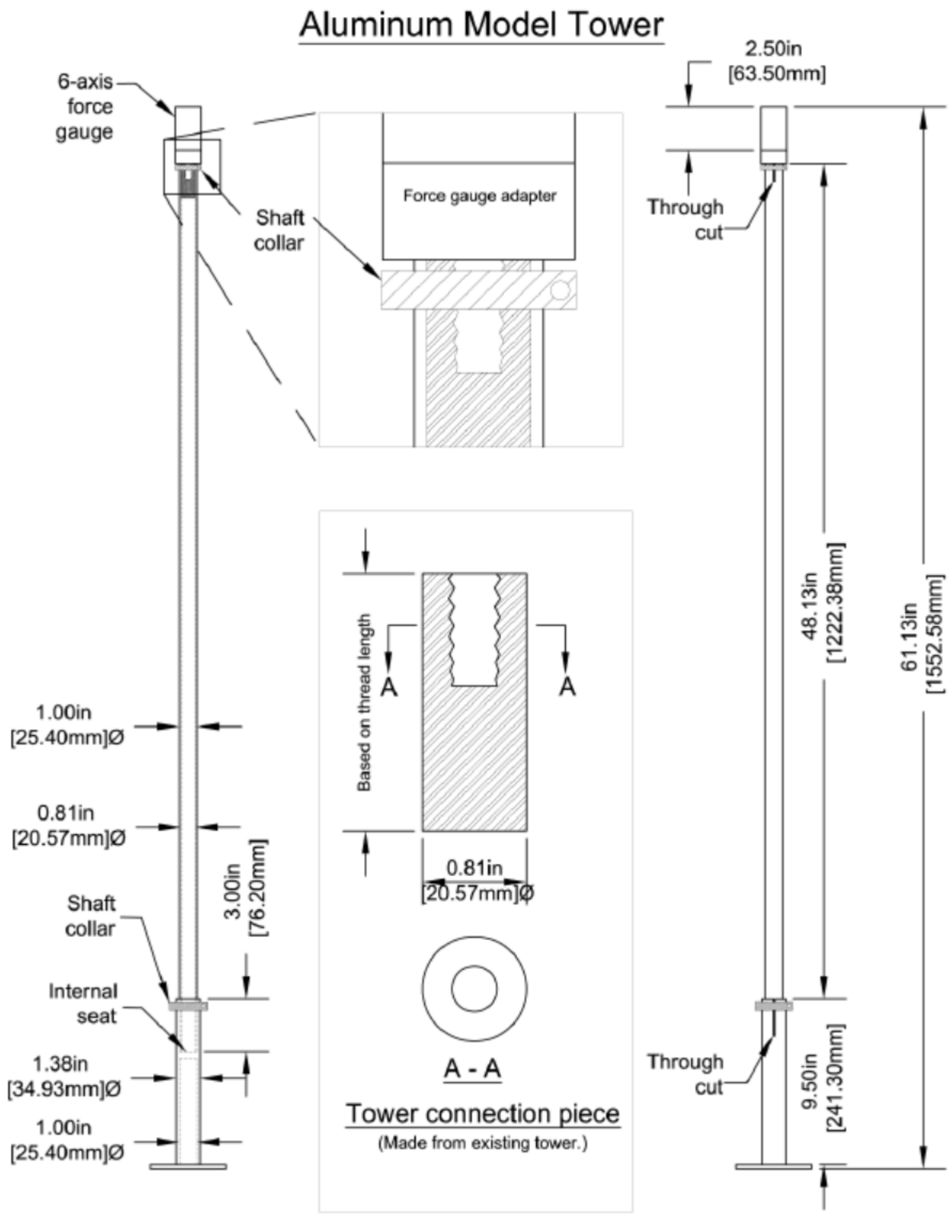


Figure 3-1: 2011 Tower Design at Model Scale (OC5 tower design is truncated version of this) [Martin, 2012]

3.4 Floating Platform Structural Properties

Table 3-9 summarizes the undisplaced platform properties. The inertias are found by multiplying MARIN provided radii of gyration (squared) by the mass of the platform. Again, it may be beneficial to modify the platform mass to obtain a system equilibrium. Note that these properties are for the platform only. Some may want to lump the six-axis force and moment transducer at the base of the tower in with these values so that it is considered as part of the more rigid platform, and not as part of the flexible tower.

Table 3-9: Floating Platform Structural Properties

Platform mass, including ballast	1.2919E+7kg
CM location below SWL	14.09 m
Platform roll inertia about CM	7.5534E+9 kg-m^2
Platform pitch inertia about CM	8.2236E+9 kg-m^2
Platform yaw inertia about CM	1.3612E+10 kg-m^2

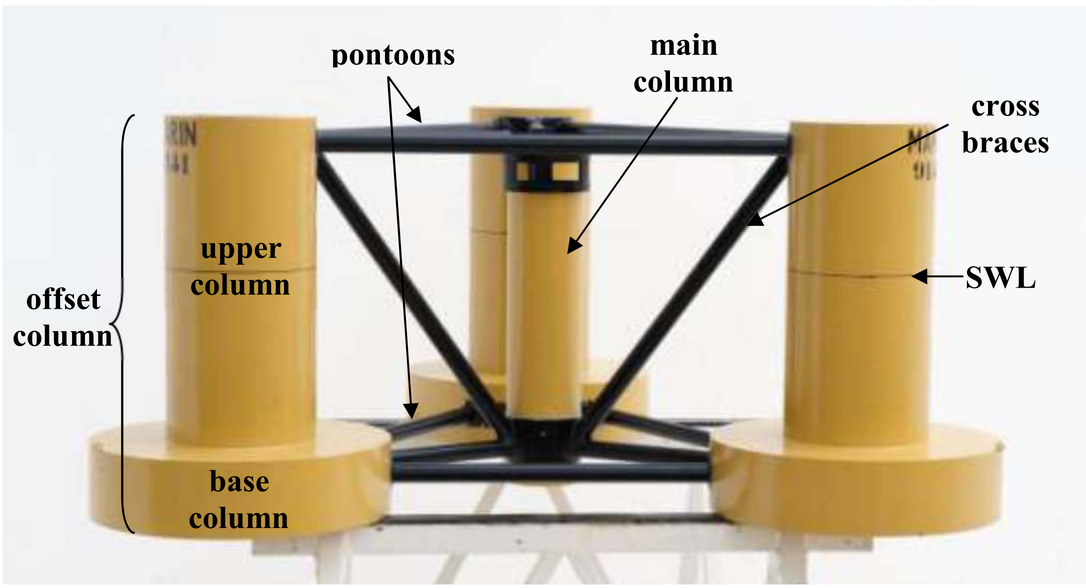


Figure 3-2: As-built picture of DeepCwind semisubmersible for 1/50th scale tests

3.4.1 General Properties

The tower is cantilevered at an elevation of 10 m above the SWL to the top of the main column (MC) of the floating platform. The draft of the platform is 20 m. Between the top and bottom of the platform, the OC5-DeepCwind semisubmersible consists of a main column attached to the tower, and three offset columns that are connected to the main column through a series of smaller diameter pontoons and cross members. There are five sets of these smaller members (members in black in Figure 3-1):

- Two sets of three pontoons (for a total of six members) connecting the offset columns with each other, forming a delta, both at the top (DU 1-3) and bottom (DL 1-3) of the semi
- Two sets of three pontoons (for a total of six members) connecting the offset columns with the main column, forming a y-connection, both at the top (YU 1-3) and bottom (YL 1-3) of the semi
- Three cross braces connecting the bottom of the main column with the top of the offset columns

Each offset column (UC 1-3) starts above the SWL and continues beneath the water. At the base of the three offset columns is a larger diameter cylinder, or base column (BC 1-3), which helps to suppress motion (particularly in the heave direction, but also in surge, sway, roll, and pitch). A summary of the geometry, including the diameters of each of the members is given in Table 3-10 and Table 3-11. These properties are all relative to the undisplaced position of the platform.

