MooringSense – GA 851703

Mooring System Integrity Management through Monitoring, Digital Twin and Control Technologies for Cost Reduction and Increased Efficiency

D3.2 Version 1.0

Simulation Dataset

Supporting document to the simulation dataset obtained with the numerical coupled model and selected load cases

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Executive Summary

This report is a deliverable of WP3, namely D3.2 titled "Simulation Dataset". The simulations are produced with an initial version of the coupled numerical model of the floating offshore wind turbine. The Dataset will be used for: (a) the initial development of the Structural Health Monitoring System (SHM) solution through a data-driven approach and for (b) testing and validation of the Smart Sensor. This document describes the numerical model and the load cases selected to generate the dataset.

Task 3.3 of the MooringSense project consists of the implementation of a high-fidelity, numerical coupled model of the SATH 10 MW floating offshore wind turbine (FOWT), which was previously described in deliverable D2.3. This report describes the model implemented in SIMA, in addition to the definition of an initial set of simulation load cases.

The objective with a coupled model is to have the most appropriate formulations for each of the FOWT components. In SIMA, this is done by running two software simultaneously, viz. SIMO and RIFLEX. While the former solves the equations of motions for rigid-bodies, the latter is based on a finite-element formulation for slender marine structures. Then, mooring lines, tower, and wind turbine are modelled as flexible structures, while the platform is assumed as a rigid body. Wind turbine aerodynamics are included in the model, through a BEM formulation.

The load cases are then introduced, presenting the combinations of wind, wave, and current conditions adopted in the simulations. In addition, the mooring system failures considered in the simulations dataset are described. Finally, the simulation parameters and numerical procedures are provided.

Table of Contents

Disclaimer 2
Document Control 2
Executive Summary 3
Authors.... **¡Error! Marcador no definido.**
Table of Contents 5
List of tables 6
List of figures 6
List of Acronyms and Abbreviations....7
1. Introduction....8
  1.1 Purpose and scope 8
  1.2 Intended audience / Classification 8
  1.3 Document structure 8
2. SIMA model....9
  2.1 SIMA.... 9
  2.2 Model.... 10
    2.2.1 Platform 10
    2.2.2 Wind turbine 10
      2.2.2.1 Wind turbine controller 10
    2.2.3 Mooring system 11
      2.2.3.1 Marine growth 11
  2.3 Rotor-wind alignment 12
3. Load cases and simulation procedure 13
  3.1 Environmental conditions 13
    3.1.1 Wind model.... 13
    3.1.2 Sea states.... 14
    3.1.3 Current profile and water depth.... 15
  3.2 Mooring system integrity conditions 16
    3.2.1 Mooring system damaged conditions.... 16
    3.2.2 Load cases nomenclature 17
  3.3 Simulation procedure 17
4. Simulation dataset....18
  4.1 File name convention and data format.... 18
5. References 19
Appendix A Verification of numerical wind spectra against theoretical Kaimal formulation 20
Appendix B List of load cases....22

List of tables

Table 1.1: Application documents .... **¡Error! Marcador no definido.**
Table 3.1 – Turbulence intensity according to Class C of IEC 61400-1. 13
Table 3.2 – Significant wave height associated to hub wind speed. 15
Table 3.3 – Wave peak periods associated to significant wave heights. 15
Table 3.4 – Current profile. 16
Table B.1 – Load cases HNMG (healthy, without marine growth). 22
Table B.2 – Load cases HMG (healthy, with marine growth). 23
Table B.3 – Load cases NL4S (line 4 removed at first time step). 24
Table B.4 – Load cases NL4M (line 4 removed at T = 1500.0 s). 25
Table B.5 – Load cases LT (locked turret). 26
Table B.6 – Load cases FRS (10% increased stiffness of fibre rope cross section). 27
Table B.7 – Load cases CWL4 (clump weight loss at line 4). 28
Table B.8 – Load cases BL4 (2nd upper buoy loss at line 4). 29

List of figures

Figure 2.1 – External turret system – adapted from (Gallego, et al., 2020). 11
Figure A.1 – Numerical and theoretical (Kaimal) wind spectra comparison. 21

List of Acronyms and Abbreviations

Term	Description
BEM	Blade element momentum
EWM	Extreme wind model
FE	Finite element
FOWT	Floating offshore wind turbine
IPC	Individual pitch control
NTM	Normal turbulence model
PI	Proportional integral
SPM	Single point mooring

1. Introduction

1.1 Purpose and scope

This report describes the main assumptions and procedures adopted in the implementation of the high-fidelity numerical model of the base-case FOWT. In addition, it describes the combination of load cases and modelling of environmental loads considered in the simulations.

The simulation model is implemented with the primary objective of generating datasets, for the specified load cases, to be used in the development of the controller by IKERLAN and TNO. Thus, the scope of this report is to:

- describe SIMA, and its most relevant functionalities for the project;
- explain how the FOWT is modelled, and present which formulations are adopted for each part of the model;
- present and justify the assumptions and simplifications adopted, where relevant;
- introduce the load cases, justify their selection, and present the methods and assumptions adopted in their inclusion in the SIMA model;
- explain the simulation procedure and format of the output files.

1.2 Intended audience / Classification

This is a public deliverable, thus the document is intended for all interested readers. The purpose of the document is to describe the Dataset and provide the information necessary for its use by other researchers.

1.3 Document structure

Section 2 describes SIMA and the numerical model. Section 3 provides the load cases, including the models for environmental loads, the mooring system failures, and the simulation procedure. Appendix A presents the comparison between the numerical wind spectrum and the corresponding theoretical curves, based on Kaimal formulation.

2. SIMA model

A SIMA model for the SATH platform, designed to support the DTU 10 MW turbine, is implemented. The model includes the platform/tower properties, hydrodynamic data, and mooring system specification provided by SAITEC. The DTU 10 MW wind turbine (Bak, et al., 2013) is also modelled and coupled to the platform.

This section first describes SIMA and its features of most interest in the context of the project. Following, details on the implementation of the SATH 10 MW digital twin are provided.

