Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

Project acronym	LIFES50+
Grant agreement	640741
	Collaborative project
Start date	2015-06-01
Duration	40 months

Deliverable D4.2 Public Definition of the Two LIFES50+ 10MW Floater Concepts

Lead Beneficiary	University of Stuttgart
Due date	2017-05-31
Delivery date	2018-04-12
Dissemination level	public
Status	Final
Classification	Unrestricted

Keywords	Floating wind turbine, public models, LIFES50+, semi-submersible
Company document number	Click here to enter text.

The research leading to these results has received funding from the European Union Horizon2020 programme under the agreement H2020-LCE-2014-1-640741.

Disclaimer

The content of the publication herein is the sole responsibility of the publishers and it does not necessarily represent the views expressed by the European Commission or its services.

While the information contained in the documents is believed to be accurate, the authors(s) or any other participant in the LIFES50+ consortium make no warranty of any kind with regard to this material including, but not limited to the implied warranties of merchantability and fitness for a particular purpose.

Neither the LIFES50+ Consortium nor any of its members, their officers, employees or agents shall be responsible or liable in negligence or otherwise howsoever in respect of any inaccuracy or omission herein.

Without derogating from the generality of the foregoing neither the LIFES50+ Consortium nor any of its members, their officers, employees or agents shall be liable for any direct or indirect or consequential loss or damage caused by or arising from any information advice or inaccuracy or omission herein.

Document information

Version	Date	Description	
01	2017-04-28	First Draft	
		Prepared by	Wei Yu, Kolja Müller, Frank Lemmer
		Reviewed by	Henrik Bredmose, Michael Borg, Amy Robertson, Maxime Thys, Petter Andreas Berthelsen, Gustavo Sanchez, Trond Landbø
		Approved by	Wei Yu
02	2017-07-04	Final version with first set of platform concepts	
		Prepared by	Kolja Müller, Frank Lemmer, Wei Yu
		Reviewed by	Henrik Bredmose, Michael Borg, Friedemann Borisade Maxime Thys, Petter Andreas Berthelsen, Trond Landbø
		Approved by	Wei Yu
03	2017-12-21	Draft version with second set of platform concepts	
		Prepared by	Kolja Müller, Frank Lemmer, Wei Yu
		Reviewed by	Henrik Bredmose, Michael Borg, Friedemann Borisade Maxime Thys, Petter Andreas Berthelsen, Trond Landbø
		Approved by	Wei Yu
04	2018-03-19	Final version with second set of platform concepts	
		Prepared by	Kolja Müller, Frank Lemmer, Wei Yu
		Reviewed by	Maxime Thys, Josean Galvan
		Approved by	Wei Yu
Final	2018-04-12	Final version for QA before submission	
		Prepared by	Kolja Müller, Frank Lemmer, Wei Yu
		Reviewed by	Jan Arthur Norbeck
		Approved by	Petter Andreas Berthelsen

Authors	Organization
Wei Yu	USTUTT
Kolja Müller	USTUTT
Frank Lemmer	USTUTT

Contributors	Organization
Christian Molter	USTUTT
Ricardo Faerron Guzmán	USTUTT
Friedemann Borisade	USTUTT
David Schlipf	USTUTT
Henrik Bredmose	DTU
Michael Borg	DTU
Josean Galvan	TECNALIA
Miren Josune Sánchez-Lara	TECNALIA
Iñigo Mendikoa	TECNALIA
Trond Landbø	Olav Olsen
Håkon Andersen	Olav Olsen

Definitions & Abbreviations	
AST	Administrative Support Team
PC	Project Coordinator
PM	Project Manager
WPL	Work Package Leader
SISO	Single-Input-Single-Output
TLP	Tension-Leg Platform
MSL	Mean Sea Level
RNA	Rotor-Nacelle Assembly
DOF	Degree of Freedom
DTU	Technical University of Denmark
DLL	Dynamic-Link-Library
CM	Centre of Mass
C_D	Drag Coefficient for Morison's Equation
KC	Keulegan-Carpenter number
Re	Reynolds number
H_s	Significant wave height
T_p	Peak wave period
ζ	Damping Ratio
δ	Log Decrement
η_0	Amplitude of Oscillation
ν	Kinematic Viscosity
ω_{dt}	Drivetrain natural frequencies
$\omega_{eig,sg}$	Surge natural frequencies

Executive Summary

This report compiles the information of design results for substructures for DTU 10 MW floating wind turbine. The two concepts are public versions of a four-column semi-submersible (NAUTILUS-10 floating substructure) and a semi-submersible by Olav Olsen (LIFES50+ OO-Star Wind Floater Semi 10MW). The public versions have been defined by Olav Olsen, NAUTILUS S.L. and TECNALIA, University of Stuttgart and DTU for the purpose of physical model testing and numerical research in the LIFES50+ project. While the public concepts may have similarities with real commercial designs, the specifications of the public concepts can by no means be taken as confirmed values for any commercial design. It is expected, though, that the two public designs will be of benefit for wider research on floating wind turbines due to their open specification.

The concepts are defined for a water depth of 130m and were initially up-scaled from the existing substructure concepts for 5MW wind turbine of Olav Olsen and NAUTILUS. The focus lies on the definition of geometries, structural dynamic and basic hydrodynamic properties, which allow the reader to set up a numerical or experimental model. Further detail with respect to e.g. hydrodynamic coefficients will be addressed in future work of LIFES50+.

The resulting designs will be tested with a down scaled model in WP3 in both wave tank (SINTEF) and wind tunnel (POLIMI). Based on the description of this deliverable, two numerical FAST models will be developed. The FAST models will be released as deliverable D4.5 of LIFES50+. Additionally, high fidelity models for investigation of advanced load effects will be established and the results of the experimental model tests will be used for the validation of these numerical models.

Contents

1 Introduction

The second stage of the LIFES50+ project puts the focus on the two selected concepts and their in-depth investigation and optimization. In order to do these both numerically (WP4) and experimentally (WP3), a definition of the platforms to be used is provided in this report. It describes the two floating support structure concepts for the DTU 10MW reference wind turbine. The focus lies on the definition of geometries, structural dynamic and basic hydrodynamic properties, which allow the reader to set up a numerical or experimental model on a system level. A public numerical FAST8 model will be provided in LIFES50+ deliverable 4.5, [1]. In Chapter 2, relevant information of the DTU 10MW reference turbine is summarized. The LIFES50+ OO-Star Wind Floater Semi 10MW concept, based on the OO-Star concept [2] is presented in Chapter 3. Chapter 4 introduces the *NAUTILUS-10* floating substructure, which is developed inside the LIFES50+ project as well.

The coordinate system used for the support structure is identical to the conventional definition in offshore wind, see Figure 1. The coordinate system origin is fixed to the Mean Sea Level (MSL), at the centre of flotation of the floating platform (centroid of the water plane area) in calm water in equilibrium position without aerodynamic or hydrostatic forcing. The six different motion components are named as surge, sway, heave, roll, pitch, and yaw. The surge direction points to the nominal downwind direction.

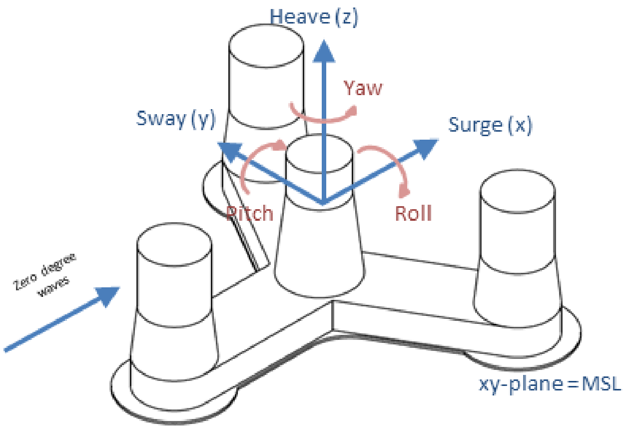

Figure 1: Coordinate system, wind and waves assumed co-aligned

1.1 Acknowledgements

We are grateful to both selected designers of LIFES50+ for the good collaboration and the efforts put in the publication of their designs. Dr. techn. Olav Olsen AS for the permission and contribution to set up the public semi-submersible design based on their concept of the OO Star Wind Floater (www.olavolsen.no) and Nautilus Floating Solutions for providing the full FAST model of the *NAUTILUS-10* floating substructure (www.nautilusfs.com) and the support writing the present document.

1.2 Public FAST Models

Public FAST Models of the herein presented public models have been derived as part of LIFES50+ efforts. A summary of this together with public FAST models is provided in LIFES50+ deliverable D4.5 [1], as well as links to download locations. As research on the public models is expected to continue, the authors of this study propose to communicate any beneficial variations or updates of the public models with the primary hosts of the models. This will help to organize the available versions and hence facilitate and harmonize future research to the best extend possible.

2 DTU 10MW Reference Wind Turbine Data

Characteristics of the components of the considered DTU10 MW reference wind turbine such as structural and aerodynamic properties as well as design calculations are provided in [4] and [5].

2.1 Structural Properties

Table 1 gives the overall mass properties of the rotor and the nacelle. Inertia values are calculated assuming a locked rotor. The presented values may be used for frequency analysis e.g. in BModes.

Table 1: Mass properties of the DTU 10MW reference wind turbine

Property	Unit	Value
Rotor mass	[kg]	230 717[1]
Rotor centre of mass	[m, m, m]	[-7.07, 0, 119]
Nacelle mass	[kg]	446 006[1]
Nacelle centre of mass	[m, m, m]	[2.69, 0, 118.08]
Nacelle, rotor and hub vertical centre of mass	[m]	118.39
Combined tower top masses	[kg]	676 723
Combined tower top masses centre of mass	[m, m, m]	[-0.939, 0, 2.789]
Roll moment of inertia of tower top masses[2] around tower top	[kg m^2]	1.659E+08
Pitch moment of inertia of tower top masses around tower top	[kg m^2]	1.062E+08
Yaw moment of inertia of tower top masses around tower top	[kg m^2]	1.014E+08

[1] Based on the DTU 10MW reference turbine [4].
[2] i.e. combined nacelle, rotor and hub masses

3 Platform Design 1: LIFES50+ OO-Star Wind Floater Semi 10MW

The LIFES50+ semi-submersible concept consists of a star-shaped base pontoon, which connects a central column and three outer columns. The structure is built out of post-tensioned concrete. The mooring system is a catenary system with three mooring lines. The following sections describe the structural properties of the tower and the floating platform before the hydrodynamic properties and the mooring system is introduced. Finally, preliminary controller parameters are presented.

3.1 Tower Properties

The tower of the LIFES50+ OO-Star Wind Floater Semi 10MW design is defined in segments, each having a constant wall thickness, see Figure 2. Hence, the tower thickness cannot simply be interpolated across the tower but the different section properties have to be considered. The diameter on the other hand can be linearly interpolated within each segment. The tower top connects directly to the RNA, see Table 3 with the physical tower properties. A sketch of the tower setup is shown in Figure 2. The natural frequencies and modes were calculated using BModes [6] with a clamped tower base, see Figure 3. The tower top mass properties included in the eigenvalue problem were set according to the DTU 10 MW reference wind turbine description [4]. The indicated damping ratio ζ in Table 3 is related to the logarithmic decrement δ by $\delta = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$. Note that the mode shapes of Figure 3 do not include the effects of the freely floating substructure as the tower is clamped in the analysis. They are intended as a reference to allow a cross-check for model setup. The steel density is increased to take the additional structural components (bolts, stiffeners, flanges, etc.) into account.