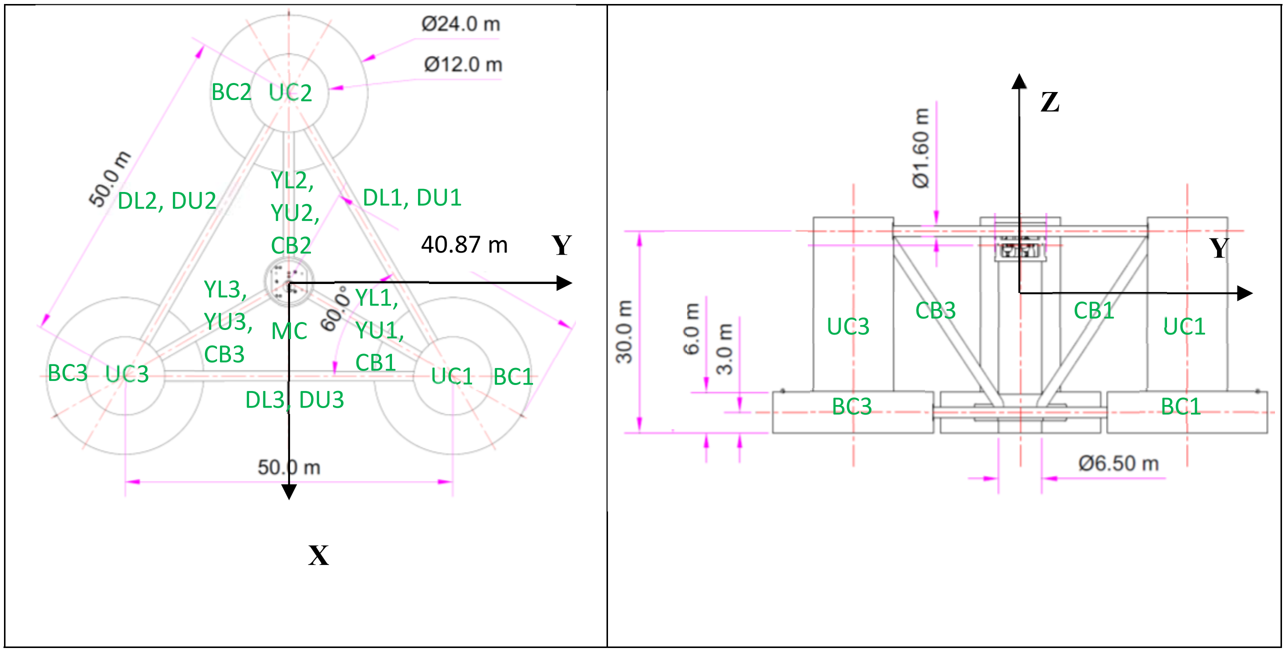


Figure 3-3: Plan (left) and Side (right) view of the DeepCwind Semisubmersible Platform (the mooring lines are numbered consistent with the column numbering)

Table 3-10: Floating Platform Geometry

Depth of platform base below SWL (total draft) – with moorings (without is 19.28 m)	20 m
Elevation of main column (tower base) above SWL	10 m
Elevation of offset columns above SWL	12 m
Spacing between offset columns	50 m
Length of upper columns	26 m
Length of base columns	6 m
Depth to top of base columns below SWL	14 m
Diameter of main column	6.5 m
Diameter of offset (upper) columns	12 m
Diameter of base columns	24 m
Diameter of pontoons and cross braces	1.6 m

Table 3-11: Member Geometry

Column Name	Abbr.	Start location (X,Y,Z)	End location (X,Y,Z)	Length (m)
Main Column	MC	(0, 0,-20)	(0, 0,10)	30
Upper Column 1	UC1	(14.43, 25, -14)	(14.43, 25, 12)	26
Upper Column 2	UC2	(-28.87, 0, -14)	(-28.87, 0, 12)	26
Upper Column 3	UC3	(14.43, -25, -14)	(14.43, -25, 12)	26
Base Column 1	BC1	(14.43, 25, -20)	(14.43, 25, -14)	6
Base Column 2	BC2	(-28.87, 0, -20)	(-28.87, 0, -14)	6
Base Column 3	BC3	(14.43, -25, -20)	(14.43, -25, -14)	6
Delta Pontoon, Upper 1	DU1	(9.20, 22, 10)	(-23.67, 3, 10)	38
Delta Pontoon, Upper 2	DU2	(-23.67, -3, 10)	(9.20, -22, 10)	38
Delta Pontoon, Upper 3	DU3	(14.43, -19, 10)	(14.43, 19, 10)	38
Delta Pontoon, Lower 1	DL1	(4, 19, -17)	(-18.47, 6, -17)	26
Delta Pontoon, Lower 2	DL2	(-18.47, -6, -17)	(4, -19, -17)	26
Delta Pontoon, Lower 3	DL3	(14.43, -13, -17)	(14.43, 13, -17)	26
Y Pontoon, Upper 1	YU1	(1.625, 2.815, 10)	(11.43, 19.81, 10)	19.62
Y Pontoon, Upper 2	YU2	(-3.25, 0, 10)	(-22.87, 0, 10)	19.62
Y Pontoon, Upper 3	YU3	(1.625, -2.815, 10)	(11.43, -19.81, 10)	19.62
Y Pontoon, Lower 1	YL1	(1.625, 2.815, -17)	(8.4, 14.6, -17)	13.62
Y Pontoon, Lower 2	YL2	(-3.25, 0, -17)	(-16.87, 0, -17)	13.62
Y Pontoon, Lower 3	YL3	(1.625, -2.815, -17)	(8.4, -14.6, -17)	13.62
Cross Brace 1	CB1	(1.625, 2.815, -16.2)	(11.43, 19.81, 9.13)	32.04
Cross Brace 2	CB2	(-3.25, 0, -16.2)	(-22.87, 0, 9.13)	32.04
Cross Brace 3	CB3	(1.625, -2.815, -16.2)	(11.43, -19.81, 9.13)	32.04

3.4.2 Material Properties

The columns of the platform are made of Styrodur® 3035 CS (a polystyrene foam), and steel weights are placed inside to achieve the reported CM location. All of the bracing in the platform are aluminum tubes with an external diameter of 1.6 m and thickness of 0.15 m. It is assumed that the platform can be considered rigid.

3.5 Mooring System Properties

3.5.1 Overview

To secure the platform, the OC5-DeepCwind semisubmersible is moored with three catenary lines spread symmetrically about the platform *Z*-axis. The lines are made of brass chain, with a small spring attached at the anchor point to obtain the correct overall axial stiffness, and a small load cell at the fairlead to measure the mooring loads. The mooring layout in the basin is shown in Figure 3-4. The geometric properties of the chain are listed in Table 3-12.

Table 3-12: Chain Properties

Chain nominal bar/wire diameter	0.0779 m
Chain length per number of links (link inner length)	0.4203 m
Chain link width (outer)	0.29 m

The fairleads (body-fixed locations where the mooring lines attach to the platform) are located at the top of the base columns, at a depth of 14.0 m below the SWL and at a radius of 40.87 m from the platform centerline. The anchors (fixed to the inertia frame) are located at a water depth of 200 m below the SWL and at a radius of 837.6 m from the platform centerline. One of the lines is directed along the positive *X*-axis (in the *XZ*-plane). The two remaining lines are distributed uniformly around the platform, such that each line, fairlead, and anchor is 120º apart when looking from above, as shown in Figure 5-1. These properties are relative to the undisplaced position of the platform. Each of the three lines has an unstretched length of 835.5 m.