2.1 SIMA

SIMA is a workbench for simulation and analyses of marine operations and ocean structures. It couples two software that have been developed by SINTEF Ocean (former MARINTEK), and experimentally validated in the context of research and commercial projects, for over 30 years:

- SIMO, a simulator of marine operations in the time domain;
- RIFLEX, a finite-element based software for analysis of slender marine structures and wind turbines.

For the specific objectives of the MooringSense project, it is important that the platform responses to waves, current, mooring system, and wind turbine loads, are accurately represented, so that the motions imposed at the mooring fairleads are realistic. In addition, the tension experienced by the mooring lines, as well as their geometric configuration, shall be reproduced with high fidelity. It is also important that the mooring system failures analysed in the project can be well represented.

SIMO is mainly used for simulating the responses of floating rigid-bodies to external loads. For the particular objectives of the project, the following functionalities are highlighted:

- Slowly-varying 2nd-order wave loads may be considered using either Newman's approximation, or full quadratic transfer functions (QTFs). A simplified formulation for wave drift damping is also available.
- Viscous damping can be represented as a combination of linear and quadratic coefficients. It is possible to separate low-frequency from wave-frequency motions, and apply different matrices of coefficients for each motion component.
- Current loads can also be applied as a combination of linear and quadratic coefficients. The relative fluid velocity is used in the computations.

RIFLEX is used for solving the structural dynamics of flexible structures. Its most relevant characteristics for the project are:

- The mooring lines can be modelled with a nonlinear FE formulation, using bar or beam elements. Cross-sectional properties can be provided according to symmetry assumptions. Nonlinear stiffness properties can be provided based on tension-elongation tables.
- Hydrodynamic loads are distributed through the flexible structures. The user has great freedom to model the hydrodynamic loads on the lines, ranging from the classical Morison formulation to other combinations of linear + quadratic viscous coefficients, plus the inertial term.
- A line can be composed of several segments, with varying cross section definitions for the modelling of hybrid line configurations. The mesh resolution can be varied easily, making it simple to reduce element length at e.g. regions of larger curvature.
- Wind turbines can be completely modelled with the software's own resources. The blades are represented by FE lines with airfoil properties assigned to its cross-sections. The *blade element momentum* (BEM) model is adopted for solving the wind turbine aerodynamics, with Øye's models for accounting for dynamic wake and dynamic stall effects. Hub and tip losses are considered with the Prandtl's reduction factor, while the Glauert's correction is used for high

induction factors. See (Hansen M. , 2008) for details on the BEM method and the models/corrections mentioned above. User-defined external control systems for the blade-pitch angles and generator torque can be adopted. Three-dimensional turbulent wind time-series generated with Turbsim or Mann's models may be loaded into the model.

The approach chosen for the project is therefore a *coupled SIMO-RIFLEX model*, with the platform modelled in SIMO, while the mooring system and wind turbine (tower + RNA) are modelled in RIFLEX. The mooring system loads and the wind turbine loads, calculated by RIFLEX, are included in SIMO's equations of motions at each time step. SIMO then provides the motions of the nodes that interface with RIFLEX, resulting in a new configuration for the FE model.

In addition to coupling SIMO and RIFLEX, SIMA also provides a modelling and visualization environment. Post-processing tools are also available, and the user can set-up workflows for batch simulations and for interfacing with external software, for pre/post- processing.

2.2 Model

The SIMA model can be divided into the platform, the mooring system, and the wind turbine. A coordinate system placed at MWL (mean waterline) and with vertical axis coinciding with the tower centre line is adopted. The main modelling characteristics of the model subsystems are provided below.

2.2.1 Platform

The platform inertia properties correspond to the steel/concrete mass distribution provided by (SAITEC, 2020). Buoyancy is assumed as an upward force applied at the platform's centre of flotation. Changes due to volume variations are taken into account with a linear hydrostatic stiffness matrix.

The hydrodynamic model comprises radiation coefficients, as an infinite-frequency added mass matrix combined with retardation functions; 1st-order wave load transfer functions; wave drift coefficients; linear + quadratic damping coefficient matrices; and quadratic current coefficients. The radiation and 1st-order loads transfer functions, as well as the damping and current coefficients, were provided by SAITEC. The wave drift coefficients were obtained independently, based on the platform geometry provided by SAITEC.

When the model tests are available, the model may be updated for improvement of the hydrodynamic model, including new estimates for the viscous coefficients and for the slowly-varying wave loads model.

2.2.2 Wind turbine

The airfoils and cross-sectional properties of the DTU 10 MW wind turbine, as specified in (Bak, et al., 2013), are implemented in the model. Beam elements with double-symmetric cross-sections are used for the blades, with mass and stiffness distribution as determined in the wind turbine definition. Blade pre-bend, twist angle, rotor pre-cone angle, and shaft tilt also follow the specifications.

The tower is modelled with beam elements and axisymmetric cross-sections, using geometric and structural properties from (SAITEC, 2020). The tower base is made solidary to the platform with a rigid connection.

2.2.2.1 Wind turbine controller

The model is prepared to run with external control system libraries, which can either be provided as a "Bladed-style" DLL, or implemented in Java and compiled as an executable ".jar" file. Controller development is the objective of work packages 5 and 6, and different versions are intended to be used in the coupled numerical model.

In the present version, the model includes two external controllers. One is a basic *variable speed - variable pitch* (VSVP) approach, with a power optimization strategy at below-rated rotor speed; and a proportional-integral (PI) controller for the blade pitch angle, above rated wind speed. The controller is implemented in Java and follows the structure of the *Basic DTU wind energy controller* (Hansen & Henriksen, 2013). The PI-controller gains are set to render the controller bandwidth below the platform pitch natural frequency, avoiding controller-motion interactions.

The other version is based on the NREL/ROSCO controller (NREL, 2020), which is a Bladed-style DLL. The reason to make this controller available is that it features further functionalities, in addition to the VSVP approach, including yaw control by IPC – as further discussed in Section **¡Error! No se encuentra el origen de la referencia.**.

2.2.3 Mooring system

The SAITEC 10 MW's mooring system consists on an "external turret" type arrangement, which allows the platform to rotate around the single-point mooring connection as in Figure 2.1.