Table 2: LIFES50+ OO-Star Wind Floater Semi 10MW distributed tower properties (elevations given w.r.t. 11m above MSL)

Section	Lower elevation	Upper elevation	Outer diameter[3]	Wall thickness	Cross sectional area[1]	Section mass
[-]	[m]	[m]	[m]	[m]	[m^2]	[kg]
1	0.000	3.946	11.385	0.075	2.665	8.667E+04
2	3.946	7.892	11.154	0.074	2.576	8.378E+04
3	7.892	11.838	10.923	0.072	2.454	7.983E+04
4	11.838	15.785	10.692	0.070	2.336	7.598E+04
5	15.785	19.731	10.462	0.068	2.220	7.222E+04
6	19.731	23.677	10.231	0.066	2.108	6.855E+04
7	23.677	27.623	10.000	0.065	2.029	6.599E+04
8	27.623	31.569	9.769	0.063	1.921	6.248E+04
9	31.569	35.515	9.538	0.061	1.816	5.908E+04
10	35.515	39.462	9.308	0.059	1.714	5.576E+04
11	39.462	43.408	9.077	0.057	1.615	5.254E+04
12	43.408	47.354	8.846	0.056	1.546	5.030E+04
13	47.354	51.300	8.615	0.054	1.452	4.724E+04
14	51.300	55.246	8.385	0.052	1.361	4.428E+04
15	55.246	59.192	8.154	0.050	1.273	4.140E+04
16	59.192	63.138	7.923	0.048	1.188	3.863E+04
17	63.138	67.085	7.692	0.047	1.129	3.672E+04
18	67.085	71.031	7.462	0.045	1.048	3.410E+04
19	71.031	74.977	7.231	0.043	0.971	3.158E+04
20	74.977	78.923	7.000	0.041	0.896	2.916E+04

[3] Values provided at section centre

21	78.923	82.869	6.769	0.039	0.825	2.682E+04
22	82.869	86.815	6.538	0.038	0.776	2.524E+04
23	86.815	90.762	6.308	0.036	0.709	2.307E+04
24	90.762	94.708	6.077	0.034	0.645	2.099E+04
25	94.708	98.654	5.846	0.032	0.585	1.901E+04
26	98.654	102.600	5.615	0.030	0.526	1.712E+04
27	102.600	104.630	5.441	0.029	0.484	8.104E+03

Table 3: LIFES50+ OO-Star Wind Floater Semi 10MW geometric tower parameters

Property	Unit	Value
Tower base elevation above MSL	[m]	11.0
Tower-top elevation above MSL	[m]	115.63
Total Mass	[Kg]	1.257E+06
Vertical centre of mass (above MSL)	[m]	49.8
Inertia about $\boldsymbol{x}, \boldsymbol{y}$-axis w.r.t. tower-CM	[kg·m²]	9.6225E8
1st fore-aft natural frequency (clamped tower)	[Hz]	0.5529
2nd fore-aft natural frequency (clamped tower)	[Hz]	2.4372
1st side-side natural frequency (clamped tower)	[Hz]	0.5439
2nd side-side natural frequency (clamped tower)	[Hz]	2.1074
Damping ratio (ζ) 1st mode (fore-aft)	[-]	0.00932
Damping ratio (ζ) 2nd mode (fore-aft)	[-]	0.07767
Damping ratio (ζ) 1st mode (side-side)	[-]	0.00932
Damping ratio (ζ) 2nd mode (side-side)	[-]	0.08947
Density ($\boldsymbol{\rho}$)	[Kg/m³]	8.243E+03
Modulus of elasticity ($\boldsymbol{E}$)	[N/m²]	2.1E+11
Shear modulus of elasticity ($\boldsymbol{G}$)	[N/m²]	8.08E+10

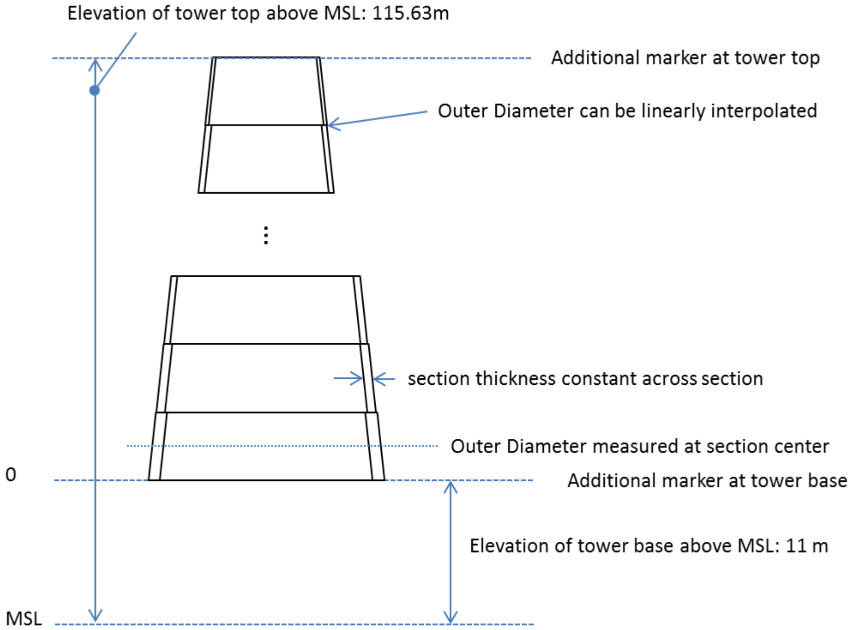

Figure 2: Sketch of LIFES50+ OO-Star Wind Floater Semi 10MW tower definition

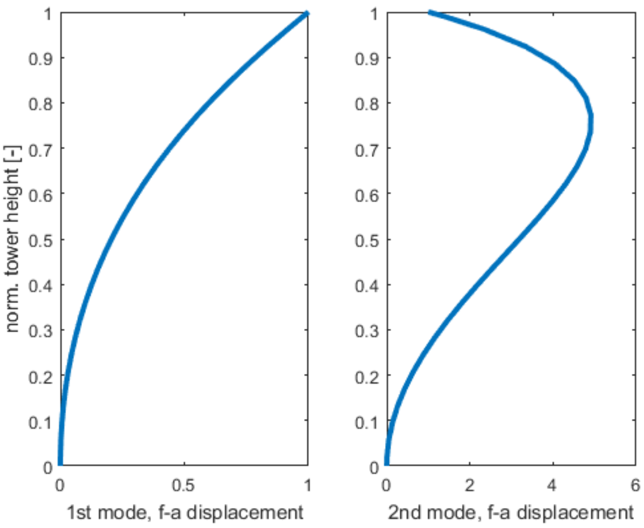

Figure 3: LIFES50+ OO-Star Wind Floater Semi 10MW tower modes (fore-aft)

3.2 Platform Structural Properties

The platform consists of a lower star-shaped pontoon, on which a central column and three outer columns are mounted. All the columns have a cylindrical upper part and a tapered lower part. The main material is post-tensioned concrete, which yields a higher displaced volume as for steel structures, see Figure 4.

The geometrical properties are marked in Figure 5 with a definition of the coordinate system in Figure 6. As can be seen, the distance between the central column and the outer column is 37 m. The horizontal pontoon elements connecting the columns have a width of 16m and a height of 7 m. The slab attached underneath the pontoons has a width of 17 m, adding 0.5 m at each side. Below the central column the slabs connect with a curvature radius of 10 meters. The central column has a diameter of 12.05 m at the tower base interface. It has a tapered shape below with a diameter which increases linearly over a length of 17.3 m to 16.2 m at the pontoon interface. The outer columns have a diameter of 13.4 m at the top, and a conical section below. The conical section has a length of 11m with a diameter of 15.8 m at the pontoon interface. The circular portions of the heave plates below the outer columns have a diameter of 22.8 meters.

The platform has an overall mass of 21709 tonnes tonne including ballast. The mass moments of inertia have been calculated about the centre of mass with a value of 9.43E+09 kg m^2 about x and y and 1.63E+10 kg m^2 about z. Important structural properties are all listed in Table 4. Essential structural information of individual members is given in Table 5.

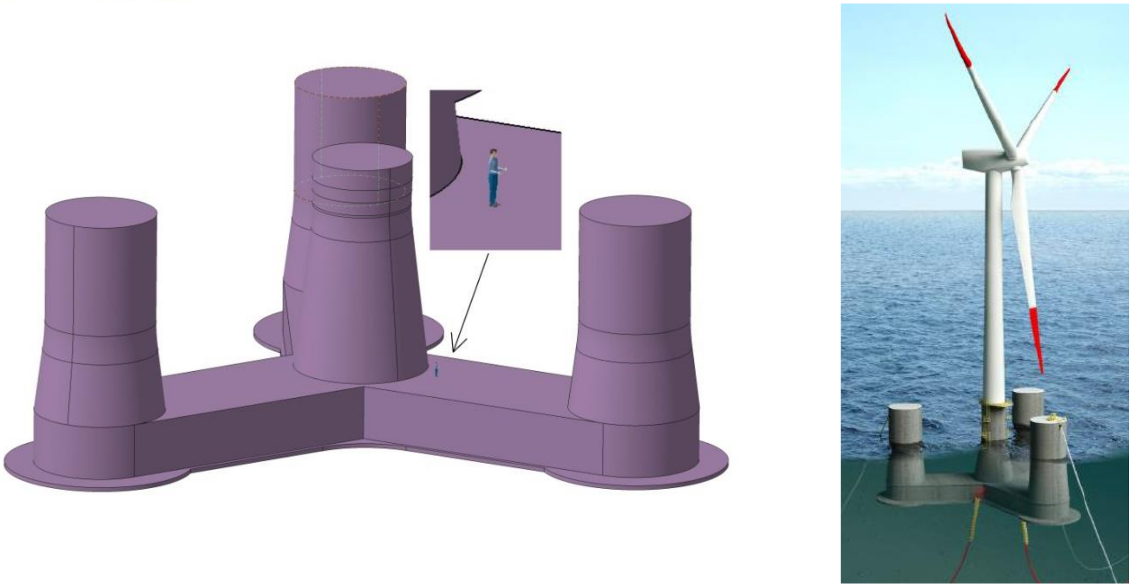

Figure 4: LIFES50+ OO-Star Wind Floater Semi 10MW structure

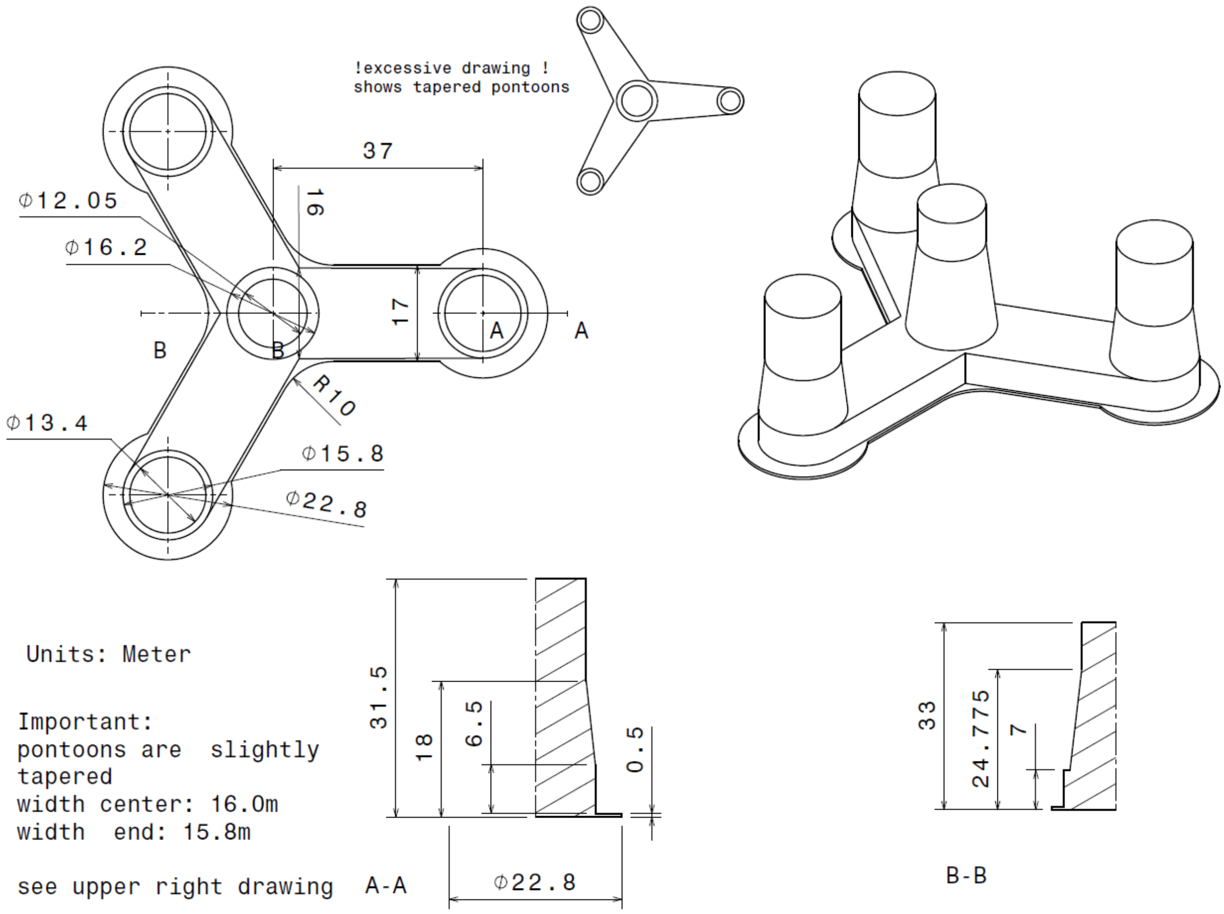

Figure 5: LIFES50+ OO-Star Wind Floater Semi 10MW main dimensions (lower drawings are sectional views as indicated in the top-view)