The mooring line properties are summarized in Table 3-13. MARIN provided information about the length of the mooring lines, the mass of each of the mooring lines in air, the submerged weight, and the stiffness per unit length. The volume-equivalent mooring line diameter was then calculated from estimating the volume of the line needed to produce the reported submerged weight. The mooring line mass density is calculated by dividing the provided dry mass by the length of the line. While MARIN provided information about each individual line, it does not necessarily mean that each line was different. NREL suggests that participants use average homogenous values for each of the lines.

In addition, MARIN provided the value of the pretension in each of the three lines (with the system held still). MARIN uses a naming system for the mooring lines of SBA = Line 1, BOW = Line 2, PSA = Line 3. If using homogenous lines, one could address the pretension variation by varying the line length. Other participants may choose to modify the mooring properties themselves to try to obtain the provided preload values.

A large cable bundle is hanging off the tower, and could create additional stiffness and preload for the system. NREL's approach is to use homogenous mooring lines, and then add an artificial stiffness and preload (in the surge direction) to approximate the effect of the cable bundle on the motion of the system (essentially approximating it as an additional mooring). Part of the motivation to do this was that NREL found that the surge natural frequency is underapproximated using the average mooring properties, and applying an additional stiffness was needed to get the frequency closer to the MARIN value.

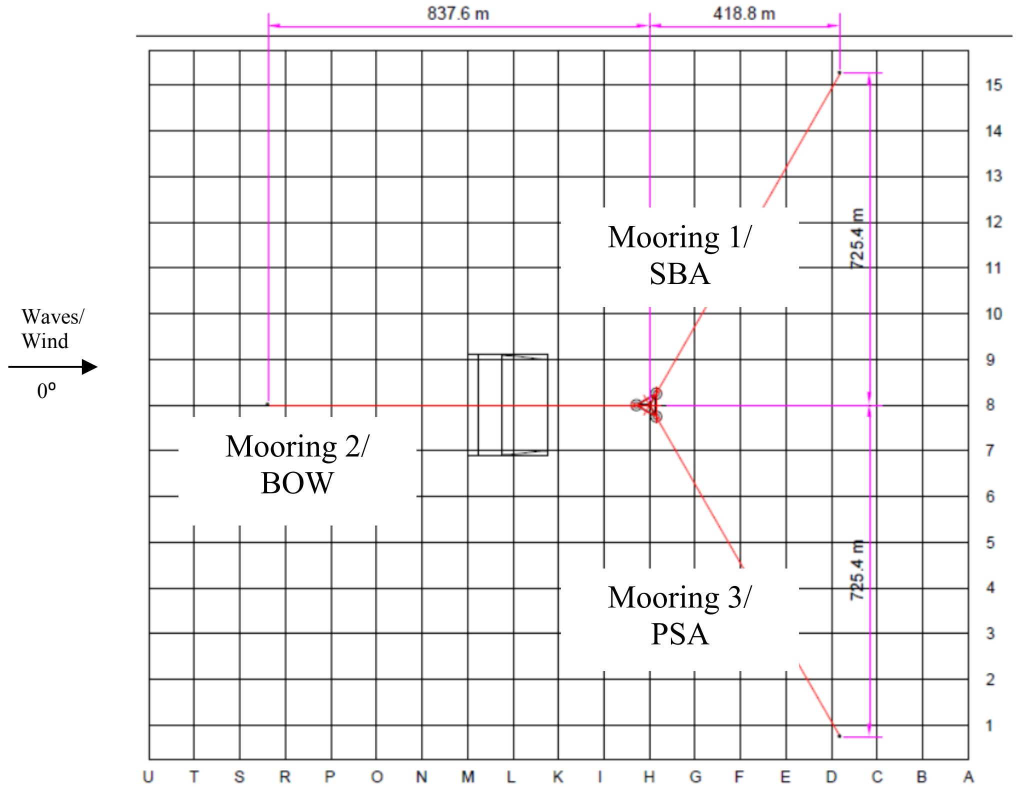


Figure 3-4: Mooring line arrangement

Table 3-13: Mooring System Properties

Number of Mooring Lines	3
Angle Between Adjacent Lines	120º
Depth to Anchors Below SWL (Water Depth)	200 m
Depth to Fairleads Below SWL	14 m
Radius to Anchors from Platform Centerline	837.6 m
Radius to Fairleads from Platform Centerline	40.868 m
Unstretched Mooring Line Length	835.5 m
Volume-Equivalent Mooring Line Diameter, Line 1 (SBA)	0.1369 m
Volume-Equivalent Mooring Line Diameter, Line 2 (BOW)	0.1398 m
Volume-Equivalent Mooring Line Diameter, Line 3 (PSA)	0.1393 m
Mooring Line Mass Density, Line 1 (SBA)	125.6 kg/m
Mooring Line Mass Density, Line 2 (BOW)	125.8 kg/m
Mooring Line Mass Density, Line 3 (PSA)	125.4 kg/m

Submerged Weight, Line 1 (SBA)	9.051 E+5 N
Submerged Weight, Line 2 (BOW)	9.017 E+5 N
Submerged Weight, Line 3 (PSA)	8.997 E+5 N
Equivalent Mooring Line Extensional Stiffness, Line 1	7.520E+8 N
Equivalent Mooring Line Extensional Stiffness, Line 2	7.461E+8 N
Equivalent Mooring Line Extensional Stiffness, Line 3	7.478E+8 N
Pretension, Line 1 (SBA)	1.107E+6 N
Pretension, Line 2 (BOW)	1.112E+6 N
Pretension, Line 3 (PSA)	1.148E+6 N

Table 3-14 and Table 3-15 provide further information about the fairlead forces in the mooring lines when the structure is displaced in the surge and sway directions compared to the analytically derived reference specification (labeled as "Theoretical"). Note that the FX and FY values are the total force in the x-direction and y-directions summed across all mooring lines.

Table 3-14: Static Offset Tests – Surge Direction

MARIN test No.	Offset [m]	FX (basin fixed) [kN]	FY (basin fixed) [kN]	Offset [m]	Theoretical FX [kN]	Theoretical FY [kN]
Surge - Direction						
				-20.0	3101	
401007	-19.84	3049.8	67.2	-18.0	2317	
401006	-15.81	1755.0	35.5	-16.0	1780	
401008	-14.92	1554.1	35.2	-14.0	1404	
401005	-11.92	1124.0	23.4	-12.0	1124	
401004	-7.76	671.0	16.0	-10.0	882	
401009	-4.87	392.2	10.9	-8.0	669	
401003	-3.87	309.3	8.2	-6.0	477	
401010	0.02	0.6	2.0	-4.0	305	
401011	1.54	-103.6	1.7	-2.0	146	
401014	2.44	-161.5	2.2	0.0	0	
401012	2.98	-201.3	1.7	2.0	-138	
401013	5.04	-334.2	2.0	4.0	-269	
				6.0	-395	

Table 3-15: Static Offset Tests – Sway Direction

MARIN test No.	Offset [m]	FX (basin fixed) [kN]	FY (basin fixed) [kN]	Offset [m]	Theoretical FX [kN]	Theoretical FY [kN]
Sway - Direction						
402005	-9.98	-98.13	762.07			
402004	-7.48	-50.6	557.29	-10.0		762
402006	-5.92	-29.0	431.9	-8.0		594
402003	-4.88	-16.8	361.3	-6.0		436
402007	-3.51	-7.4	256.5	-4.0		287
402002	-2.49	0.2	183.0	-2.0		142
402008	-0.01	2.6	-1.5	0.0		0
402009	2.45	-5.2	-175.0	2.0		-142
402014	3.46	-14.5	-246.8	4.0		-287
402010	5.00	-28.6	-364.2	6.0		-436
402013	5.94	-41.9	-431.9	8.0		-594
402011	7.45	-64.9	-554.7	10.0		-762
402012	9.93	-119.1	-761.6			
402005	-9.98	-98.13	762.07			

3.6 Control System Properties

A control system was tested, but will not be considered in this activity. All tests considered have no control applied (constant RPM, constant blade pitch, and fixed nacelle yaw).