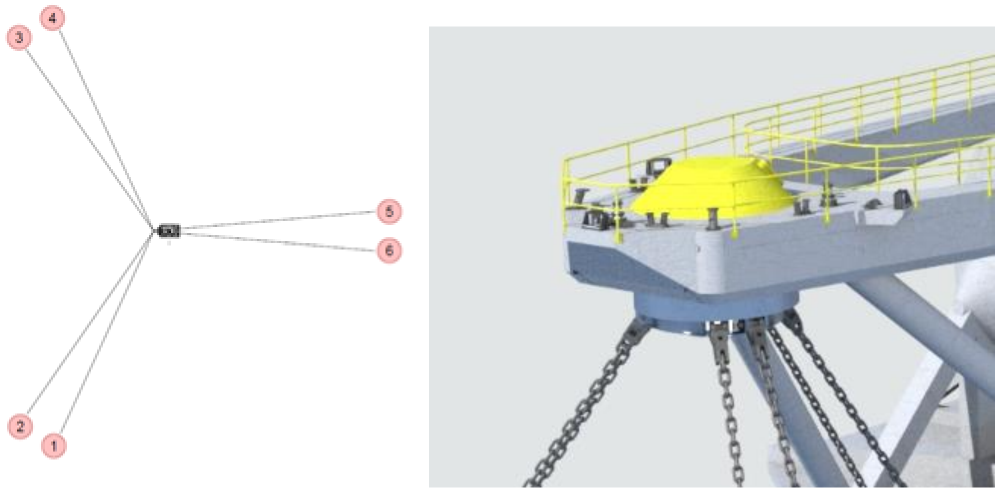

Figure 2.1 – External turret system – adapted from (Gallego, et al., 2020).

The turret is represented in the model by a rigid line with two elements, connected with a joint that allows for rotations around the line's main axis. The upper extremity of the turret is connected to the platform, while the lower extremity is connected to the fairleads.

The mooring lines consist of a combination of chain and fibre rope segments, with a clump weight and buoys distributed through the line's length. In the model, the lines are composed of bar elements, with axisymmetric cross sections. The fibre cross section assumes a nonlinear stiffness curve, while for the chain a linear stiffness relation is considered. Mass and hydrodynamic coefficients are specified as provided in (SAITEC, 2020). The force-elongation curve for the fibre rope segment is based on communication with SAITEC and BRIDON.

2.2.3.1 Marine growth

Marine growth affects the mass coefficient, external area, and drag coefficients of mooring lines. The thickness of accumulated marine growth is a function of water depth, and for the Buchan Deep site it varies as follows (Statoil, 2013):

- 100 mm, from + 2 m to -40 m water depth;
- 50 mm, below -40 m water depth.

The lines cross-sectional properties are then changed according to their actual depth. A static analysis is performed to determine which segments lie at each of the layers above. Following (DNVGL, 2018), the increase in the mass coefficient is given by:

$$M_{growth} = \frac{\pi}{4}\left[\left(D_{nom} + 2\Delta T_{growth}\right)^2 - D_{nom}^2\right]\rho_{growth}\mu \tag{2.1}$$

The drag coefficients, on the other hand, are increased according to:

$$C_{D,growth} = C_D\left[\frac{D_{nom} + 2\Delta T_{growth}}{D_{nom}}\right] \tag{2.2}$$

2.3 Rotor-wind alignment

The SATH 10 MW FOWT has, as a main characteristic, a single point mooring (SPM) system. This means that the platform can rotate freely around the turret, aligning itself with the resultant of the environmental loading – and thus reducing the loading at the mooring system. On the other hand, the resultant may not necessarily coincide with the wind direction. The nacelle should in this case rotate relatively to the tower, such that the rotor always faces the main incoming wind direction.

In the SIMA model, the wind turbine can be rotated around the tower axis prior to start of the simulation. However, in the current software version it is not possible to rotate the nacelle *during* the simulation – i.e., there is no nacelle yaw control.

Thus, a preliminary static analysis is performed, to determine the expected platform orientation for each load case. This analysis assumes the resultant of waves, current, and wind mean loads. The relative mean nacelle orientation, relative to the platform, is determined.

This initial configuration is not enough, however, to prevent the platform to rotate away from the required yaw orientation. Two approaches for keeping the platform yaw position were then considered:

1. adoption of an artificial yaw stiffness coefficient, at the platform;
2. activation of yaw control by individual pitch control (IPC), available in ROSCO. In this case, individual increments on the blade pitch induce a torque around the turret axis, allowing for control of the platform orientation with respect to the incident wind direction.

Alternative 1 has the disadvantage of introducing non-physical loads to the system, while alternative 2 may induce large cyclic loading on the blades and tower. Both alternatives are available, as an initial way to keep the rotor aligned to the wind. Other strategies should nevertheless be considered for updated versions of the numerical model and control system.

3. Load cases and simulation procedure

A list of mean hub wind speeds, associated to design situations from IEC 61400-1 (IEC, 2005), was proposed by IKERLAN. A total of 13 load cases are defined, of which 10 correspond to operational conditions, with normal turbulence model (NTM); 2 correspond to parked condition, with NTM; and one corresponds to parked condition, with extreme wind model (EWM).

The sea states associated to each wind condition are based on the metocean report for the Buchan Deep site (Statoil, 2013). The current profile is also determined according to the metocean data, and the same profile is adopted for all conditions.

Each set of 13 load cases is simulated with the 8 healthy and damaged mooring system conditions, according to damage definitions agreed with IKERLAN and SAITEC. A total of 104 simulations is therefore delivered in the dataset.

3.1 Environmental conditions

3.1.1 Wind model

A total of 10 wind speeds, ranging from 4.0 m/s to 24.0 m/s with increments of 2.0 m/s, are considered for the NTM conditions. In addition, one condition with 25.0 m/s and EWM is adopted.

For the NTM cases, turbulence intensity is based on Class C of IEC 61400-1 (IEC, 2005). This means that the standard deviation in x is assumed to be the 90% quantile, given according to:

$$\sigma_x = I_{ref}(0.75V_{hub} + 5.6) \tag{3.1}$$

where $I_{ref} = 0.12$ is the mean intensity for V_{hub}= 15.0 m/s. For the EWM case, the turbulence is equal to 0.11, also according to the standard. Table 3.1 provides the intensity values for each wind speed.