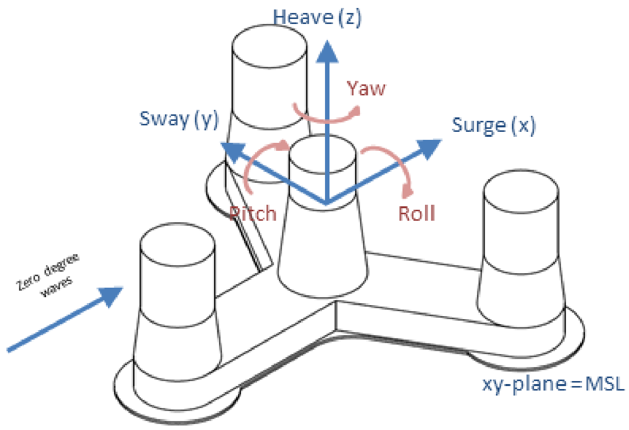

Figure 6: LIFES50+ OO-Star Wind Floater Semi 10MW coordinate system

Table 4: LIFES50+ OO-Star Wind Floater Semi 10MW platform parameters including ballast

Property	Unit	Value
Overall substructure mass (excl. tower, mooring)	[kg]	2.1709E+07
Centre of Mass (CM) below MSL	[m]	15.225
Substructure roll inertia about CM	[kg m^2]	9.43E+09
Substructure pitch inertia about CM	[kg m^2]	9.43E+09
Substructure yaw inertia about CM	[kg m^2]	1.63E+10
Tower base interface above MSL	[m]	11.0
Draft at equilibrium position with moorings (no thrust)	[m]	22.0
Displaced water volume	[m^3]	2.3509E+04
Centre of buoyancy below MSL	[m]	14.236

Table 5: LIFES50+ OO-Star Wind Floater Semi 10MW distributed structural properties

Member	Name	Radius	Mass density	Element length	EA	EIy	EIz	GJ
[-]	[-]	[m]	[kg/m]	[m]	[N]	[N m^2]	[N m^2]	[N m^2]
1	Pontoon	-	1.73E+05	21.1	6.39E+11	5.53E+12	1.97E+13	1.05E+13
2	Outer Column Lower	7.9	1.40E+05	7	5.81E+11	2.20E+13	2.20E+13	1.83E+13
3	Outer Column Conical Part	-	9.28E+04	11.5	5.36E+11	1.62E+13	1.62E+13	1.35E+13
4	Outer Column Upper	6.7	4.55E+04	13.5	4.90E+11	1.04E+13	1.04E+13	8.64E+12
5	Central Shaft Lower	8.1	1.17E+05	7	8.82E+11	2.69E+13	2.69E+13	2.24E+13
6	Central Shaft Conical Part	-	8.73E+04	17.775	7.39E+11	1.84E13	1.84E+13	1.53E+13
7	Central Shaft Upper	6.025	5.76E+04	8.225	5.96E+11	9.88E+12	9.88E+12	8.23E+12

3.3 Hydrodynamic Properties

This section provides the results of a panel code analysis with the LIFES50+ OO-Star Wind Floater Semi 10MW hull shape. Additional, estimated coefficients for the drag term of Morison's equation are given at the end.

3.3.1 Hydrostatic restoring

The hydrostatic stiffness with reference point [0, 0, 0] are given in Table 6. Notice that the stiffness in platform pitch direction includes only water plane area and the buoyancy.

Table 6: LIFES50+ OO-Star Wind Floater Semi 10MW hydrostatic restoring

Element		Unit	Value
3	3	[N/m]	5.5184E+06
5	5	[Nm/rad]	-4.0564E+08

3.3.2 Potential flow analysis

The linear potential flow problem was solved at its designed equilibrium position (with draft 22 m) and finite water depth (130 m) using ANSYS-AQWA. The result of the linear frequency-dependent hydrodynamic coefficients is shown in Figure 7 (Added mass A) and Figure 8 (Radiation damping B), respectively. Figure 9 shows the magnitude and phase of the wave excitation with the wave incident angle 0°, i.e. the nominal downwind direction. The reference point is set at MSL, i.e. [0 0 0].

For models using Morison's equation only the zero-frequency limit added mass coefficients can be used as summarized in Table 7.

Table 7: LIFES50+ OO-Star Wind Floater Semi 10MW zero-frequency added mass coefficients

Element		Unit	Value
1	1	[kg]	1.6210E+07
3	3	[kg]	3.4785E+07
5	5	[kgm^2]	1.2810E+10
1	5	[kgm]	-2.0509E+08
5	1	[kgm]	-2.1243E +08

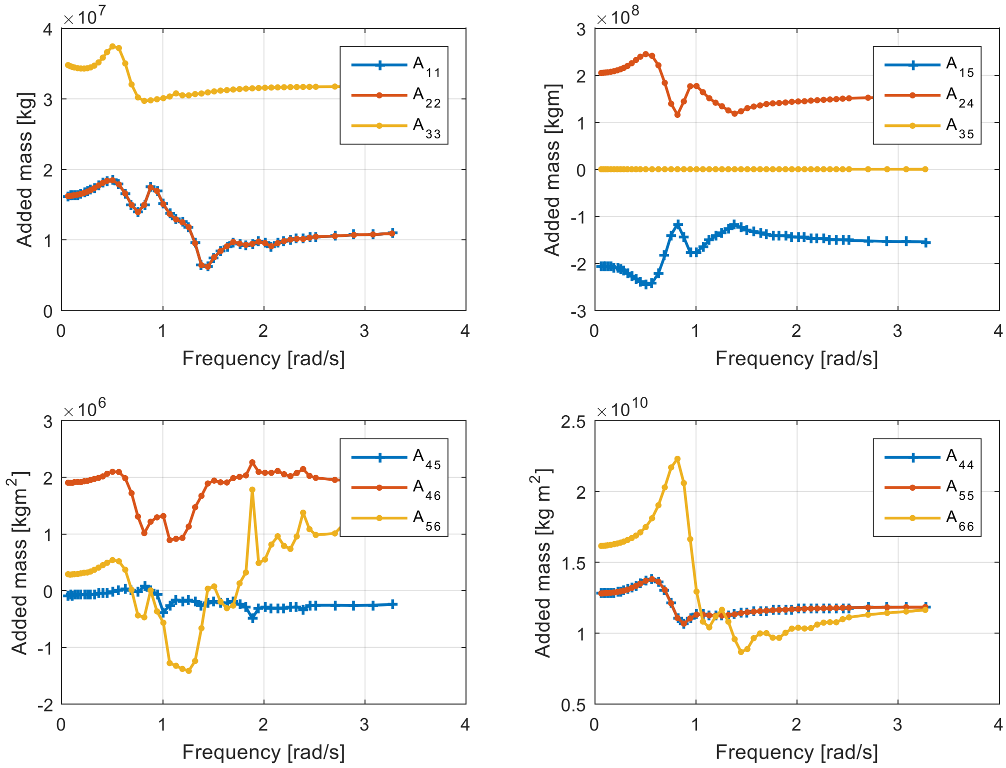

Figure 7: LIFES50+ OO-Star Wind Floater Semi 10MW hydrodynamic added mass from ANSYS-AQWA

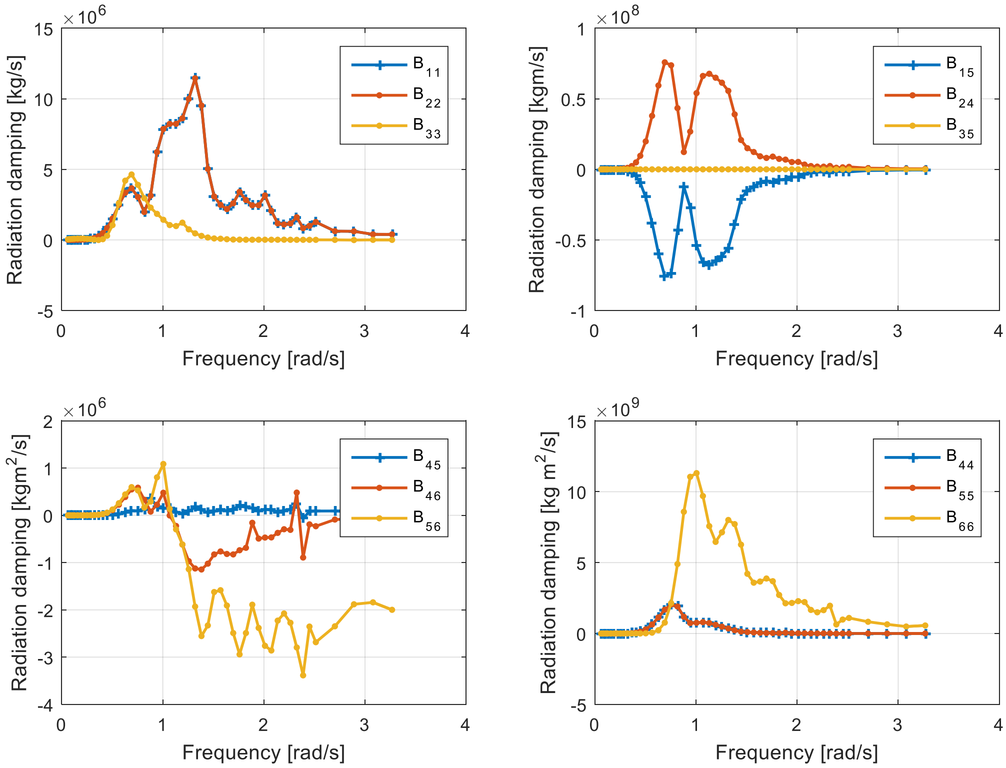

Figure 8: LIFES50+ OO-Star Wind Floater Semi 10MW hydrodynamic potential damping from ANSYS-AQWA