4 Simulations

4.1 Simulation Specifications

4.2 Load Cases

The tables in the following sections provide details about the proposed load cases to be run.

4.2.1 LC 1.X – System ID and Calibration Cases

The first set of load cases, 1.X, focus on calibrating the model. For load cases 1.3 and 1.4, the goal is to derive the 6 rigid-body natural frequencies and damping, as well as the first tower bending frequencies in the fore/aft and side/side directions. Either free decay or eigenanalysis may be used to determine these values.

Based on review of the video of the free decay tests, the rotor appeared to be locked with one blade pointing downward along the tower during these tests.

Table 4-1: Load-Case Set 1, System ID – Calibration Cases

Load Case	Description	MARIN Test #	Initial Conditions	Blade Pitch (deg)	Sim. Length (min)	Output (for comparison)
1.1	Static equilibrium					Static position and loads
1.2a	Static Load - Surge	401003-401014	-19.84, -15.81, -14.92, -11.92, -7.76, -4.87, -3.87, 0.02, 1.54, 2.44, 2.98, 5.04	0	0	Check that mooring forces in x,y directions match specification
1.2b	Static Load - Sway	402002-402014	-9.98, -7.48, -5.92, -4.88, -3.51, -2.49, -0.01, 2.45, 3.46, 5.00, 5.94, 7.45, 9.93			Check that mooring forces in x,y directions match specification
1.3	Eigenanalysis					Natural frequencies and damping coeff.
1.4a	Free decay, surge	901012	Surge = 6.30 m	90	20	Natural frequencies and damping coeff. (p and q)
1.4b	Free decay, heave	901014	Heave = 2.13 m	0	10	Natural frequencies and damping coeff. (p and q)
1.4c	Free decay, pitch	901016	Pitch = 4 deg	90	10	Natural frequencies and damping coeff. (p and q)
1.4d	Free decay, yaw	901017	Yaw = 11.2 deg	90	20	Natural frequencies and damping coeff. (p and q)
1.5	Pitch Free Decay with Steady Wind 1	901019	Pitch = 7.84 deg RPM = 12.13 Wind speed = 12.91 m/s	1.16	415 sec.	Time Series
1.6	Pitch Free Decay with Steady Wind 2	901020	Pitch = 8.65 deg RPM = 12.13 Wind Speed = 21.19 m/s	16.9	240 sec.	Time Series

Participants will only need to supply results for LC 1.1, and either 1.3 or 1.4. The format for the results from these load cases are shown below. Just simple rows of data need to be supplied.

Table 4-2: Output for LC 1.1 – Static Equilibrium

Surge (m)	Sway (m)	Heave (m)	Roll (deg)	Pitch (deg)	Yaw (deg)	Mooring Tension1 (kN)	Mooring Tension2 (kN)	Mooring Tension3 (kN)	My Tower Bottom (kN-m)

Table 4-3: Output for LC 1.3 or 1.4 – Frequencies and Damping

	Surge	Sway	Heave	Roll	Pitch	Yaw	Tower 1st F/A	Tower 1st S/S	Tower 2nd F/A	Tower 2nd S/S
Frequency (Hz)										
Linear Damping - p										
Quadratic Damping - q										

4.2.2 LC 2.X – Wind Only Cases

The second set of simulations will focus on validating the response of the turbine when only wind is applied. The first two load cases will be used for calibration and examine the measured forces on the turbine from wind when the turbine is held fixed. The last three load cases will examine the motion response of the turbine to those loads. Note that the values provided in this table for wind speed and blade pitch may not match exactly those recorded in Appendix B. Here the measured values for the wind calibration are given, whereas Appendix B reports the prescribed values.

Table 4-4: Load-Case Set 2, Wind Only

Load Case	Description	MARIN Test #	RPM	Wind Speed (m/s)	Blade Pitch (deg)	Simulation length (min)	Output (for comparison)
2.1	Steady Wind 1 Turbine Fixed	303004	5.5 – 17.0	12.91	0.86	20	C_T and C_P vs RPM
2.2	Steady Wind 2 Turbine Fixed	303013	5.5– 17.0	21.19	15.0	20	C_T and C_P vs RPM
2.3	Steady Wind 1 On Semi	901025	12.13	12.91	1.22	20	6 DOF offset, mooring tensions, and My at bottom of tower
2.4	Steady Wind 2 On Semi	901026	12.12	21.19	17.5	20	6 DOF offset, mooring tensions,

							and My at bottom of tower
2.5	Dynamic Wind 1 On Semi	901027	12.13	NPD spectrum μ = 13.05	1.16	180	Time series Data Range for calibrated wind = Pts: [1:152735] Shift for exp with turbine = 25321

The format for the results for these load cases is given below, except for the time series. The output for all load cases requesting a time series is the same, and is summarized in Section 4.3.

LC 2.1 and 2.2:

Table 4-5: Output for LC 2.1 and 2.2

	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0
2.1 Ct																			
2.1 Cp																			
2.1 My Bottom																			
2.2 Ct																			
2.2 Cp																			
2.2 My Bottom																			

Table 4-6: Output for LC 2.3 and 2.4

Surge (m)	Sway (m)	Heave (m)	Roll (deg)	Pitch (deg)	Yaw (deg)	Mooring Tension1 (kN)	Mooring Tension2 (kN)	Mooring Tension3 (kN)	My Tower Bottom (kN-m)

4.2.3 LC 3.X – Wave Only Cases

The third set of load cases focuses on the response of the system to wave-only excitation. Two regular wave cases are examined, and three irregular cases. Make sure to run the simulation longer than the prescribed length, such that initial transients can be removed. The data range that we will be comparing to is given in the 'Wave Data Range' column. If inputting the wave elevation directly, you may want to start before this time point, and then only output in this range, to eliminate transients in your response. But, the results provided should start at time 0. For those creating their own regular waves, the selected region starts at a wave peak with decreasing magnitude – a cosine signal. Note, that the wave data supplied is the measured calibrated wave without the structure present. It is shifted in time slightly from the wave generated for the individual tests. So, when comparing simulations to the measured data, the measured data will need to be shifted by the "Shift" value shown in the wave data range column. The output for all load cases requesting a time series is the same, and is summarized in Section 4.3.

Table 4-7: Load-Case Set 3, Waves Only

Load Case	Descrip-tion	MARIN Test #	Blade Pitch (deg)	Wave Condition	Sim. Length (min)	Wave Data Range	Output (for comparison)
3.1	Regular Wave 1	902001	90	Regular Airy: H = 7.37 m, T = 12.07 s	20	Time = [883.1804 - 2083.2168] Pts = [12491:29462] 16972 total points Shift: 427	Time series
3.2	Regular Wave 2	902002	90	Regular Airy: H = 9.41 m, T = 14.3 s	20	Time = [888.9080-2088.9443] Pts = [12572:29543] 16972 total points Shift = -185	Time series
3.3	Operational Wave	906001	90	Irregular Airy: H_s = 7.1 m, T_p = 12.1 s, γ=2.2, JONSWAP spectrum	176	Pts for calibrated wave: [3395:152735] 149341 pts Shift to exp: 25459	Time series
3.4	Design Wave	907001	90	Irregular Airy: H_s = 10.5 m, T_p = 14.3 s, γ=3.0, JONSWAP spectrum	180	Pts for calibrated wave: [1:152735] Shift to exp: 416	Time series
3.5	White Noise Wave	915001	90	White noise, : H_s = 10.5 m, T_{range} =6-26 s	180	Pts for calibrated wave: [1:152735] Shift to exp: 334	Time series

4.2.4 LC 4.X – Combined Wind and Waves

The final set of load cases, LC 4.X, focus on the response of the system to combined wind and wave excitation. Make sure to run the simulation longer than the prescribed 3 hours, such that initial transients can be removed. The portion of the calibrated wave and dynamic wind that should be used for these load cases is the same for the wind-only and wave-only cases.