Table 3.1 – Hub mean wind speeds and associated turbulence intensity.

V_{hub} (m/s)	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	24.0	25.0
Intensity (-)	0.26	0.20	0.17	0.16	0.15	0.14	0.13	0.13	0.12	0.12	0.11

Wind shear is considered following the power law proposed in IEC 61400-3:

$$V_w(z) = V_{ref}\left(\frac{z}{z_{hub}}\right)^{\alpha} \tag{3.2}$$

where α = 0.14, for the NTM wind; and α=0.11, for the EWM.

In SIMA, the wind incidence direction uses the "going to" convention. Based on this convention, all the wind conditions have incidence direction of 330 deg.

Turbulence time-series

The turbulence time-series are generated with Mann's model (Mann, 1998). The following grid properties are adopted:

- Grid width: 200.0 m
- Grid height: 200.0 m
- Grid points Y: 32
- Grid points Z: 32

The box length and grid points number in X direction are determined based on the required time-step, simulation length, and mean wind speed at hub height. A time step of 0.032 s is used, and all files have a total of 4200 s of duration, corresponding to 131072 grid points. The grid length is determined by the time step and the mean wind speed for each condition:

$$\begin{gathered}\Delta x = V_{mean} \times \Delta t \\ L_x = N_x \Delta x\end{gathered} \tag{3.3}$$

Verification against theoretical Kaimal spectrum

The spectra of the x-direction turbulent timeseries at gridpoint (y=16,z=16) are plotted against the theoretical Kaimal spectum, as described in IEC 61400-I, in Appendix A.

3.1.2 Sea states

In order to ensure good representativeness, the wave significant heights associated to each wind speed were determined based on the metocean report for the Buchan Deep site (Statoil, 2013). The document provides long-term distributions for wind velocity, significant wave heights and wave peak periods, current, and tide. In addition, an exponential relation between H_s and wind speed (U_w) is provided:

$$H_s = 0.719 \exp(0.0832 U_w) \tag{3.4}$$

The wave significant heights are determined based on this relation. The only exception is the wave height associated with 25.0 m/s wind speed, since it is supposed to represent the 50-year *extreme sea state* (ESS). In this case, the 50-year wave height is obtained from the metocean data directly. The significant wave heights associated to each wind speed are given in Table 3.2.

It is stressed that the sea states correspond to the wind speeds provided by an exponential relation. This is expected to differ to some extent from what could be obtained with a joint distribution for U_w, H_s, and T_p.

The wave incoming direction of 0 deg is used in all cases. The JOSNWAP spectrum with gamma 3.3 is adopted, and long-crested waves are assumed.

Table 3.2 – Significant wave height associated to hub wind speed.

Wind speed (m/s)		
Hub (z = 108.3 m)	Ref. (z = 100.0 m)	H_s
4.00	3.99	1.0
6.00	5.97	1.2
8.00	7.96	1.4
10.00	9.95	1.7
12.00	11.93	1.9
14.00	13.91	2.3
16.00	15.91	2.7
18.00	17.88	3.2
20.00	19.87	3.8
24.00	23.84	5.2
25.00	24.83	10.5

The associated wave peak periods correspond to the most probable peak period for the newly calculated H_s[1], and were obtained based on the joint distribution provided in the metocean report.

Table 3.3 – Wave peak periods associated to significant wave heights.

H_s (m)	1.00	1.18	1.39	1.65	1.94	2.29	2.70	3.18	3.76	5.23	10.50
T_p (s)	6.00	6.28	6.53	6.79	7.14	7.60	8.02	8.52	9.08	10.29	14.30

3.1.3 Current profile and water depth

The metocean report indicates that the mean current at 25.0 m water depth is 0.40 m/s, which following the power law provided in (DNV, 2010) corresponds to 0.41 m/s at the surface. The current profile in Table 3.4 is adopted.

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[1] The most probable peak period corresponds to maximum probability of occurrence, in the joint Hs-Tp distribution, for a given Hs.

Table 3.4 – Current profile.

z (m)	V_c (m/s)
0.0	0.41
-10.0	0.41
-20.0	0.40
-30.0	0.40
-40.0	0.39
-50.0	0.38
-60.0	0.37
-70.0	0.36
-80.0	0.35
-90.0	0.34
-100.0	0.32
-110.0	0.29
-120.0	0.00

The mooring system designed by SAITEC assumed a water depth of 120.0 m. This value is also adopted for the simulations.

3.2 Mooring system integrity conditions

The objective of the simulations is to provide a dataset based on both intact and damaged mooring system conditions. The intact configuration should be analysed both with and without marine growth (as specified in Section 2.2.3), which for the Buchan Deep site is expected to reach a constant added thickness to the mooring lines two years after installation (Statoil, 2013). All the damaged conditions, on the other hand, are simulated assuming lines with marine growth.

3.2.1 Mooring system damaged conditions

The damaged conditions consist of the following failures/property modifications:

- Removal of line 4 (both before and during the simulation).
- 10% increase in the fibre-rope stiffness properties of all lines[2].
- Clump weight loss at line 4.
- 2nd upper buoy loss at line 4.
- Locking of the turret.

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[2] Fibre properties changes are actually more complex than simply increasing the cross-sectional stiffness. More realistic degradation conditions can be considered, based on the accumulated cyclic loading for the given site and detailed line properties.

One SIMA model is created for each of the damages above, in addition to the healthy condition. A total of 8 combinations (2 healthy + 6 damaged) are then considered.

3.2.2 Load cases nomenclature

All the 13 load cases are simulated for each of the 8 mooring system conditions above. The following nomenclature is adopted for identifying the cases:

- HNMG – healthy, without marine growth.
- HMG – healthy, with marine growth.
- NL4S – loss of line 4, at the start of the simulation (T = 0 s).
- NL4M – loss of line 4, during the simulation (T = 1500 s).
- LT – locked turret.
- FRS – fibre rope stiffness increased in 10%, for all lines.
- CLW4 – loss of clump weight from line 4.
- BWL4 – loss of 2nd upper buoy from line 4.

Appendix B summarizes the load cases, in combination with the mooring system integrity conditions above.