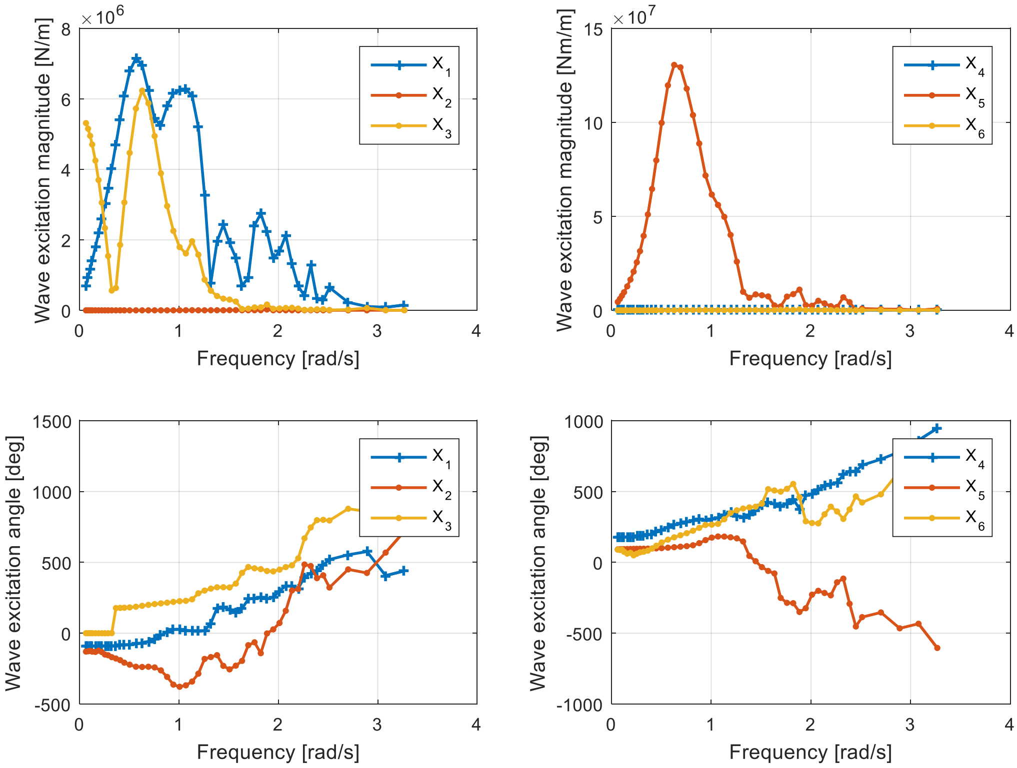

Figure 9: LIFES50+ OO-Star Wind Floater Semi 10MW first order hydrodynamic wave excitation forces from ANSYS-AQWA (Results are given for 0° wave heading direction)

3.3.3 Viscous damping

Viscous flow is of importance for determining the hydrodynamic damping. Thus, additionally to the potential flow hydrodynamic properties, the quadratic viscous drag forces of cylindrical bodies will be taken into account by using Morison's equation. Viscous drag coefficients (drag term of Morison's equation) for the cylindrical columns of LIFES50+ OO-Star Wind Floater Semi 10MW are provided in this subsection, based on the Reynolds number (Re) and Keulegan-Carpenter number (KC).

For an estimation of the state of the flow about the structural members and a derivation of the drag coefficients the Keulegan-Carpenter number (KC) for fixed bodies in harmonically oscillating flow can be used, with the velocity amplitude U, the period of oscillation T and the fundamental length L or with the amplitude of oscillation η_0. The KC number is represented as

$$KC = \frac{UT}{L} = 2\pi\frac{\eta_0}{L}. \qquad \textbf{(1)}$$

The Reynolds number is defined with the fluid kinematic viscosity ν as

$$Re = \frac{UL}{\nu}. \qquad \textbf{(2)}$$

3.3.3.1 Vertical columns

For the vertical columns L is taken equal to the element diameter. The values of KC and Re vary over the sea states and the dimension of the cross sections. Several sea states for fatigue loads from the fatigue load case in the definition of environmental conditions of LIFES50+, see Table 8, taken from [7], are used to calculate the KC and Re to estimate the drag coefficients.

Table 8: Sea state definition

Sea state	Hs	Tp
[-]	[m]	[s]
1	1.67	8.0
2	2.20	8.0
3	3.04	9.5
4	4.29	10.0
5	6.20	12.5
6	8.31	12.0

The non-dimensional numbers are plotted in Figure 10 for the LIFES50+ OO-Star Wind Floater Semi 10MW outer columns. According to [8], the drag coefficient C_D is derived based on the non-dimensional roughness (k/D), where k is the surface roughness and D the diameter. Regarding the condition without marine growth, k for concrete can be roughly chosen as 3mm. For the different diameters of the vertical columns, C_D is than calculated in Table 9. Note that the coefficients given in this section are rough estimates, which are not verified by experiments.

Table 9: Drag coefficient for the vertical columns

D	k/D	C_D
[m]	[-]	[-]
12.05	2.49E-04	0.729
16.2	1.85 E-04	0.704
13.4	2.24 E-04	0.720
15.8	1.90 E-04	0.706

3.3.3.2 Horizontal pontoons

In this report the drag coefficient of the horizontal pontoons and of the LIFES50+ OO-Star Wind Floater Semi 10MW with quasi rectangular cross-section has not been included. Further CFD simulations or model tests are needed to calibrate this part of the viscos damping.

3.3.3.3 Heave plates

For the heave plates underneath the outer columns the fundamental frequency is also estimated based on [9]. Figure 11 shows the experimental result of a heave plate with a frequency of oscillation of 1 Hz, taken from [9]. A trend of C_D decreasing nonlinearly with increasing KC can be observed. The KC number in this figure is calculated as

$$KC = \frac{2\pi\eta_0}{D}, \quad (3)$$

where η_0 is the amplitude of the heave plate movement. Since the heave plate diameter of the LIFES50+ OO-Star Wind Floater Semi 10MW is relatively large, the KC number will be low. If $\eta_0 \leq$ 2m, KC is kept under 0.4, which is quite a conservative assumption under normal operation. Thus, a value of $C_{DZ} = 11$ is chosen which corresponds to the value found in Figure 11 when $KC = 0.4$.

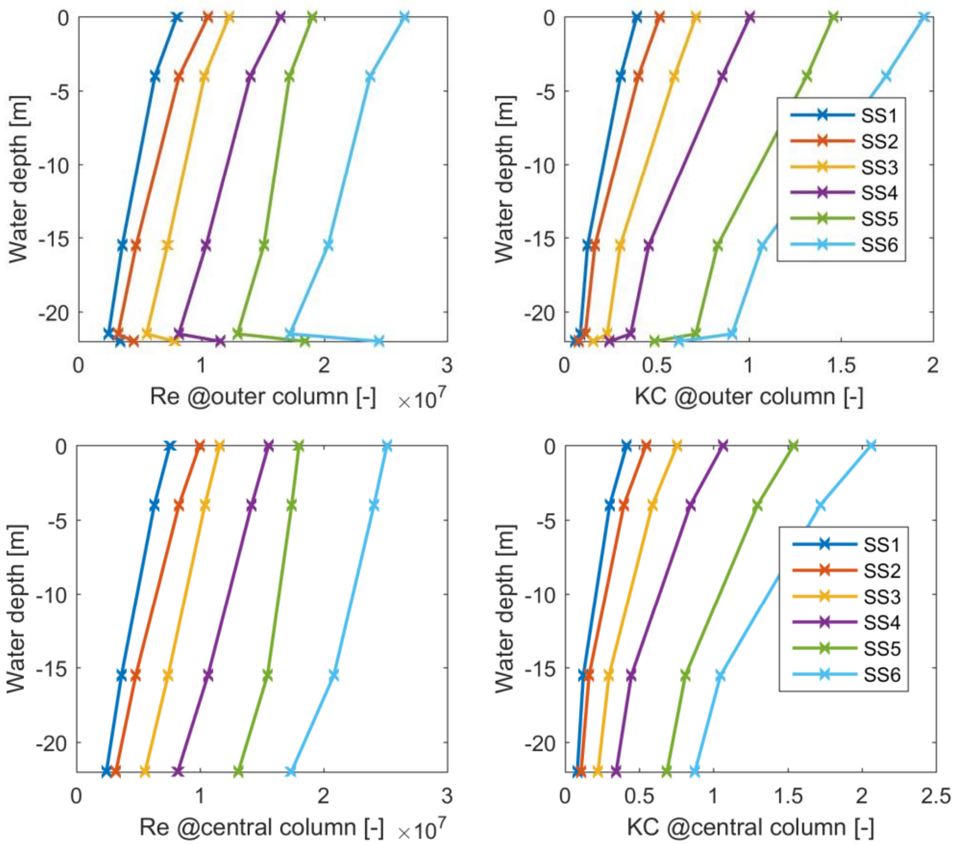

Figure 10: LIFES50+ OO-Star Wind Floater Semi 10MW Re and KC number at the corner column over water depth in various sea states

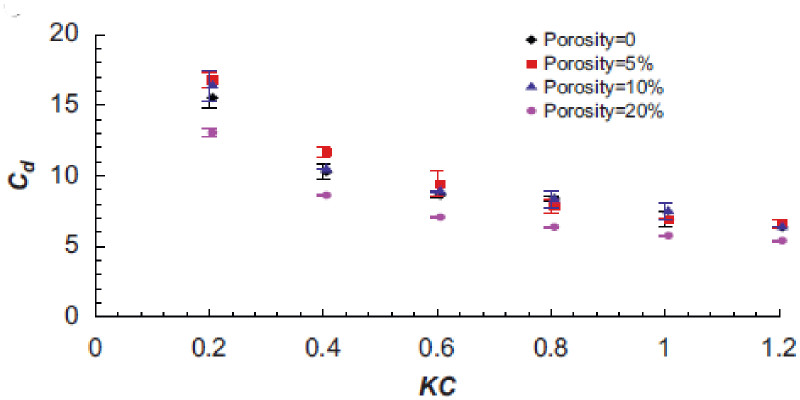

Figure 11: Cd vs. KC for heave plate of different porosities [8]

3.4 Mooring System Properties

The layout of the mooring system is shown in Figure 12. It consists of three chains, the horizontal angle in between two chains is 120°. A clump mass is attached to each line, separating the line in two segments. The upper segment, which is connected to the fairlead, is 160 m long. The lower segment is 543 m long. Important parameters of the mooring system are summarized in Table 10. The chain parameters are equal for the portions above and below the clump mass.

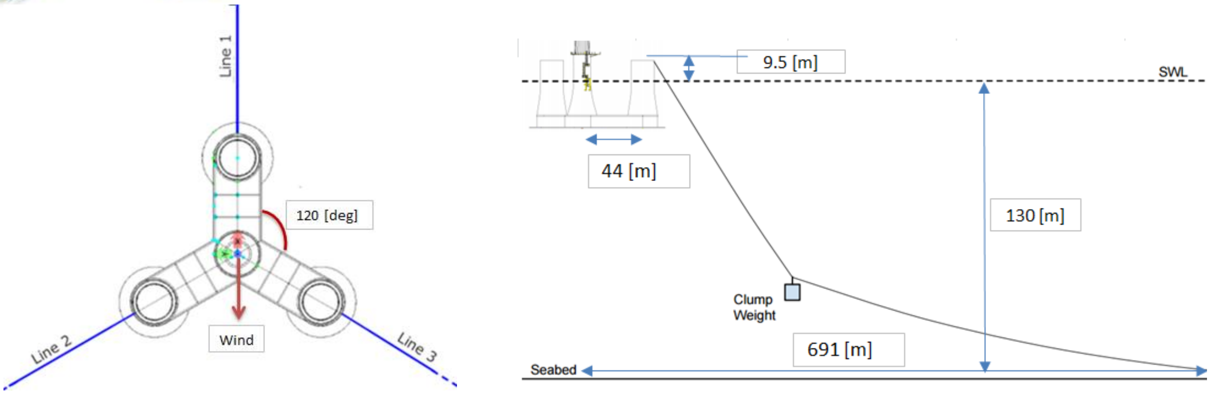

Figure 12: LIFES50+ OO-Star Wind Floater Semi 10MW mooring line arrangement in the top view (left) and side view (right)

Table 10: LIFES50+ OO-Star Wind Floater Semi 10MW mooring system properties

Property	Unit	Value
Number of lines	[-]	3
Angle between adjacent lines	[deg]	120
Equivalent total mass in water of the clump mass	[kg]	50000
Unstretched mooring line length, upper part	[m]	118
Unstretched mooring line length, lower part	[m]	585
Vertical position of fairleads above MSL	[m]	9.5
Radius to anchors from platform centreline	[m]	691
Anchor position below MSL	[m]	130.0
Radius to fairleads from platform centreline	[m]	44
Initial vertical position of clump mass below MSL	[m]	90.45
Initial radius to lump mass from centreline	[m]	148.6
Pre tension	[N]	1.67E+06
Soil stiffness	[Pa/m]	3.0E+06
Soil damping	[PaS/m]	3.0E+05
Equivalent mass per length in air	[kg/m]	375.38
Equivalent weight per length in water	[N/m]	3200.6
Extensional stiffness EA	[N]	1.506E+09
Hydrodynamic added mass coefficient	[-]	0.8
Hydrodynamic drag coefficient	[-]	2.0
Effective hydraulic diameter of the chain	[m]	0.246
Physcial chain diameter	[m]	0.137

3.5 Control System Properties

The DTU 10MW RWT is here installed on a floating platform. Therefore, the baseline onshore controller cannot be used here due to the negative damping problem (see, for example, [10]). In LIFES50+ the basic DTU Wind Energy controller [11] is employed. The DTU controller consists of two different controllers for the partial load region (i.e. operation below rated wind speed) and the full load region (i.e. operation above rated wind speed), and a mechanism that smoothly switches between these two controllers around rated wind speed. The pole-placement method [12] was used to tune the proportional-integral (PI) controller for the present floating wind turbine configuration.