Table 4-8: Load-Case Set 4, Full-System Dynamics

Load Case	Description	MARIN Test #	RPM	Wind Condition (m/s)	Blade Pitch (deg)	Wave Condition	Sim. Length (min)
4.1	Operational Wave Steady Wind 1	906007	12.1	$V_{hub,x} = 12.91$ $V_{hub,z} = -0.3431$ $\sigma_x = 0.5456$ $\sigma_z = 0.2376$	1.0	Irregular Airy: H_s = 7.1 m, T_p = 12.1 s, γ=2.2, JONSWAP spectrum	180

4.2	Operational Wave Steady Wind 2	906006	12.1	$V_{hub,x}$ = 21.19 $V_{hub,z}$ = -0.6002 σ_x = 0.9630 σ_z = 0.4327	17.2	Irregular Airy: H_s = 7.1 m, T_p = 12.1 s, γ=2.2, JONSWAP spectrum	180
4.3	Operational Wave Dynamic Wind 1	906011	12.1	NPD spec., μ = 13.05	1.0	Irregular Airy: H_s = 7.1 m, T_p = 12.1 s, γ=2.2, JONSWAP spectrum	180
4.4	Design Wave Steady Wind 1	907002	12.1	$V_{hub,x}$ = 12.91 $V_{hub,z}$ = -0.3431 σ_x = 0.5456 σ_z = 0.2376	1.0	Irregular Airy: H_s = 10.5 m, T_p = 14.3 s, γ=3.0, JONSWAP spectrum	180
4.5	White Noise Wave Steady Wind 1	915002	12.1	$V_{hub,x}$ = 12.91 $V_{hub,z}$ = -0.3431 σ_x = 0.5456 σ_z = 0.2376	1.0	White noise, : H_s = 10.5 m, T_p =6-26 s	180

4.3 Outputs

When time series outputs are requested, this is the list of outputs that should be provided. The output files should have two header lines, and then 30 columns of data delimited by a space, comma, or semi-colon. The data should be output at 0.1 second intervals, starting at 0, for the full time length requested.

Table 4-9: Description of Outputs

Col. No.	OC5 Name	MARIN Name	Unit	Sensor description	Convention
1.	Time	Time	s	Simulation Time	Starts at 0s
2.	WindVxi	VXWIND CL	m/s	Longitudinal Wind Speed	Measured at the hub height in a free stream
3.	WindVzi				
4.	WaveElev	WAVE CL	m	Wave Elevation at Undisplaced Tower Centerline	Relative to SWL
5.	CP	CP		Power Coefficient	Positive when generating power, negative when motoring
6.	CT	CT		Thrust Coefficient	
7.	RotSpeed	RPM	rpm	Low-Speed Shaft Speed	Positive clockwise when looking downwind
8.	TTAccFA	X TOP ACC	m	Tower-Top Fore-Aft Acceleration	Absolute acceleration (relative to the inertial frame) measured in a local coordinate system at the accelerometer location, which is initially consistent with the tower coordinate system (translated), but translates and rotates with the platform motion and tower deflection.
9.	TTAccSS	Y TOP ACC	m	Tower-Top Side-to-Side Acceleration	
10.	PtfmSurge	X MWL	m	Platform translation in surge direction	Reference point is located at the intersection of the undisplaced tower centerline and SWL. Rotations are computed using Euler angles defined in
11.	PtfmSway	Y MWL	m	Platform translation in sway direction	
12.	PtfmHeave	Z MWL	m	Platform translation in heave direction	

13.	PtfmRoll	ROLL SEMI	deg	Platform rotation in roll direction	the yaw-pitch-roll rotation sequence. For codes which assume small rotational platform displacements, the rotation sequence does not matter.
14.	PtfmPitch	PITCH SEMI	deg	Platform rotation in pitch direction	
15.	PtfmYaw	YAW SEMI	deg	Platform rotation in yaw direction	
16.	YawBrFxp	FX TOP	kN	Tower-Top Fore-Aft Shear Force	Nacelle coordinate system (translates and rotates as platform moves and tower bends)
17.	YawBrFyp	FY TOP	kN	Tower-Top Side-to-Side Shear Force	
18.	YawBrFzp	FZ TOP	kN	Tower-Top Vertical Force	
19.	YawBrMxp	MX TOP	kNm	Tower-Top Side-to-Side Bending Moment	
20.	YawBrMyp	MY TOP	kNm	Tower-Top Fore-Aft Bending Moment	
21.	YawBrMzp	MZ TOP	kNm	Tower-Top Yawing Moment	
22.	TwrBsFxt	FX BOT	kN	Tower Base Fore-Aft Shear Force	Tower-base coordinate system (translates and rotates with platform)
23.	TwrBsFyt	FY BOT	kN	Tower Base Side-to-Side Shear Force	
24.	TwrBsFzt	FZ BOT	kN	Tower Base Vertical Force	
25.	TwrBsMxt	MX BOT	kNm	Tower Base Side-to-Side Bending Moment	
26.	TwrBsMyt	MY BOT	kNm	Tower Base Fore-Aft Bending Moment	
27.	TwrBsMzt	MZ BOT	kNm	Tower Base Yawing Moment	
28.	Fair1Ten	FLINE SBAT	kN	Line 1 fairlead (F1) tension	A positive value when in tension
29.	Fair2Ten	FLINE BOWT	kN	Line 2 fairlead (F2) tension	
30.	Fair3Ten	FLINE PSAT	kN	Line 3 fairlead (F3) tension	

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Appendix A: NPD Wind Spectrum (Helder, et al.)

For the dynamic wind spectra calibration, a time trace of the specified wind spectrum was generated and calibrated at nacelle height (90 m above still water level). For this, the NPD spectral formulation was used, resulting in the following definition for the spectral density of the wind profile:

$$S_U(\omega) = \frac{\left(\frac{320}{2\pi}\right)\left(\frac{U_0}{10}\right)^2\left(\frac{z}{10}\right)^{0.45}}{(1+t^n)^{5/3n}}$$

$$t = \left(\frac{172}{2\pi}\right)\omega\left(\frac{U_0}{10}\right)^{-0.75}\left(\frac{z}{10}\right)^{2/3}$$

With $S_U(\omega)$ [m^2/s] the spectral density of the wind velocity, ω [rad/s] the frequency, U_0 [m/s] the one hour mean wind speed at 10 m above sea level, z [m] the elevation above the mean sea level at nacelle height (z = 90 m) and n = 0.468.

Time traces were generated using the random phase method. The wind velocity amplitude is calculated with the specified spectral density for a particular frequency step size. The phases of the frequencies are randomly chosen. Phase values vary between 0 and 2π and are uniformly distributed.

$$U(t) = \sum_{i=1}^{N}\left[\sqrt{2S_U(\omega_i)d\omega}\cdot cos(\omega_i t + \varphi_i)\right] + U(90)$$

With U(t) [m/s] the wind velocity, $S_U(\omega_i)$ [m^2/s] the spectral density of the wind velocity for index "i", $d\omega$ [rad/s] the frequency step, ω_i [rad/s] the frequency for index "i", t [s] time, φ_i [rad] phase shift for index "i" and U(90) [m/s] the wind velocity at nacelle height.
The calibrated wind spectra can be found in Volume II of this report, and results are summarized in the table below.