3.3 Simulation procedure

A nonlinear FE formulation is adopted, with numerical integration following the Newmark procedure with $1\backslash\beta = 3.9$ and $\gamma = 0.505$. Rayleigh damping is adopted for improving numerical stability. A global stiffness-proportional damping factor of 0.005 is used, while no mass-proportional damping is considered, in order to prevent artificially damped LF motions – see (Cook, Malkus, Plesha, & Witt, 2001) for details on numerical integration and Rayleigh damping.

The simulation length is 4200.0 s for all cases, with a time step of 0.0125 s. The first 600.0 s are assumed as transient and should thus be disregarded from analyses.

Wave kinematics in the FE elements are modelled linearly, according to Airy theory, assuming the static configuration. Wave loads time series are generated with a fast Fourrier transform before each simulation, for a set of relative incidence directions, and interpolated during the dynamic analysis.

The cases with parked turbine assume idling turbine, with no generator speed and blade pitch angle of 88 deg. This configuration results in a slow rotation, providing a small amount of aerodynamic damping.

4. Simulation dataset

The simulation dataset is intended to be published in a repository, to be indicated at the MooringSense project website.

All simulation parameters are included in the result files, including environment setup, cross-sectional properties, mooring line segment length, and anchor positions. A "readme" file explaining the parameters will also be available in the repository.

4.1 File name convention and data format

The following convention is adopted to identify the simulation files:

LCID_ctrID.h5

where "LCID" can be any of the load cases nomenclature acronym provided in Section 3.2.2, while "ctrID" is an identifier for the control strategy adopted in the simulation.

For the simulation dataset submitted together with this report, the identifier "BLAYS" (BaseLine controller, Artificial Yaw Stiffness) is adopted. For example, the times series for load case 5, with locked turret, are written in the file *5LT_BLAYS.h5*.

Hierarchical Data Format version 5 (HDF5) is chosen for storage of the time series. A MATLAB script is provided together with the dataset, for accessing the time series in the files. HDF5 files can also be accessed with Python, using the h5py package (see https://docs.h5py.org/en/stable/index.html for more information).

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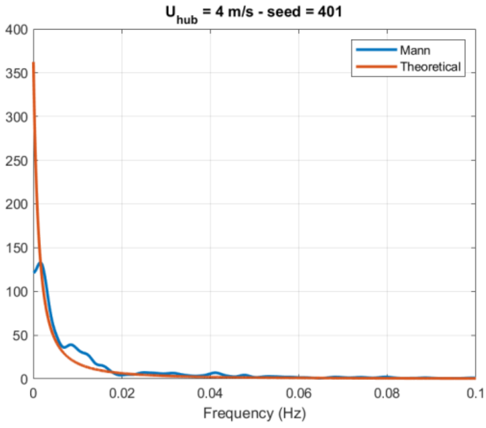
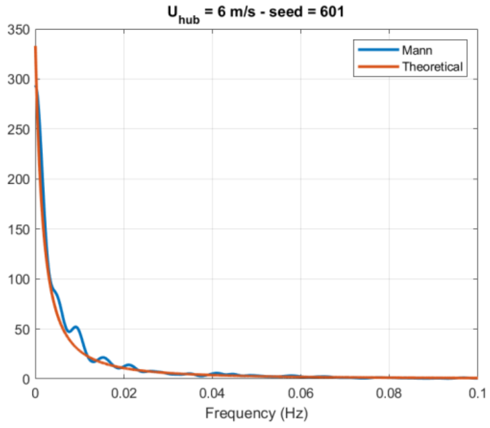
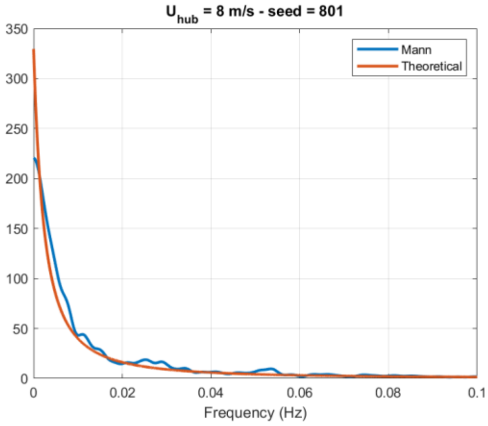
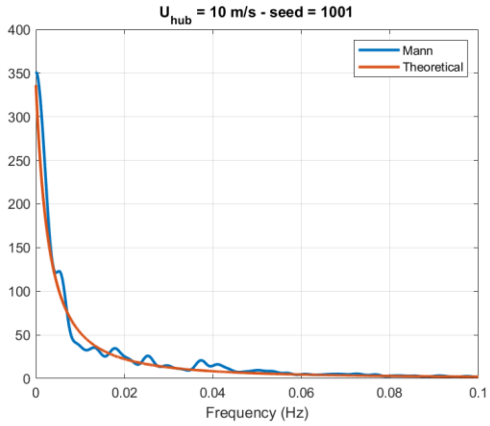
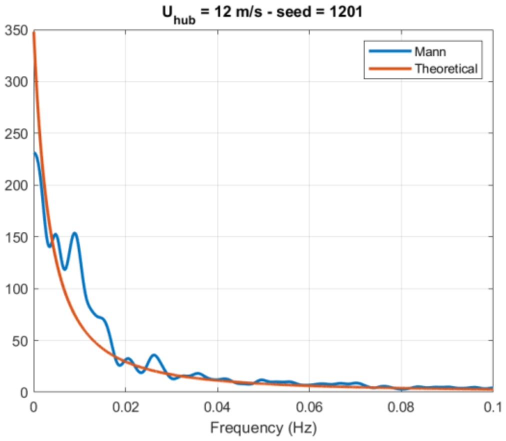
Appendix A Verification of numerical wind spectra against theoretical Kaimal formulation