Here below in Table 11 the blade pitch controller parameters tuned by Olav Olsen are presented.

Table 11: Full load region controller parameters

Basic DTU controller	Units	Value
Generator control switch [1=constant power, 2=constant torque]	[-]	2
Proportional gain of pitch controller	[rad/(rad/s)]	0.1922009003
Integral gain of pitch controller	[rad/rad]	0.00879819899
Differential gain of pitch controller	[rad/(rad/s^2)]	0.0
Proportional power error gain	[rad/W]	$0.4 \cdot 10^{-8}$
Integral power error gain	[rad/(Ws)]	$0.4 \cdot 10^{-8}$
Coefficient of linear term in aerodynamic gain scheduling, KK1	[deg]	198.32888
Coefficient of quadratic term in aerodynamic gain scheduling, KK2 (if zero, KK1 = pitch angle at double gain)	[deg^2]	693.22213
Relative speed for double nonlinear gain	[-]	1.3

3.6 Overall System Properties

Table 12 includes the overall mass of the ballasted platform, the tower and the turbine without the mooring lines. The natural frequencies have been calculated with the coupled FAST8 model in free-decay simulations including the mooring system. Therefore, the frequencies are system frequencies with all DOFs enabled but without aerodynamic damping. It is highlighted here that FAST8 calculations in this chapter considered a rigid platform. However, it should be noted that the flexibility of the pontoons and columns have an important influence on the system natural frequencies. Considering a flexible substructure, the first natural frequency of the tower becomes 0.59 Hz.

Table 12: LIFES50+ OO-Star Wind Floater Semi 10MW System Properties

Property	Unit	Value
Total mass	[kg]	2.3618E+07
Natural frequency surge	[Hz]	0.0055
Natural frequency heave	[Hz]	0.049
Natural frequency pitch	[Hz]	0.032
Natural frequency yaw	[Hz]	0.0086
Natural frequency tower	[Hz]	0.786

4 Platform Design 2: *NAUTILUS-10* floating substructure

The *NAUTILUS-10* Semi-Submersible consists of a quadratic ring base pontoon with a flat lower surface, which connects four outer columns at the bottom. These four columns are connected on the top as well with an integrated cross-shaped element which, in its centre, supports the *NAUTILUS-10* tower of the wind turbine. The structure is built out of steel S-355-J2H. *NAUTILUS-10* mooring system is a catenary system with four mooring lines. A description of the system can also be found in the TECNALIA technical report [3]. The following sections describe the structural properties of the tower and the floating platform before the hydrodynamic properties and the mooring system is introduced. Finally, preliminary controller parameters are presented.

4.1 Tower Properties

The original tower design of *NAUTILUS-10* floating substructure for Gulf of Maine was composed by five conical sections bolted by means of their bottom and top flanges (multiple section tower design); nevertheless, in order to: (1) avoid the implementation of new capabilities in the WT controller public version such as: exclusion zones, (2) avoid employing tuned mass-dampers to obtain a soft/stiff tower design and (3) simplify the analysis and the reduced scale model fabrication; the tower has been redesigned as a conical single piece tower of linearly varying thickness. This "academic" tower definition, which avoids the use of connection flanges between tower sections, has been previously employed by other researchers, noticeable differences can however be expected between real-world and academic designs. The tower is made of steel S-355-J2H (ρ=7.850 kg/m^3, E=210 GPa and ν=0.3) where the material density has been augmented 8,500 kg/m^3 to account for the mass of "realistic" tower sections flanges, bolts, secondary structures and painting as it was done in other public WT tower models. The tower base presents an outer diameter of 10.5 m, meanwhile the tower top conserves the 5.5 m outer diameter to fulfil RNA requirements [2]. Tower base and top thickness are 0.040 m and 0.037 m, respectively. The tower has a total length of 107 m. The geometrical definition in the same format as in Table 3 for the LIFES50+ OO-Star Wind Floater Semi 10MW with only one segment is shown in Table 13. More detailed information can be found in [3]. Note that the tower height is subject to some variation due to the characteristics of the implemented active ballast system, see section 4.5 for more details.

The natural frequencies and modes were calculated using BModes [6] with a clamped tower base, see Figure 13. The tower top mass properties included in the eigenvalue problem were set according to the DTU 10 MW reference wind turbine description [4]. The indicated damping ratio ζ in Table 14 is related to the logarithmic decrement δ by $\delta = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$. Note that the mode shapes of Figure 13 do not include the effects of the freely floating substructure as the tower is clamped in the analysis. They are intended as a reference to allow a cross-check for model setup. The steel density is increased here for taking the additional structural components (bolts, stiffeners, flanges, etc.) into account.

Table 13: *NAUTILUS-10* tower properties (elevations given w.r.t. tower base)

Section	Lower elevation	Upper elevation	Outer diameter	Wall Thickness	Cross sectional area	Section mass
[-]	[m]	[m]	[m]	[m]	[m^2]	[kg]
1	0.00	0.00	10.5	0.04	1.3144	879,381
2	107.00	107.00	5.5	0.037	0.635	

Table 14: *NAUTILUS-10* tower geometric parameters

Property	Unit	Value
Tower-base elevation above MSL considering full active ballast, see section 4.5	[m]	7.667
Tower-top elevation above MSL considering full active ballast, see section 4.5	[m]	114.667
Total Mass	[kg]	879,381
Vertical center of mass (above MSL)	[m]	54.908
Inertia about $\boldsymbol{x}, \boldsymbol{y}$-axis w.r.t. tower-CM	[kg·m²]	814.922E+06
1st fore-aft natural frequency (clamped tower)	[Hz]	0.397
2nd fore-aft natural frequency (clamped tower)	[Hz]	2.237
1st side-side natural frequency (clamped tower)	[Hz]	0.393
2nd side-side natural frequency (clamped tower)	[Hz]	1.949
Damping ratio ($\boldsymbol{\zeta}$) 1st mode (fore-aft)	[-]	0.019
Damping ratio ($\boldsymbol{\zeta}$) 2nd mode (fore-aft)	[-]	0.1
Damping ratio ($\boldsymbol{\zeta}$) 1st mode (side-side)	[-]	0.019
Damping ratio ($\boldsymbol{\zeta}$) 2nd mode (side-side)	[-]	0.1
Density ($\boldsymbol{\rho}$)	[Kg/m³]	8500
Modulus of elasticity ($\boldsymbol{E}$)	[N/m²]	2.1E+11
Shear modulus of elasticity ($\boldsymbol{G}$)	[N/m²]	8.08E+10

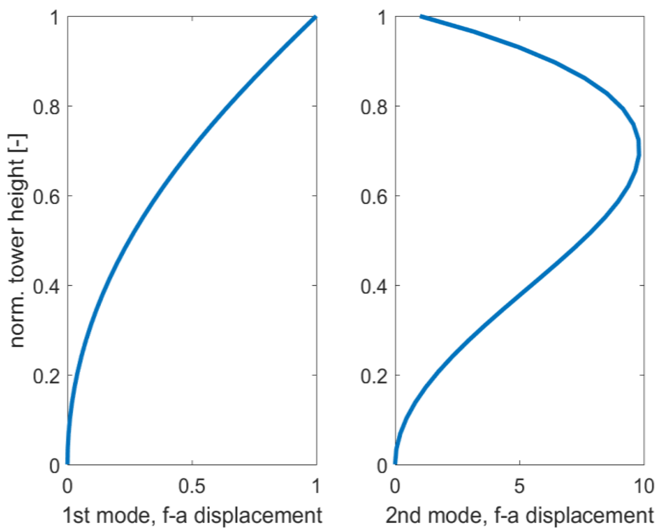

Figure 13: *NAUTILUS-10* tower modes (fore-aft)

4.2 Platform Structural Properties

NAUTILUS-10 semisubmersible is a symmetric floating platform (see Figure 14) composed by four columns connected at keel plane by a square-shaped ring pontoon and by a X-shaped main deck at columns top. The transition piece to connect the tower is embedded in the main deck central position. All the structure is compartmented in order to keep water tight the structure. The main coordinate system (in-line with the main wind direction is shown in Figure 16).

Opposite to *NAUTILUS-5*, an experimentally tested 5 MW concept, the 10 MW concept does not in-clude a central heave plate which was originally designed to increase FOWT added mass in order to avoid heave, roll and pitch natural periods to overlap with longest wave excitations. The structure is made of structural steel S-275 J2 and S355.

The platform has an overall mass of 9.337e6 kg including ballast (full active and passive). The main mass properties of the platform can be found in Table 15.