Table 4-3: Calibrated dynamic wind spectra

Dynamic Wind Spectra (NPD)				
MARIN test No.	Wind condition	Specified velocity U_0 10 m above sea level [m/s]	Mean velocity at nacelle height, CL, in rotor plane	
			Specified [m/s]	Realized [m/s]
204006	Dynamic Wind 1	10.8	13.0	13.05
205003	Dynamic Wind 2	17.0	21.0	21.02

APPENDIX B: Test Matrices

Table A-1: Calibration and System ID Tests

	MARIN Test No.	Test Name	Time [hr]	Wave Characteristics				Wind Characteristics		
				Dir. [deg]	H_s [m]	T_p [s]	γ [-]	RPM	V_w [m/s]	Blade Pitch [deg]
Wind/Wave Calibration	101001	Regular Wave 1 Calibration		180	3.806	12.10	-	-	-	-
	101002	Regular Wave 2 Calibration		180	5.25	14.30	-	-	-	-
	101010	Operation Wave Calibration	½+3	180	7.1	12.10	2.20	-	-	-
	101006	Design Wave Calibration	½+3	180	10.5	14.30	3.00	-	-	-
	101007	White Noise Wave Calibration	½+3	180	10.5	-	-	-	-	-
	203010	Steady Wind 1 Calibration	3	-	-	-	-	-	13.0	-
	203011	Steady Wind 2 Calibration	3	-	-	-	-	-	21.0	-
	204006	Dynamic Wind 1 Calibration	3	-	-	-	-	-	13.0	-
	205003	Dynamic Wind 2 Calibration	3	-	-	-	-	-	21.0	-
Hammer Tests	901006	Hammer – Bottom – X-direction	-	-	-	-	-	-	-	-
	901007	Hammer – Bottom – Y-direction	-	-	-	-	-	-	-	-
	901008	Hammer – Top – X-direction	-	-	-	-	-	-	-	-
	901009	Hammer– Top – Y-direction	-	-	-	-	-	-	-	-
RPM Sweep Tests	303018	Const. Wind - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	7.0	1.0
	303019	Const. Wind - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	7.0	3.0
	303020	Const. Wind - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	7.0	5.0
	303002	Steady Wind 1 - RPM Sweep – Fixed	-	-	-	-	-	5.7-15.5	13.0	-1.0
	303003	Steady Wind 1 - RPM Sweep – Fixed	-	-	-	-	-	5.7-15.5	13.0	0.0
	303004	Steady Wind 1 - RPM Sweep – Fixed	-	-	-	-	-	5.7-15.5	13.0	1.0
	303005	Steady Wind 1 - RPM Sweep – Fixed	-	-	-	-	-	5.7-15.5	13.0	2.0
	303006	Steady Wind 1 - RPM Sweep – Fixed	-	-	-	-	-	5.7-15.5	13.0	3.0
	303007	Steady Wind 1 - RPM Sweep – Fixed	-	-	-	-	-	5.7-15.5	13.0	4.0
	303008	Steady Wind 1 - RPM Sweep – Fixed	-	-	-	-	-	5.7-15.5	13.0	5.0
	303009	Steady Wind 2 - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	21.0	1.0
	303010	Steady Wind 2 - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	21.0	3.0
	303011	Steady Wind 2 - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	21.0	5.0
	303012	Steady Wind 2 - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	21.0	10.0
	303013	Steady Wind 2 - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	21.0	15.0
	303014	Steady Wind 2 - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	21.0	20.0
	303016	Steady Wind 2 - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	21.0	25.0
	303017	Steady Wind 2 - RPM Sweep – Fixed	-	-	-	-	-	5.7-17.0	21.0	30.0
Static Load Tests	401007	Static Load, Surge Offset = -19.84 m	-	-	-	-	-	-	-	-
	401006	Static Load, Surge Offset = -15.81 m	-	-	-	-	-	-	-	-
	401008	Static Load, Surge Offset = -14.92 m	-	-	-	-	-	-	-	-
	401005	Static Load, Surge Offset = -11.92 m	-	-	-	-	-	-	-	-
	401004	Static Load, Surge Offset = -7.76 m	-	-	-	-	-	-	-	-
	401009	Static Load, Surge Offset = -4.87 m	-	-	-	-	-	-	-	-
	401003	Static Load, Surge Offset = -3.87 m	-	-	-	-	-	-	-	-
	401010	Static Load, Surge Offset = 0.02 m	-	-	-	-	-	-	-	-
	401011	Static Load, Surge Offset = 1.54 m	-	-	-	-	-	-	-	-
	401014	Static Load, Surge Offset = 2.44 m	-	-	-	-	-	-	-	-
	401012	Static Load, Surge Offset = 2.98 m	-	-	-	-	-	-	-	-
	401013	Static Load, Surge Offset = 5.04 m	-	-	-	-	-	-	-	-
	402005	Static Load, Sway Offset = -9.98 m	-	-	-	-	-	-	-	-
	402004	Static Load, Sway Offset = -7.48 m	-	-	-	-	-	-	-	-
	402006	Static Load, Sway Offset = -5.92 m	-	-	-	-	-	-	-	-
	402003	Static Load, Sway Offset = -4.88 m	-	-	-	-	-	-	-	-
	402007	Static Load, Sway Offset = -3.51 m	-	-	-	-	-	-	-	-
	402002	Static Load, Sway Offset = -2.49 m	-	-	-	-	-	-	-	-

	402008	Static Load, Sway Offset = -0.01 m	-	-	-	-	-	-	-	-
	402009	Static Load, Sway Offset = 2.45 m	-	-	-	-	-	-	-	-
	402014	Static Load, Sway Offset = 3.46 m	-	-	-	-	-	-	-	-
	402010	Static Load, Sway Offset = 5.00 m	-	-	-	-	-	-	-	-
	402013	Static Load, Sway Offset = 5.94 m	-	-	-	-	-	-	-	-
	402011	Static Load, Sway Offset = 7.45 m	-	-	-	-	-	-	-	-
	402012	Static Load, Sway Offset = 9.93 m	-	-	-	-	-	-	-	-
Free Decay	101011	Pitch Free Decay, no cables	-	-	-	-	-	-	-	90
	901012	Surge Free Decay	-	-	-	-	-	-	-	90
	901013	Sway Free Decay	-	-	-	-	-	-	-	0
	901014	Heave Free Decay	-	-	-	-	-	-	-	0
	901015	Roll Free Decay	-	-	-	-	-	-	-	0
	901016	Pitch Free Decay	-	-	-	-	-	-	-	90
	901017	Yaw Free Decay	-	-	-	-	-	-	-	90
	901019	Pitch Free Decay *2, Steady Wind 1	-	-	-	-	-	-	13.0	1.0
	901020	Pitch Free Decay *1, Steady Wind 2	-	-	-	-	-	-	21.0	17.2