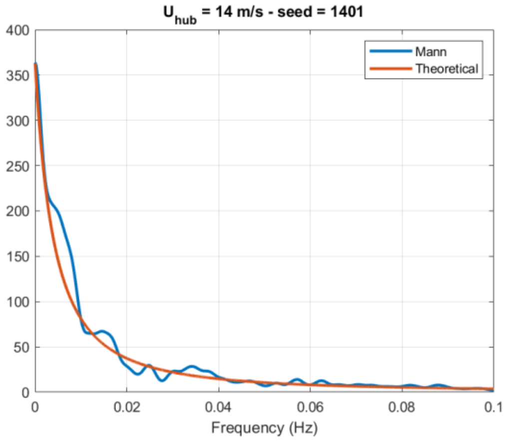












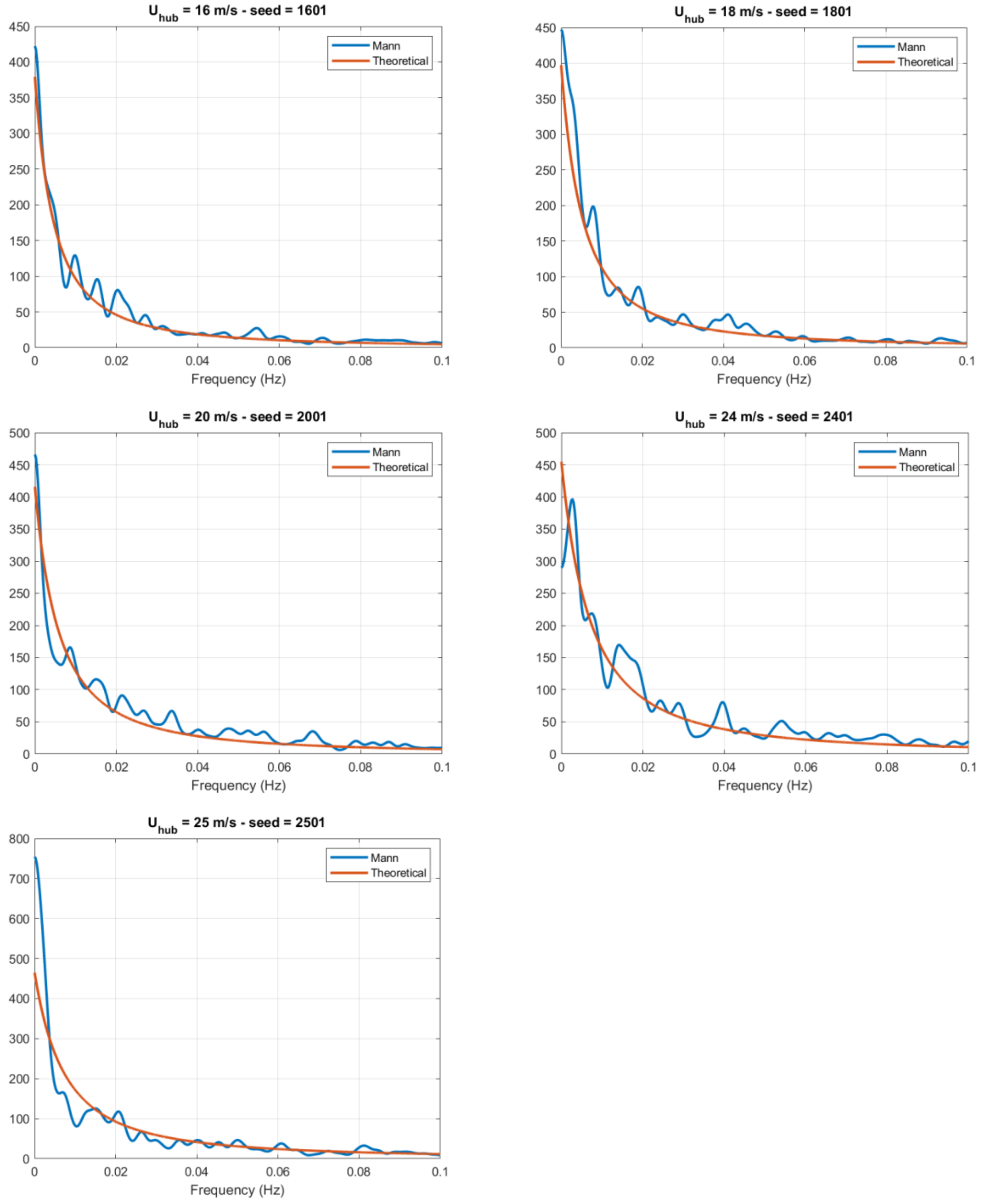


Figure A.1 – Numerical and theoretical (Kaimal) wind spectra comparison.

Appendix B List of load cases

Table B.1 – Load cases HNMG (healthy, without marine growth).

Simulation ID	DLC	WIND					SEA						DAMAGE
							WAVE				CURRENT		
		MEAN WIND SPEED AT HUB HEIGHT [m/s]	WIND DIRECTION [deg] (No wind direction change within the simulation)	POWER LAW FOR WIND PROFILE	TURBULENCE			SPECTRAL PARAMETERS					
					MODEL	INTENSITY	WAVE SPECTRUM	SIGNIFICANT WAVE HEIGHT [m]	PEAK PERIOD [s]	WAVE DIRECTION (assuming long-crested sea) [deg]	CURRENT DIRECTION AT ANY DEPTH [deg]	SPEED [m/s]	
1 HNMG	6.1.a	25.0	330.0	0.11	Extreme	0.11	JOSNWAP	10.5	14.3	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
2 HNMG	6.4	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
3 HNMG	6.4	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
4 HNMG	1.2	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
5 HNMG	1.2	6.0	330.0	0.14	Normal	0.20	JOSNWAP	1.2	6.3	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
6 HNMG	1.2	8.0	330.0	0.14	Normal	0.17	JOSNWAP	1.4	6.5	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
7 HNMG	1.2	10.0	330.0	0.14	Normal	0.16	JOSNWAP	1.7	6.8	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
8 HNMG	1.2	12.0	330.0	0.14	Normal	0.15	JOSNWAP	1.9	7.1	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
9 HNMG	1.2	14.0	330.0	0.14	Normal	0.14	JOSNWAP	2.3	7.6	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
10 HNMG	1.2	16.0	330.0	0.14	Normal	0.13	JOSNWAP	2.7	8.0	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
11 HNMG	1.2	18.0	330.0	0.14	Normal	0.13	JOSNWAP	3.2	8.5	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
12 HNMG	1.2	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH
13 HNMG	1.2	24.0	330.0	0.14	Normal	0.12	JOSNWAP	5.2	10.3	0.0	0.0	0.41	HEALTHY, NO MARINE GROWTH

Table B.2 – Load cases HMG (healthy, with marine growth).