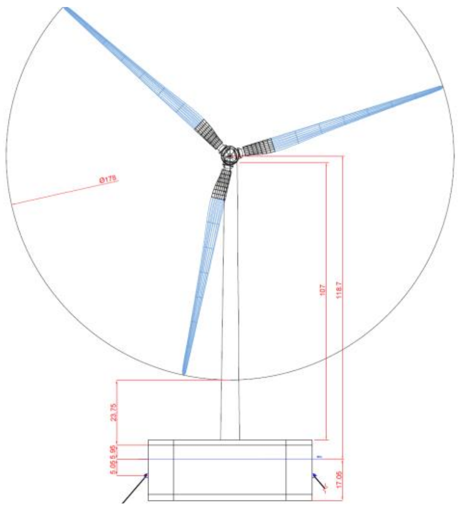


Figure 14: ***NAUTILUS-DTU10*** **MW FOWT structure**

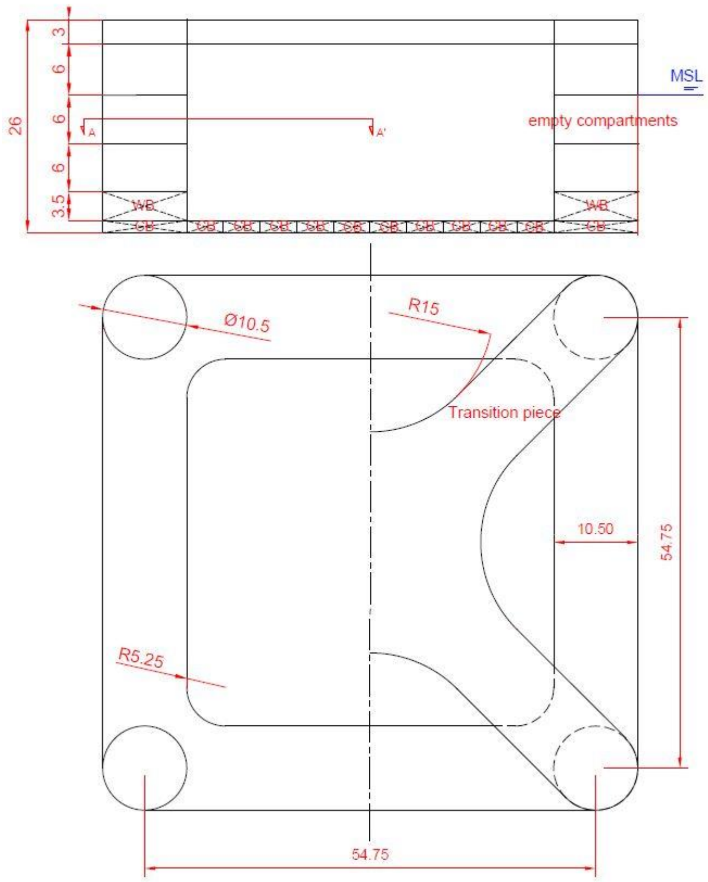

Figure 15: ***NAUTILUS-10*** **semisubmersible main dimensions**

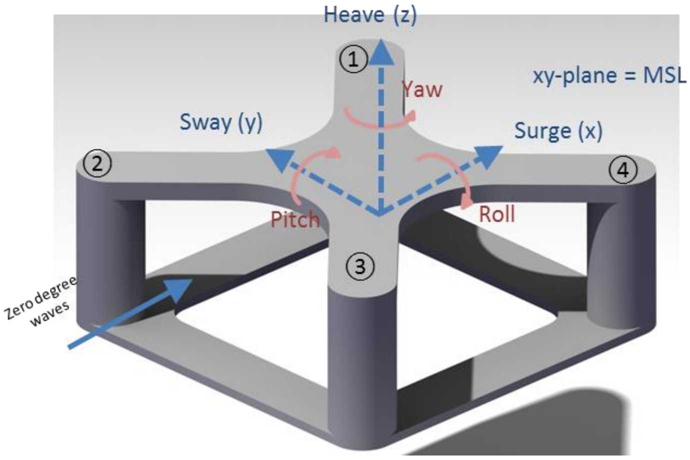

Figure 16: *NAUTILUS-10* semisubmersible coordinate system

Table 15: *NAUTILUS-10* semisubmersible platform parameters including active and passive ballast. Values are given with full active ballast ("full") and without any active ballast ("empty"), considering also the installed DTU wind turbine.

Property	Unit	Active ballast	
		empty	full
Overall substructure mass (excl. tower, mooring)	[kg]	6.581E06	7.781E06
Centre of Mass (CM) below MSL	[m]	10.748	14.283
Substructure roll inertia about CM	[kg m^2]	3.920E9	4.829E9
Substructure pitch inertia about CM	[kg m^2]	3.920E9	4.829E9
Substructure yaw inertia about CM	[kg m^2]	5.636E9	7.451E9
Draft at equilibrium position with moorings (no thrust)	[m]	14.952	18.333
Displaced water volume with moorings (no thrust)	[m^3]	8,113.06	9,280.96

Table 16: NAUTILUS-10 semisubmersible platform parameters excluding active and passive ballast.

Structural properties of the hull	Value	Unit
Total steel mass (includes coating and corrosion protection system)	2.70E+06	[kg]
CMx	0	[m]
CMy	0	[m]
CM location above keel line	9.75	[m]
System roll inertia about COG	1.99E+09	[kg m^2]
System pitch inertia about COG	1.99E+09	[kg m^2]
System yaw inertia about COG	2.31E+09	[kg m^2]
System roll radius of gyration about COG	27.2	[m]
System pitch radius of gyration about COG	27.2	[m]
System yaw radius of gyration about COG	29.3	[m]

Table 17: NAUTILUS-10 semisubmersible platform parameters passive ballast only.

Structural properties of the concrete passive ballast (CB)	Value	Unit
Mass	3.89E+06	[kg]
CMx	0	[m]
CMy	0	[m]
CMz location above keel line	0.356	[m]

System roll inertia about COG	1.79E+09	[kg m^2]
System pitch inertia about COG	1.79E+09	[kg m^2]
System yaw inertia about COG	3.33E+09	[kg m^2]
System roll radius of gyration about COG	21.472	[m]
System pitch radius of gyration about COG	21.472	[m]
System yaw radius of gyration about COG	29.264	[m]

4.3 Hydrodynamic Properties

This section provides the results of a panel code analysis with the *NAUTILUS-10* semisubmersible hull shape.

4.3.1 Hydrostatic restoring

The hydrostatic stiffness with reference point [0, 0, 0] are given in Table 18. Notice that the stiffness in platform pitch direction includes only water plane area and the buoyancy.

Table 18: *NAUTILUS-10* semisubmersible hydrostatic restoring

Element		Unit	Value
3	3	[N/m]	3.5045E+06
5	5	[Nm/rad]	1.5513E+09

4.3.2 Potential flow analysis

The linear potential flow problem was solved at its designed equilibrium position (with draft 18.333 m) and finite water depth (130 m) using ANSYS-AQWA. The result of the linear frequency-dependent hydrodynamic coefficients is shown in Figure 17 (Added mass A) and Figure 18 (Radiation damping B), respectively. Figure 19 shows the magnitude and phase of the wave excitation with the wave incident angle 0°, i.e. the nominal downwind direction. The reference point is set at MSL, i.e. [0 0 0].

For models using Morison’s equation, only the zero-frequency limit added mass coefficients can be used as summarized in Table 19.

Table 19: *NAUTILUS-10* semisubmersible zero-frequency added mass coefficients

Element		Unit	Value
1	1	[kg]	5.696E+06
3	3	[kg]	2.295E+07
5	5	[kgm^2]	1.07E+10
1	5	[kgm]	-2.457E+07
5	1	[kgm]	-2.445E +07

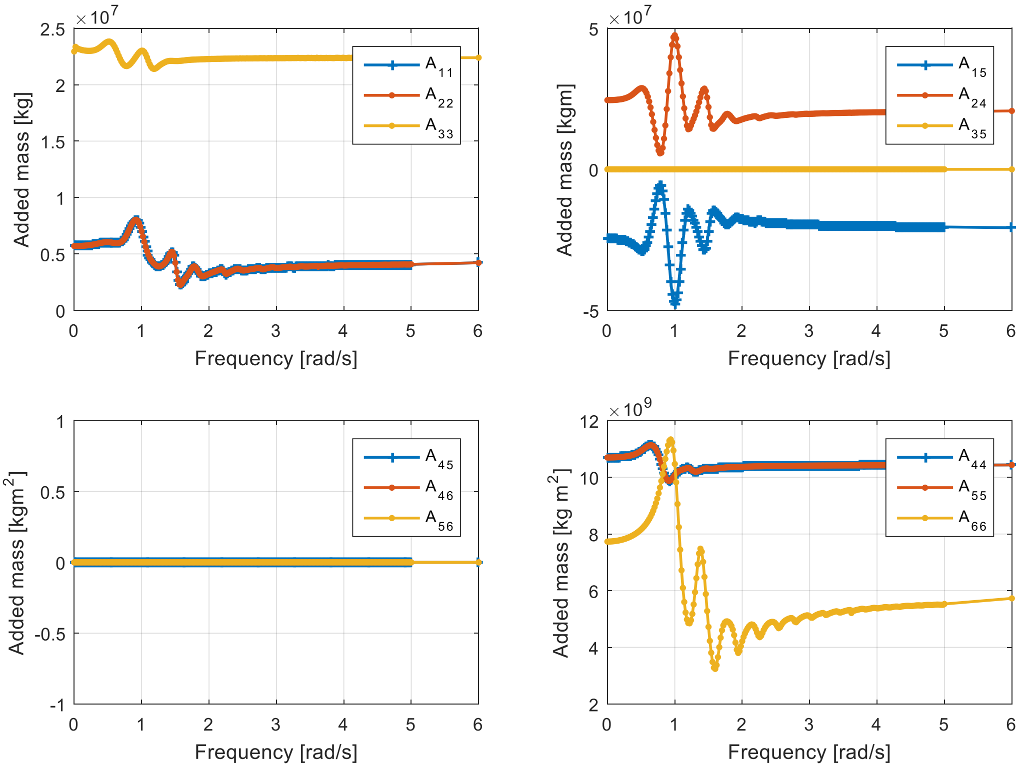

Figure 17: *NAUTILUS-10* semisubmersible hydrodynamic added mass from ANSYS-AQWA

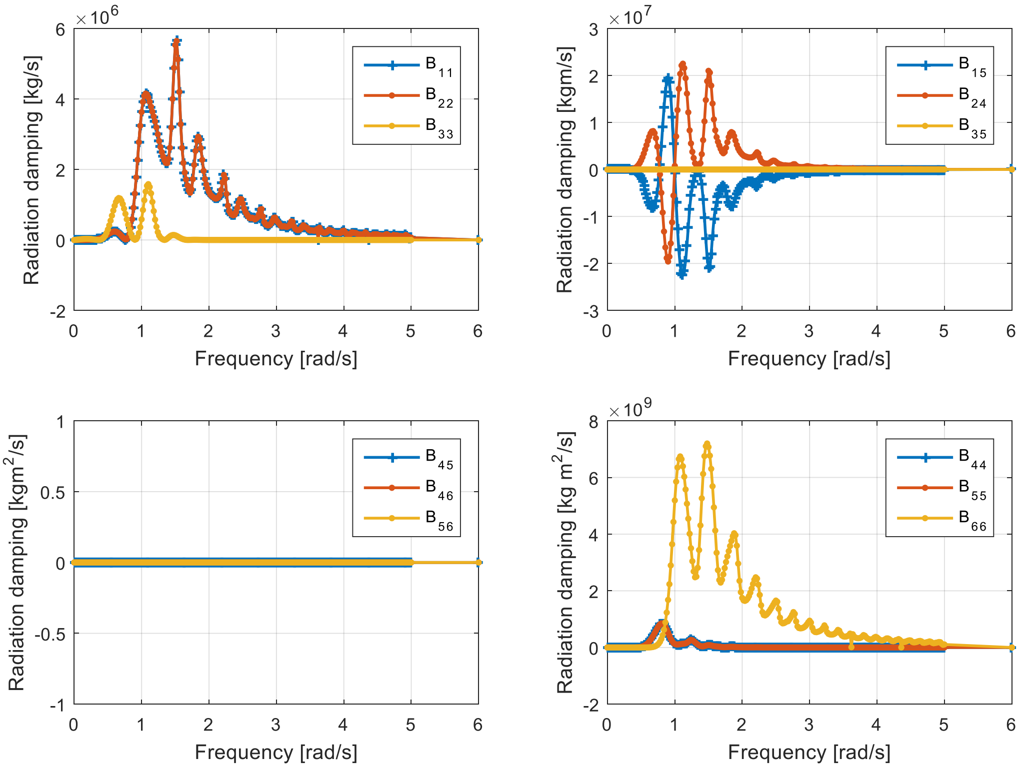

Figure 18: *NAUTILUS-10* semisubmersible hydrodynamic potential damping from ANSYS-AQWA