Table A-2: Wind/Wave Test Matrix

	MARIN Test No.	Test Name	Time [hr]	Wave Characteristics				Wind Characteristics		
				Dir. [deg]	H_s [m]	T_p [s]	γ [-]	RPM	V_w [m/s]	Blade Pitch
Wind Only	901025	Steady Wind 1	1	-	-	-	-	12.1	13.0	1.0
	901026	Steady Wind 2	1	-	-	-	-	12.1	21.0	17.2
	901027	Dynamic Wind 1	½+3	-	-	-	-	12.1	13.0	1.0
	901030	Dynamic Wind 2	½+3	-	-	-	-	12.1	21.0	17.2
Wave Only	902001	Regular Wave 1	½	180	7.1	12.1	-	0.0	-	90.0
	902002	Regular Wave 2	½	180	10.5	14.3	-	0.0	-	90.0
	906001	Operational Wave	½+3	180	7.1	12.1	2.2	0.0	-	90.0
	907001	Design Wave	½+3	180	10.5	14.3	3.0	0.0	-	90.0
	915001	White Noise Wave	½+3	180	10.5	6-26	-	0.0	-	90.0
Wind+Waves	906007	Operation Wave + Steady Wind 1	½+3	180	7.1	12.1	2.2	12.1	13.0	1.0
	906006	Operation Wave + Steady Wind 2	½+3	180	7.1	12.1	2.2	12.1	21.0	17.2
	906011	Operation Wave + Dynamic Wind 1	½+3	180	7.1	12.1	2.2	12.1	13.0	1.0
	906005	Operation Wave + Dynamic Wind 2	½+3	180	7.1	12.1	2.2	12.1	21.0	17.2
	907002	Design Wave + Steady Wind 1	½+3	180	10.5	14.3	3.0	12.1	13.0	1.0
	907003	Design Wave + Dynamic Wind 1	½+3	180	10.5	14.3	3.0	12.1	13.0	1.0
	915002	White Noise Wave + Steady Wind 1	½+3	180	10.5	6-26	-	12.1	13.0	1.0

APPENDIX C: Channels in Output Files

Column #	Channel Name	Units
1	TIME	's'
2	'WAVE 180	'm '
3	'WAVE 225	'm '
4	'V WIND REF '	'm/s '
5	'VWIND VERT '	'm/s '
6	'WIND DIR '	'deg '
7	'ROLL SEMI '	'deg '
8	'PITCH SEMI '	'deg '
9	'YAW SEMI '	'deg '
10	'AX BOW '	'm/s2 '
11	'AY BOW '	'm/s2 '
12	'AZ BOW '	'm/s2 '
13	'AX PSA '	'm/s2 '
14	'AY PSA '	'm/s2 '
15	'AZ PSA '	'm/s2 '
16	'AX SBA '	'm/s2 '
17	'AY SBA '	'm/s2 '
18	'AZ SBA '	'm/s2 '
19	'AX TOP '	'm/s2 '
20	'AY TOP '	'm/s2 '
21	'AZ TOP	'm/s2 '
22	'FLINE BOWT	'kN '
23	'FLINE PSAT	'kN '
24	'FLINE SBAT	'kN '
25	'RPM '	'rpm '
26	'T QTTRANSD	'kN '
27	'Q QTTRANSD	'kNm '
28	'PITCHBLADE '	'deg '
29	'X COG '	'm '
30	'Y COG '	'm '
31	'Z COG '	'm '
32	'X MWL '	'm '
33	'Y MWL '	'm '
34	'Z MWL '	'm '
35	'X TOP ACC '	'm '
36	'Y TOP ACC '	'm '
37	'Z TOP ACC '	'm '
38	'ROLL ACC '	'deg/s2 '
39	'PITCH ACC '	'deg/s2 '
40	'YAW ACC '	'deg/s2 '
41	'AX COG '	'm/s2 '
42	'AY COG '	'm/s2 '
43	'AZ COG '	'm/s2 '
44	'AX MWL '	'm/s2 '
45	'AY MWL '	'm/s2 '
46	'AZ MWL '	'm/s2 '
47	'AX TOP ACC '	'm/s2 '
48	'AY TOP ACC '	'm/s2 '
49	'AZ TOP ACC '	'm/s2 '
50	'FX TOP '	'kN '
51	'FY TOP '	'kN '
52	'FZ TOP '	'kN '
53	'MX TOP '	'kNm '
54	'MY TOP '	'kNm '
55	'MZ TOP '	'kNm '
56	'FX BOT '	'kN '
57	'FY BOT '	'kN '
58	'FZ BOT '	'kN '
59	'MX BOT '	'kNm '
60	'MY BOT '	'kNm '
61	'MZ BOT '	'kNm '
62	'OMEGA '	'rad/s '
63	'TSR '	'- '
64	'CT '	'- '
65	'CT 6CF TOP '	'- '
66	'CP '	'- '
67	'CP 6CF TOP '	'- '
68	'INRT T QT '	'kN '
69	'INRT FXTOP '	'kN '
70	'T QT CORI '	'kN '
71	'FXTOP CORI '	'kN '
72	'CT CORI '	'kN '
73	'CT6CF CORI'	'kN '

APPENDIX D

Round Root Section with a CD of 0.50

Coefficients obtained as documented in ISOPE 2015-TPC-0174

1	Number of airfoil tables in this file
0	Table ID parameter
0.0	No longer used, enter zero
0.0	No longer used, enter zero
0.0	No longer used, enter zero
0.0	Stall angle (deg)
0.0	Zero Cn angle of attack (deg)
0.0	Cn slope for zero lift (dimensionless)
0.0	Cn extrapolated to value at positive stall angle of attack
0.0	Cn at stall value for negative angle of attack
0.0	Angle of attack for minimum CD (deg)
0.50	Minimum CD value

-180	0	0.5
0	0	0.5
180	0	0.5

MARIN Stock Wind Turbine AG04 Mod Airfoil

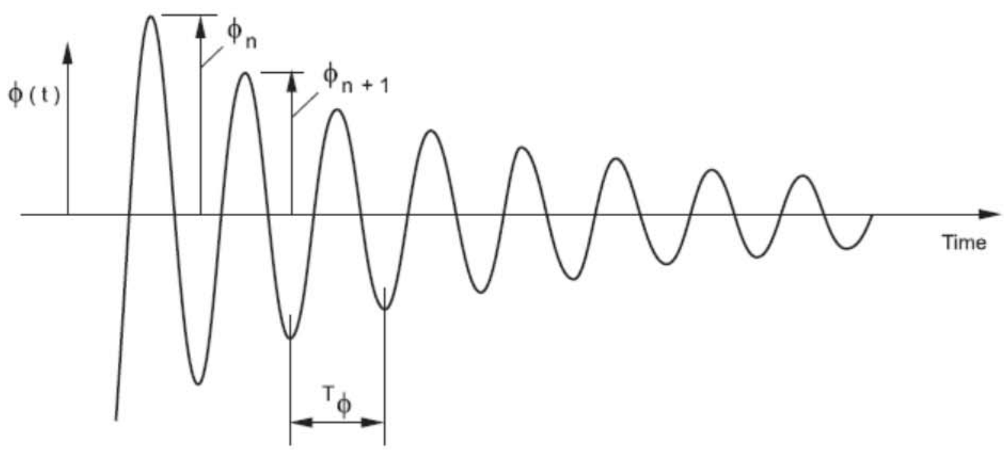
Coefficients obtained as documented in ISOPE 2015-TPC-0174

1	Number of airfoil tables in this file
0	Table ID parameter
0.0	No longer used, enter zero
0.0	No longer used, enter zero
0.0	No longer used, enter zero
6.00	Stall angle (deg)
-0.7360	Zero Cn angle of attack (deg)
6.5004	Cn slope for zero lift (dimensionless)
0.7642	Cn extrapolated to value at positive stall angle of attack
-0.8000	Cn at stall value for negative angle of attack
-0.50	Angle of attack for minimum CD (deg)
0.0218	Minimum CD value