Simulation ID	DLC	WIND					SEA						DAMAGE
							WAVE				CURRENT		
					TURBULENCE			SPECTRAL PARAMETERS					
		MEAN WIND SPEED AT HUB HEIGHT [m/s]	WIND DIRECTION [deg] (No wind direction change within the simulation)	POWER LAW FOR WIND PROFILE	MODEL	INTENSITY	WAVE SPECTRUM	SIGNIFICANT WAVE HEIGHT [m]	PEAK PERIOD [s]	WAVE DIRECTION (assuming long-crested sea) [deg]	CURRENT DIRECTION AT ANY DEPTH [deg]	SPEED [m/s]	
1 HMG	6.1.a	25.0	330.0	0.11	Extreme	0.11	JOSNWAP	10.5	14.3	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
2 HMG	6.4	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
3 HMG	6.4	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
4 HMG	1.2	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
5 HMG	1.2	6.0	330.0	0.14	Normal	0.20	JOSNWAP	1.2	6.3	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
6 HMG	1.2	8.0	330.0	0.14	Normal	0.17	JOSNWAP	1.4	6.5	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
7 HMG	1.2	10.0	330.0	0.14	Normal	0.16	JOSNWAP	1.7	6.8	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
8 HMG	1.2	12.0	330.0	0.14	Normal	0.15	JOSNWAP	1.9	7.1	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
9 HMG	1.2	14.0	330.0	0.14	Normal	0.14	JOSNWAP	2.3	7.6	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
10 HMG	1.2	16.0	330.0	0.14	Normal	0.13	JOSNWAP	2.7	8.0	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
11 HMG	1.2	18.0	330.0	0.14	Normal	0.13	JOSNWAP	3.2	8.5	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
12 HMG	1.2	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	HEALTHY, MARINE GROWTH
13 HMG	1.2	24.0	330.0	0.14	Normal	0.12	JOSNWAP	5.2	10.3	0.0	0.0	0.41	HEALTHY, MARINE GROWTH

Table B.3 – Load cases NL4S (line 4 removed at first time step).

Simulation ID	DLC	WIND					SEA						DAMAGE
							WAVE				CURRENT		
		MEAN WIND SPEED AT HUB HEIGHT [m/s]	WIND DIRECTION [deg] (No wind direction change within the simulation)	POWER LAW FOR WIND PROFILE	TURBULENCE			SPECTRAL PARAMETERS					
					MODEL	INTENSITY	WAVE SPECTRUM	SIGNIFICANT WAVE HEIGHT [m]	PEAK PERIOD [s]	WAVE DIRECTION (assuming long-crested sea) [deg]	CURRENT DIRECTION AT ANY DEPTH [deg]	SPEED [m/s]	
1 NL4S	6.1.a	25.0	330.0	0.11	Extreme	0.11	JOSNWAP	10.5	14.3	0.0	0.0	0.41	NO LINE 4, T = 0 s
2 NL4S	6.4	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	NO LINE 4, T = 0 s
3 NL4S	6.4	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	NO LINE 4, T = 0 s
4 NL4S	1.2	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	NO LINE 4, T = 0 s
5 NL4S	1.2	6.0	330.0	0.14	Normal	0.20	JOSNWAP	1.2	6.3	0.0	0.0	0.41	NO LINE 4, T = 0 s
6 NL4S	1.2	8.0	330.0	0.14	Normal	0.17	JOSNWAP	1.4	6.5	0.0	0.0	0.41	NO LINE 4, T = 0 s
7 NL4S	1.2	10.0	330.0	0.14	Normal	0.16	JOSNWAP	1.7	6.8	0.0	0.0	0.41	NO LINE 4, T = 0 s
8 NL4S	1.2	12.0	330.0	0.14	Normal	0.15	JOSNWAP	1.9	7.1	0.0	0.0	0.41	NO LINE 4, T = 0 s
9 NL4S	1.2	14.0	330.0	0.14	Normal	0.14	JOSNWAP	2.3	7.6	0.0	0.0	0.41	NO LINE 4, T = 0 s
10 NL4S	1.2	16.0	330.0	0.14	Normal	0.13	JOSNWAP	2.7	8.0	0.0	0.0	0.41	NO LINE 4, T = 0 s
11 NL4S	1.2	18.0	330.0	0.14	Normal	0.13	JOSNWAP	3.2	8.5	0.0	0.0	0.41	NO LINE 4, T = 0 s
12 NL4S	1.2	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	NO LINE 4, T = 0 s
13 NL4S	1.2	24.0	330.0	0.14	Normal	0.12	JOSNWAP	5.2	10.3	0.0	0.0	0.41	NO LINE 4, T = 0 s

Table B.4 – Load cases NL4M (line 4 removed at T = 1500.0 s).