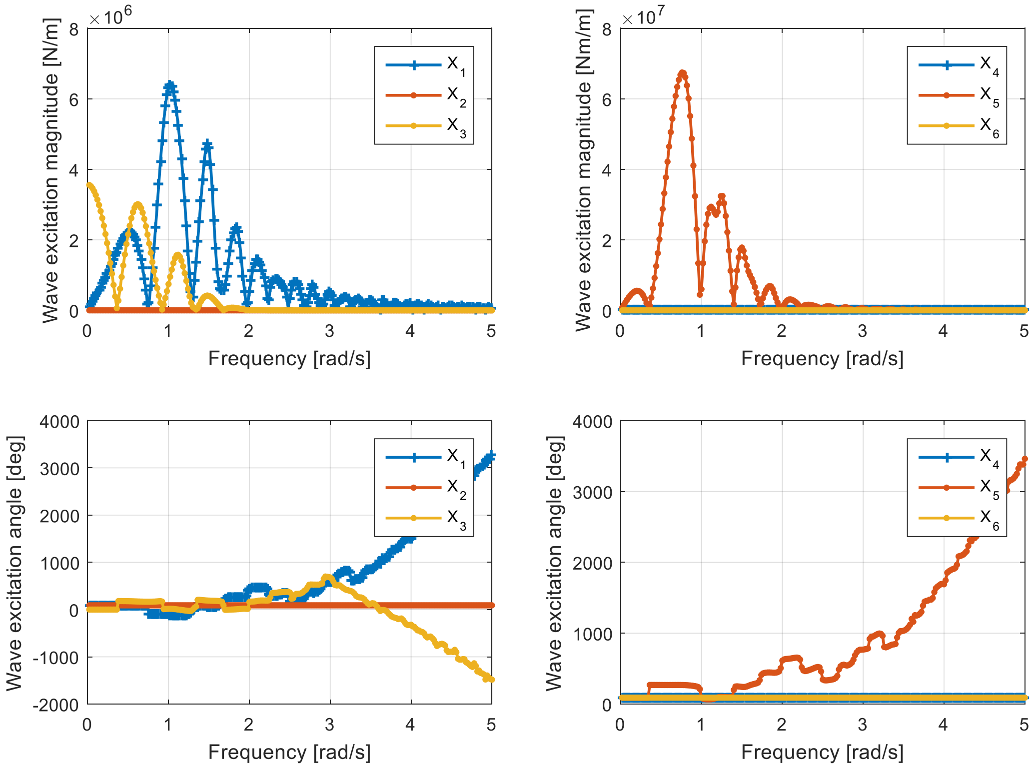

Figure 19: *NAUTILUS-10* semisubmersible first order hydrodynamic wave excitation forces from ANSYS-AQWA (Results are given for 0° wave heading direction)

4.3.3 Viscous damping

Viscous damping coefficients were determined by Nautilus FS based based on the upscaling of the NAUTILUS-NREL5 platform. They are given as lumped linear and quadratic damping coefficients for the entire platform with respect to the center of flotation in Table 20.

Table 20: *NAUTILUS-10* semisubmersible lumped viscous damping coefficients

Linear				Quadratic			
Element		Unit	Value	Element		Unit	Value
1	1	[Ns/m]	0	1	1	[Ns^2/m^2]	1.1010E+06
2	2	[Ns/m]	0	2	2	[Ns^2/m^2]	8.2731E+05
3	3	[Ns/m]	3.3548E+05	3	3	[Ns^2/m^2]	5.6380E+06
4	4	[Nms/rad]	2.1197E+08	4	4	[Nms^2/rad^2]	3.8515E+10
5	5	[Nms/rad]	2.2217E+08	5	5	[Nms^2/rad^2]	4.1618E+10
6	6	[Nms/rad]	2.2560E+07	6	6	[Nms^2/rad^2]	7.0665E+09

4.4 Mooring System Properties

NAUTILUS-10 Station-Keeping System (SKS) consists of 4 lines as shown in Figure 20. The fairleads are located 12 m above the floater's keel line which let them 6.333 m below MSL when the FOWT is in its undisplaced position (draft of 18.333 m), and 43.96 m, in xy-plane, from platform centreline.

The anchors are fixed to seabed at 793.50 m from fairlead position and therefore to 837.46 m from the platform centerline. All mooring lines have the same unstretched length of 833.24 m. The mooring lines selected are studless chains of 97 mm of bar nominal diameter (R3 quality). The line distributed mass density is 188.2 kg/m and the extensional (axial) stiffness EA_{Line} provided by this type of line is 803.5 MN. For hydrodynamic calculations, the physical chain diameter may be used in combination with the provided hydrodynamic coefficients.

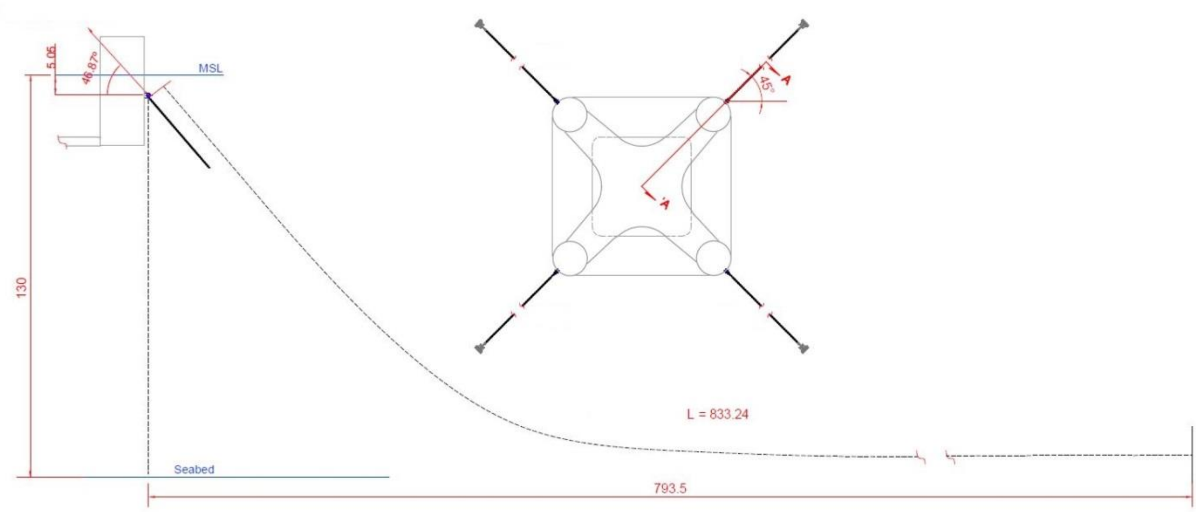

Figure 20: *NAUTILUS-10* mooring line arrangement in the top view (left) and side view (right)

Table 21: *NAUTILUS-10* SKS properties

Property	Unit	Value
Number of lines	[-]	4
Angle between adjacent lines	[deg]	90
Unstretched mooring line length	[m]	833.24
Vertical position of fairleads above MSL	[m]	-6.333
Radius to anchors from platform centreline	[m]	837.46
Anchor position below MSL	[m]	130.0
Radius to fairleads from platform centreline	[m]	43.9637
Line pre-tension	[kN]	406.3
Soil stiffness	[Pa/m]	3.0E+06
Soil damping	[PaS/m]	3.0E+05
Soil friction coefficient	[-]	0
Mooring lines structural damping ratio	[%]	0
Equivalent mass per length in air	[kg/m]	188.2
Extensional stiffness EA	[N]	8.035E+08
Hydrodynamic added mass coefficient (normal)[4]	[-]	1.0
Hydrodynamic drag coefficient (normal) [4]	[-]	2.4
Hydrodynamic added mass coefficient (axial) [4]	[-]	0.16
Hydrodynamic drag coefficient (axial)[4]	[-]	0.5
Physical chain diameter	[m]	0.097

[4] To be used with given value for chain diameter, see [3]

4.5 Active Ballast System

NAUTILUS-10 semisubmersible has an active ballast system with sea-water pumps transferring water in and out of column 1 and 4 (in the case of zero heading wind), see Figure 16. The ballast distribution is controlled by the Platform Trim System (PTS) whose main objective is to reduce the wind-induced trimming. Thus, floating platform mass, CM location, inertia properties, draft, suspended line length, hub height and other draft-dependant properties and parameters need to be updated for different wind speeds and -directions. Table 22 provides the system parameters as a function of wind speed, assuming a wind direction of 0°. The system parameters given therein are to be linearly interpolated between the wind speeds. Some investigations may require the consideration of different wind speeds. For this, a simplified procedure is provided in [3], which is summarized in the appendix of this document.

The PTS leads to a variation of mean draft of the overall system with changing wind speed, which in turn leads to a variation of the hub height between roughly 118m and 119.6m as described in [3]. The active ballast is also adjusted according to the wind direction. In order to calculate the wind direction dependent system properties, the impact of the changing water ballast on the overall structure has to be considered. The information to do this is also given in the appendix.

Table 22: NAUTILUS-10 semisubmersible system parameters including active ballast (0° wind-inflow direction). Values correspond to whole semisubmersible (hull + concrete ballast + active ballast, but no wind turbine) (for active ballast only, see Table 23)

Wind speed	Mass	CMx	CMy	CMz[5]	System roll inertia about CM	System pitch inertia about CM	System yaw inertia about CM	Tower top elevation[6]	Displaced volume[7]
[m/s]	[kg]	[m]	[m]	[m]	[kg·m2]	[kg·m2]	[kg·m2]	[m]	[m3]
4	7.69E+06	-0.31	0	-14.05	4.76E+09	4.76E+09	7.32E+09	114.91	9195
5	7.64E+06	-0.49	0	-13.91	4.73E+09	4.72E+09	7.24E+09	115.05	9147
6	7.59E+06	-0.70	0	-13.75	4.68E+09	4.68E+09	7.16E+09	115.21	9092
7	7.53E+06	-0.91	0	-13.59	4.64E+09	4.63E+09	7.07E+09	115.37	9037
8	7.47E+06	-1.13	0	-13.42	4.60E+09	4.59E+09	6.97E+09	115.53	8978
9	7.39E+06	-1.45	0	-13.17	4.53E+09	4.52E+09	6.84E+09	115.76	8898
10	7.30E+06	-1.81	0	-12.90	4.46E+09	4.44E+09	6.70E+09	116.02	8809
11	7.20E+06	-2.22	0	-12.58	4.39E+09	4.35E+09	6.53E+09	116.31	8710
11.5	7.24E+06	-2.04	0	-12.72	4.42E+09	4.39E+09	6.61E+09	116.18	8754
12	7.29E+06	-1.85	0	-12.86	4.46E+09	4.43E+09	6.68E+09	116.05	8799
13	7.36E+06	-1.56	0	-13.09	4.51E+09	4.49E+09	6.80E+09	115.85	8870
14	7.41E+06	-1.39	0	-13.22	4.54E+09	4.53E+09	6.87E+09	115.72	8914
15	7.44E+06	-1.27	0	-13.31	4.57E+09	4.56E+09	6.92E+09	115.64	8943
16	7.46E+06	-1.18	0	-13.38	4.59E+09	4.58E+09	6.96E+09	115.57	8967
17	7.48E+06	-1.10	0	-13.44	4.60E+09	4.59E+09	6.99E+09	115.51	8987
18	7.50E+06	-1.04	0	-13.49	4.61E+09	4.61E+09	7.01E+09	115.46	9003
19	7.51E+06	-0.98	0	-13.53	4.63E+09	4.62E+09	7.04E+09	115.42	9017

[5] With respect to MSL
[6] With overall tower height of 107m
[7] Taking into account tower, nacelle and rotor masses as well of an assumed constant mass of mooring lines of 1.75E3 kg.

Wind speed	Mass	CMx	CMy	CMz[5]	System roll inertia about CM	System pitch inertia about CM	System yaw inertia about CM	Tower top elevation[6]	Displaced volume[7]
20	7.52E+06	-0.94	0	-13.56	4.63E+09	4.63E+09	7.05E+09	115.39	9028
21	7.53E+06	-0.90	0	-13.59	4.64E+09	4.63E+09	7.07E+09	115.36	9038
22	7.54E+06	-0.88	0	-13.61	4.65E+09	4.64E+09	7.08E+09	115.34	9045
23	7.55E+06	-0.84	0	-13.64	4.65E+09	4.65E+09	7.09E+09	115.32	9053
24	7.56E+06	-0.82	0	-13.66	4.66E+09	4.65E+09	7.10E+09	115.30	9060
25	7.56E+06	-0.79	0	-13.68	4.66E+09	4.66E+09	7.12E+09	115.28	9067
44	7.74E+06	-0.141	0	4.046	4.80E+09	4.80E+09	7.39E+09	114.91	9241

4.6 Control System Properties

The DTU 10MW RWT is here installed on a floating platform. Therefore, the baseline onshore controller cannot be used here due to the negative damping problem (see, for example, [10]). In LIFES50+ the basic DTU Wind Energy controller [11] is employed. The DTU controller consists of two different controllers for the partial load region (i.e. operation below rated wind speed) and the full load region (i.e. operation above rated wind speed), and a mechanism that smoothly switches between these two controllers around rated wind speed. The pole-placement method [12] was used to tune the proportional-integral (PI) controller for the present floating wind turbine configuration.