-180	0.0000	0.0625
-170	0.4660	0.0993
-160	0.4280	0.2053
-150	0.4650	0.3674
-140	0.4840	0.5656
-130	0.4620	0.7755
-120	0.3960	0.9710
-110	0.2890	1.1278
-100	0.1520	1.2261
-90	0.0000	1.2530
-80	-0.1692	1.2261
-70	-0.3193	1.1278
-60	-0.4360	0.9710
-50	-0.5087	0.7755
-40	-0.5350	0.5656
-30	-0.5184	0.3674
-20	-0.4825	0.2053
-10	-0.5208	0.0992
-9.0	-0.5199	0.0880
-8.0	-0.5166	0.0765
-7.0	-0.5100	0.0650
-6.0	-0.4993	0.0537
-5.0	-0.4838	0.0428
-4.5	-0.4277	0.0378
-4.0	-0.3713	0.0341
-3.5	-0.3149	0.0310
-3.0	-0.2584	0.0285
-2.5	-0.2017	0.0265
-2.0	-0.1451	0.0249
-1.5	-0.0883	0.0237
-1.0	-0.0314	0.0228
-0.5	0.0255	0.0218
0.0	0.0824	0.0221
0.5	0.1393	0.0220
1.0	0.1963	0.0221
1.5	0.2532	0.0224
2.0	0.3101	0.0231
2.5	0.3669	0.0239
3.0	0.4237	0.0252
3.5	0.4804	0.0265
4.0	0.5370	0.0282
4.5	0.5935	0.0305
5.0	0.6500	0.0338
5.5	0.7063	0.0382
6.0	0.7625	0.0422
6.5	0.7619	0.0495
7.0	0.7603	0.0625
7.5	0.7579	0.0807
8.0	0.7544	0.0926
8.5	0.7500	0.1019
9.0	0.7456	0.1099
9.5	0.7423	0.1179
10	0.7410	0.1270
11	0.7482	0.1482
12	0.7679	0.1708
13	0.7970	0.1946
14	0.8322	0.2191
15	0.8706	0.2441
16	0.9090	0.2693
17	0.9442	0.2943
18	0.9733	0.3188
19	0.9930	0.3425
20	1.0002	0.3650
25	0.9534	0.4683
30	0.8794	0.5668
35	0.8284	0.6597
40	0.7807	0.7487
45	0.7354	0.8359
50	0.6890	0.9183
60	0.5803	1.0627
70	0.4187	1.1705
80	0.2183	1.2351
90	0.0000	1.2530
100	-0.1520	1.2261
110	-0.2890	1.1278
120	-0.3960	0.9710
130	-0.4620	0.7755
140	-0.4840	0.5656
150	-0.4650	0.3674
160	-0.4280	0.2053
170	-0.4660	0.0993
180	0.0000	0.0625

Appendix E: Damping Coefficient Methodology (Helder, et al.)

From the recorded decay curves of motion decay tests, the natural period and damping coefficients can be derived. The figure below shows a typical time trace for a decay test of a lightly damped motion, e.g. roll for a free floating ship.



in which:

$\phi(t)$ = time trace of motion ϕ

ϕ_n = motion amplitude of n-th oscillation, [m], [deg]

T_ϕ = natural period of motion ϕ, [s]

Equation of motion

It is assumed that the motion $\phi(t)$ in the free extinction test can be described by the following equation of motion:

$$a_{\varphi\varphi} \cdot \ddot{\varphi} + b^{(1)}_{\varphi\varphi} \cdot \dot{\varphi} + b^{(2)}_{\varphi\varphi} \cdot \dot{\varphi} \cdot |\dot{\varphi}| + c_{\varphi\varphi} \cdot \varphi = 0$$

in which:

$a_{\phi\phi}$ = total mass (ship mass + added mass) in mode of motion ϕ, [t], [t.m^2]

$b^{(1)}_{\varphi\varphi}$ = linear damping coefficient in mode of motion ϕ, [kNs/m], [kNms/rad]

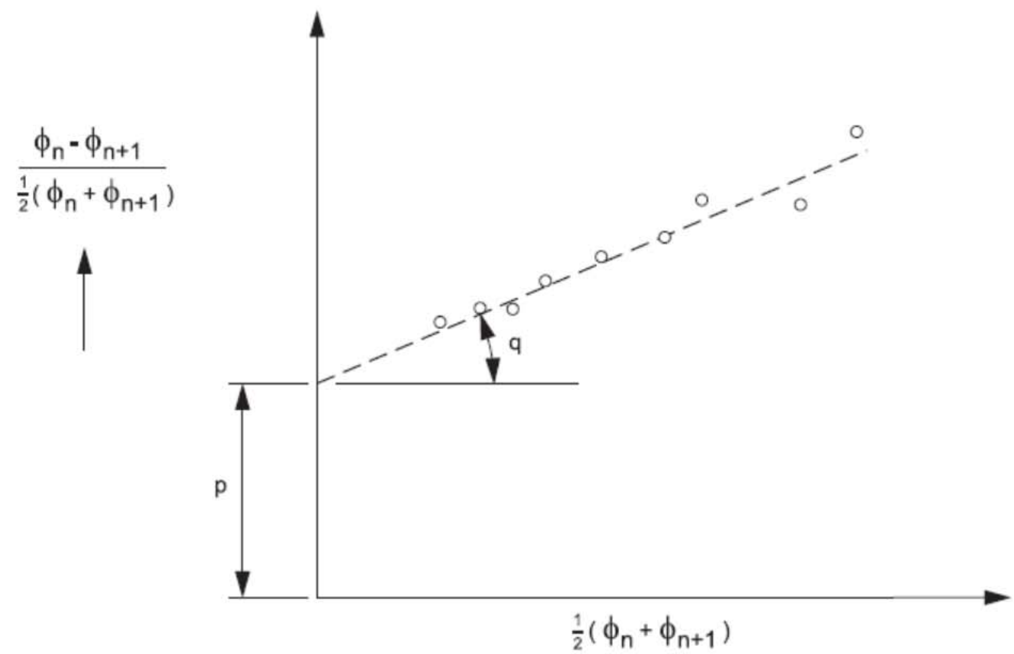
$b^{(2)}_{\varphi\varphi}$ = quadratic damping coefficient in mode of motion ϕ, [kNs^2/m^2], [kNms^2/rad^2]

$c_{\phi\phi}$ = restoring coefficient in mode of motion ϕ, [kN/m], [kNm/rad]

Now the time traces recorded in the motion decay tests can be analysed in a number of different manners, assuming a system with linear damping only (first analysis method) or assuming a system with both linear and quadratic damping (second analysis method). Furthermore, it is possible to make a qualitative estimate of the damping level (third analysis method). All three methods are further explained in this appendix.

Linear and quadratic damping (Method 2)

The linear and quadratic damping coefficients can be obtained from the results of a motion decay test in the following manner. First, the decrease of motion amplitude divided by the mean motion amplitude is plotted against the mean motion amplitude, see the plot below.



The values for p and q are determined by fitting a line through the data points found from the decay tests. The coefficients p and q can be used to calculate the linear and quadratic damping coefficients $b^{(1)}$ and $b^{(2)}$, through the following formulas.

$$b^{(1)} = 2 \cdot p \cdot \frac{\Delta + a_{11}}{T_0}$$

$$b^{(2)} = \frac{3}{8} \cdot q \cdot (\Delta + a_{11})$$

in which:

$b^{(1)}$ = linear roll damping, [kNms/rad]

$b^{(2)}$ = quadratic roll damping, [kNms^2/rad^2]

The equivalent linearized damping at a particular amplitude x_a can be calculated from the linear and quadratic damping by:

$$b_x = 2 . (p + q . x_a) . \frac{a_x}{T_x} = b_x^{(1)} + b_x^{(2)} \frac{16}{3} \frac{x_a}{T_x}$$

in which:

x_a = amplitude at which damping decay is linearized

Combination of the formulas above with the formulas for the natural period and critical damping of an undamped linear system allows to express these damping values as percentage of critical damping:

$$B^{(1)} = \frac{p}{2.\pi}.100\%$$

$$B^{(2)} = \frac{\frac{3}{8} \cdot q \cdot T_0}{4.\pi}.100\%$$

in which:

$B^{(1)}$ = linear roll damping coefficient, [% $B_{critical}$]

$B^{(2)}$ = quadratic roll damping coefficient, [% $B_{critical}$]

T_0 = natural period (s)

Δ = vessel displacement (t)

a_{11} = low frequency added mass (t)