Here below in Table 23 the blade pitch controller parameters tuned by TECNALIA are presented.

Table 23: Full load region controller parameters

Basic DTU controller	Units	Value
Generator control switch [1=constant power, 2=constant torque]	[-]	2
Proportional gain of pitch controller	[rad/(rad/s)]	0.208004
Integral gain of pitch controller	[rad/rad]	0.041415
Differential gain of pitch controller	[rad/(rad/s^2)]	0.0
Proportional power error gain	[rad/W]	$0.4 \cdot 10^{-8}$
Integral power error gain	[rad/(Ws)]	$0.4 \cdot 10^{-8}$
Coefficient of linear term in aerodynamic gain scheduling, KK1	[deg]	5.498310
Coefficient of quadratic term in aerodynamic gain scheduling, KK2(if zero, KK1 = pitch angle at double gain)	[deg^2]	386.005941
Relative speed for double nonlinear gain	[-]	1.3

4.7 Overall System Properties

Table 24 includes the overall mass of the ballasted platform, the tower and the turbine without the mooring lines. The natural frequencies have been calculated with the coupled FAST8 model in free-decay simulations including the mooring system. Therefore, the frequencies are system frequencies with all DOFs enabled but without aerodynamic damping. It is highlighted here that FAST8 calculations in this chapter considered a rigid platform. However, it should be noted that the flexibility of the pontoons and columns could have an influence on the system natural frequencies.

Table 24: *NAUTILUS-DTU10* MW FOWT Properties

Property	Unit	Value
Total mass including fully loaded active and passive ballast	[t]	9337.093
Natural frequency surge	[Hz]	0.008
Natural frequency heave	[Hz]	0.053
Natural frequency pitch	[Hz]	0.033
Natural frequency yaw	[Hz]	0.010
Natural frequency tower	[Hz]	0.541

5 Bibliography

[1] A. Pegalajar-Jurado, F. J. Madsen, M. Borg and H. Bredmose, "LIFES50+ D4.5: State-of-the-art models for the two public 10MW floater concepts," Risø, Denmark, 2018.

[2] O. Olsen, "OO-Star Wind Floater," [Online]. Available: http://www.olavolsen.no/nb/node/149. [Accessed 09 05 2017].

[3] J. Galvan, M. Sanchez-Lara, I. Mendikoa, V. Nava, F. Boscolo-Papo, C. Garrido-Mendoza and B. J., "Definition and Analysis of NAUTILUS-DTU10 MW Floating Offshore Wind Turbine at Gulf of Maine. Experiments at Sintef Ocean and PoliMi.," Tecnalia R&I, Derio, Basque Country, Spain, 2018.

[4] C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L. Henriksen, A. Natarajan and M. Hansen, "Description of the DTU 10 MW Reference Wind Turbine," DTU Wind Energy, 2013.

[5] M. Borg, M. Mirzaei and H. Bredmose, "LIFES50+ D1.2: Wind turbine models for the design," 2015.

[6] N. I. P. (BModes), 29 09 2014. [Online]. Available: https://nwtc.nrel.gov/BModes. [Accessed 09 05 2017].

[7] A. Krieger, G. K. V. Ramachandran, L. Vita , P. G. Alonso, G. G. Almería, J. Berque and G. Aguirre , "LIFES50+ D7.2: Design Basis," 2015.

[8] DNVGL, "Environmental conditions and environmental loads," 2017.

[9] L. Tao and D. Dray, "Hydrodynamic Performance of Solid and Porous Heave Plates," *Ocean Engineering*, vol. 35, pp. 1006-1014, jul 2008.

[10] T. J. Larsen and T. D. Hanson, "A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine," *Journal of Physics: Conference Series*, vol. 75, 2007.

[11] M. Hansen and L. C. Henriksen, "Basic DTU Wind Energy controller, Tech. Rep. No. E-0028,"

2013.

[12] M. Hansen, A. Hansen, T. Larsen, S. Øye, P. Sørensen and P. Fuglsang, "Control design for a pitch-regulated, variable-speed wind turbine Tech. rep. No. R-1500," Risø, Denmark, 2005.

[13] T. Sarpkaya, Wave forces on offshore structures, Cambridge: Cambridge University Press, 2010.

[14] B. Sumer and S. Fredsøe, Hydrodynamics around cylinderical structures, Singapore: World Scientific Publishing Co. Pte. Ltd., 1997.

[15] D. N. Veritas, "Offshore standard DNV-OS-E301 position mooring," 2008.

[16] Vryhof Anchors, "Vryhof Manual - The guide to anchoring," Vryhof Anchors BV, 2015 - Fifth edition.

[17] J. M. Cimbala and Y. A. Çengel, Essentials of fluid mechanics: fundamentals and applications, McGraw-Hill Higher Education, 2008.

6 Appendix

6.1 Wind Speed Dependent Structural Parameters For *NAUTILUS-10* floating substructure

Wind direction dependent values can be approximated based on the following analytical equations with wind turbine orientation α, a positive α meaning anticlockwise, or positive rotation about the vertical axis pointing upwards, as described in [3]. Baseline values (underscore 0) from Table 15, Table 22 and Table 26 are used:

Table 25: Approximation of relationship of substructure structural parameters with changing wind turbine orientation α

Rotated center of mass for active ballast	$CM_{x,WB,\alpha} = CM_{x,WB,0} \cdot \cos(\alpha) - CM_{y,WB,0} \cdot \sin(\alpha)$ $CM_{y,WB,\alpha} = CM_{x,WB,0} \cdot \sin(\alpha) + CM_{y,WB,0} \cdot \cos(\alpha)$ $CM_{z,WB,\alpha} = CM_{z,WB,0}$
Rotated moments of inertia	$I_{xx,WB,\alpha} = I_{xx,WB,0} \cdot \cos(\alpha) - I_{yy,WB,0} \cdot \sin(\alpha)$ $I_{yy,WB,\alpha} = I_{xx,WB,0} \cdot \sin(\alpha) + I_{yy,WB,0} \cdot \cos(\alpha)$
Rotated center of mass of platform	$CM_{x,PF,\alpha} = CM_{x,WB,\alpha} \cdot \frac{m_{WB}}{m_{PF}}$ $CM_{y,PF,\alpha} = CM_{y,WB,\alpha} \cdot \frac{m_{WB}}{m_{PF}}$ $CM_{z,PF,\alpha} = CM_{z,PF,0}$
Rotated moments of inertia of platform	$I_{xx,PF,\alpha} = I_{xx,H,0} + m_H \left(\left(CM_{y,H,0} - CM_{y,PF,\alpha} \right)^2 + \left(CM_{z,H,0} - CM_{z,PF,\alpha} \right)^2 \right) + \cdots$ $I_{xx,CB,0} + m_{CB} \left(\left(CM_{y,CB,0} - CM_{y,PF,\alpha} \right)^2 + \left(CM_{z,CB,0} - CM_{z,PF,\alpha} \right)^2 \right) + \cdots$ $I_{xx,WB,0} + m_{WB} \left(\left(CM_{y,WB,\alpha} - CM_{y,PF,\alpha} \right)^2 + \left(CM_{z,WB,\alpha} - CM_{z,PF,\alpha} \right)^2 \right)$

$$I_{yy,PF,\alpha} = I_{yy,H,0} + m_H \left(\left(CM_{x,H,0} - CM_{x,PF,\alpha} \right)^2 + \left(CM_{z,H,0} - CM_{z,PF,\alpha} \right)^2 \right) + \cdots$$
$$I_{yy,CB,0} + m_{CB} \left(\left(CM_{x,CB,0} - CM_{x,PF,\alpha} \right)^2 + \left(CM_{z,CB,0} - CM_{z,PF,\alpha} \right)^2 \right) + \cdots$$
$$I_{yy,WB,0} + m_{WB} \left(\left(CM_{x,WB,\alpha} - CM_{x,PF,\alpha} \right)^2 + \left(CM_{z,WB,\alpha} - CM_{z,PF,\alpha} \right)^2 \right)$$
$$I_{zz,PF,\alpha} = I_{zz,PF,0}$$

Note that the masses are not influenced by the wind direction. Indicative values are provided in [3] for selected wind directions, which may be used for cross checking the implementation of the above equations. Note also that a simplified approach was used here, assuming that the moments of inertias for the concrete ballast and the hull are not changed during the rotation. Also, cross-terms (e.g. I_{xy}) are neglected.

Table 26: Structural properties of water ballast for different wind speeds for a zero wind direction.

Wind speed	Mass	CMx	CMy	CMz[8]	System roll inertia about CM	System pitch inertia about CM	System yaw inertia about CM
[m/s]	[kg]	[m]	[m]	[m]	[kg·m^2]	[kg·m^2]	[kg·m^2]
4	1.11E+06	-2.16	0	3.09	8.42E+08	8.37E+08	1.68E+09
5	1.06E+06	-3.51	0	3.03	8.05E+08	7.92E+08	1.60E+09
6	1.01E+06	-5.25	0	2.98	7.62E+08	7.34E+08	1.50E+09
7	9.50E+05	-7.19	0	2.94	7.20E+08	6.71E+08	1.39E+09
8	8.91E+05	-9.50	0	2.92	6.74E+08	5.94E+08	1.27E+09
9	8.09E+05	-13.25	0	2.92	6.12E+08	4.70E+08	1.08E+09
10	7.17E+05	-18.45	0	2.98	5.43E+08	2.99E+08	8.40E+08
11	6.15E+05	-26.00	0	3.16	4.66E+08	5.00E+07	5.15E+08
11.5	6.61E+05	-22.31	0	3.06	5.01E+08	1.72E+08	6.71E+08
12	7.07E+05	-19.10	0	2.99	5.35E+08	2.78E+08	8.11E+08
13	7.80E+05	-14.75	0	2.93	5.90E+08	4.21E+08	1.01E+09
14	8.24E+05	-12.48	0	2.91	6.24E+08	4.96E+08	1.12E+09
15	8.54E+05	-11.08	0	2.91	6.47E+08	5.42E+08	1.19E+09
16	8.79E+05	-9.98	0	2.91	6.66E+08	5.78E+08	1.24E+09
17	9.00E+05	-9.13	0	2.92	6.81E+08	6.06E+08	1.29E+09
18	9.16E+05	-8.49	0	2.93	6.94E+08	6.28E+08	1.32E+09
19	9.30E+05	-7.95	0	2.93	7.04E+08	6.45E+08	1.35E+09
20	9.41E+05	-7.53	0	2.94	7.13E+08	6.59E+08	1.37E+09
21	9.51E+05	-7.16	0	2.94	7.20E+08	6.72E+08	1.39E+09
22	9.59E+05	-6.89	0	2.95	7.26E+08	6.80E+08	1.40E+09
23	9.68E+05	-6.57	0	2.95	7.33E+08	6.91E+08	1.42E+09
24	9.74E+05	-6.34	0	2.96	7.38E+08	6.99E+08	1.43E+09
25	9.81E+05	-6.11	0	2.96	7.43E+08	7.06E+08	1.45E+09
44	1.16E+06	-0.94	0	3.15	8.78E+08	8.77E+08	1.75E+09

[8] (given w.r.t. keel line)