		WIND					SEA						
							WAVE				CURRENT		
					TURBULENCE			SPECTRAL PARAMETERS					
Simulation ID	DLC	MEAN WIND SPEED AT HUB HEIGHT [m/s]	WIND DIRECTION [deg] (No wind direction change within the simulation)	POWER LAW FOR WIND PROFILE	MODEL	INTENSITY	WAVE SPECTRUM	SIGNIFICANT WAVE HEIGHT [m]	PEAK PERIOD [s]	WAVE DIRECTION (assuming long-crested sea) [deg]	CURRENT DIRECTION AT ANY DEPTH [deg]	SPEED [m/s]	DAMAGE
1 NL4M	6.1.a	25.0	330.0	0.11	Extreme	0.11	JOSNWAP	10.5	14.3	0.0	0.0	0.41	NO LINE 4, T = 1500 s
2 NL4M	6.4	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	NO LINE 4, T = 1500 s
3 NL4M	6.4	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	NO LINE 4, T = 1500 s
4 NL4M	1.2	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	NO LINE 4, T = 1500 s
5 NL4M	1.2	6.0	330.0	0.14	Normal	0.20	JOSNWAP	1.2	6.3	0.0	0.0	0.41	NO LINE 4, T = 1500 s
6 NL4M	1.2	8.0	330.0	0.14	Normal	0.17	JOSNWAP	1.4	6.5	0.0	0.0	0.41	NO LINE 4, T = 1500 s
7 NL4M	1.2	10.0	330.0	0.14	Normal	0.16	JOSNWAP	1.7	6.8	0.0	0.0	0.41	NO LINE 4, T = 1500 s
8 NL4M	1.2	12.0	330.0	0.14	Normal	0.15	JOSNWAP	1.9	7.1	0.0	0.0	0.41	NO LINE 4, T = 1500 s
9 NL4M	1.2	14.0	330.0	0.14	Normal	0.14	JOSNWAP	2.3	7.6	0.0	0.0	0.41	NO LINE 4, T = 1500 s
10 NL4M	1.2	16.0	330.0	0.14	Normal	0.13	JOSNWAP	2.7	8.0	0.0	0.0	0.41	NO LINE 4, T = 1500 s
11 NL4M	1.2	18.0	330.0	0.14	Normal	0.13	JOSNWAP	3.2	8.5	0.0	0.0	0.41	NO LINE 4, T = 1500 s
12 NL4M	1.2	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	NO LINE 4, T = 1500 s
13 NL4M	1.2	24.0	330.0	0.14	Normal	0.12	JOSNWAP	5.2	10.3	0.0	0.0	0.41	NO LINE 4, T = 1500 s

Table B.5 – Load cases LT (locked turret).

Simulation ID	DLC	WIND					SEA						DAMAGE
							WAVE				CURRENT		
		MEAN WIND SPEED AT HUB HEIGHT [m/s]	WIND DIRECTION [deg] (No wind direction change within the simulation)	POWER LAW FOR WIND PROFILE	TURBULENCE			SPECTRAL PARAMETERS					
					MODEL	INTENSITY	WAVE SPECTRUM	SIGNIFICANT WAVE HEIGHT [m]	PEAK PERIOD [s]	WAVE DIRECTION (assuming long-crested sea) [deg]	CURRENT DIRECTION AT ANY DEPTH [deg]	SPEED [m/s]	
1 LT	6.1.a	25.0	330.0	0.11	Extreme	0.11	JOSNWAP	10.5	14.3	0.0	0.0	0.41	LOCKED TURRET
2 LT	6.4	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	LOCKED TURRET
3 LT	6.4	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	LOCKED TURRET
4 LT	1.2	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	LOCKED TURRET
5 LT	1.2	6.0	330.0	0.14	Normal	0.20	JOSNWAP	1.2	6.3	0.0	0.0	0.41	LOCKED TURRET
6 LT	1.2	8.0	330.0	0.14	Normal	0.17	JOSNWAP	1.4	6.5	0.0	0.0	0.41	LOCKED TURRET
7 LT	1.2	10.0	330.0	0.14	Normal	0.16	JOSNWAP	1.7	6.8	0.0	0.0	0.41	LOCKED TURRET
8 LT	1.2	12.0	330.0	0.14	Normal	0.15	JOSNWAP	1.9	7.1	0.0	0.0	0.41	LOCKED TURRET
9 LT	1.2	14.0	330.0	0.14	Normal	0.14	JOSNWAP	2.3	7.6	0.0	0.0	0.41	LOCKED TURRET
10 LT	1.2	16.0	330.0	0.14	Normal	0.13	JOSNWAP	2.7	8.0	0.0	0.0	0.41	LOCKED TURRET
11 LT	1.2	18.0	330.0	0.14	Normal	0.13	JOSNWAP	3.2	8.5	0.0	0.0	0.41	LOCKED TURRET
12 LT	1.2	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	LOCKED TURRET
13 LT	1.2	24.0	330.0	0.14	Normal	0.12	JOSNWAP	5.2	10.3	0.0	0.0	0.41	LOCKED TURRET

Table B.6 – Load cases FRS (10% increased stiffness of fibre rope cross section).

		WIND					SEA						DAMAGE
							WAVE				CURRENT		
					TURBULENCE			SPECTRAL PARAMETERS					
Simulation ID	**DLC**	**MEAN WIND SPEED AT HUB HEIGHT [m/s]**	**WIND DIRECTION [deg]** (No wind direction change within the simulation)	**POWER LAW FOR WIND PROFILE**	**MODEL**	**INTENSITY**	**WAVE SPECTRUM**	**SIGNIFICANT WAVE HEIGHT [m]**	**PEAK PERIOD [s]**	**WAVE DIRECTION (assuming long-crested sea) [deg]**	**CURRENT DIRECTION AT ANY DEPTH [deg]**	**SPEED [m/s]**	
1 FRS	6.1.a	25.0	330.0	0.11	Extreme	0.11	JOSNWAP	10.5	14.3	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
2 FRS	6.4	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
3 FRS	6.4	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
4 FRS	1.2	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
5 FRS	1.2	6.0	330.0	0.14	Normal	0.20	JOSNWAP	1.2	6.3	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
6 FRS	1.2	8.0	330.0	0.14	Normal	0.17	JOSNWAP	1.4	6.5	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
7 FRS	1.2	10.0	330.0	0.14	Normal	0.16	JOSNWAP	1.7	6.8	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
8 FRS	1.2	12.0	330.0	0.14	Normal	0.15	JOSNWAP	1.9	7.1	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
9 FRS	1.2	14.0	330.0	0.14	Normal	0.14	JOSNWAP	2.3	7.6	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
10 FRS	1.2	16.0	330.0	0.14	Normal	0.13	JOSNWAP	2.7	8.0	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
11 FRS	1.2	18.0	330.0	0.14	Normal	0.13	JOSNWAP	3.2	8.5	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
12 FRS	1.2	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.
13 FRS	1.2	24.0	330.0	0.14	Normal	0.12	JOSNWAP	5.2	10.3	0.0	0.0	0.41	10% HIGHER FIBRE ROPE STIFF.

Table B.7 – Load cases CWL4 (clump weight loss at line 4).

		WIND					SEA						
							WAVE				CURRENT		
					TURBULENCE			SPECTRAL PARAMETERS					
Simulation ID	**DLC**	**MEAN WIND SPEED AT HUB HEIGHT [m/s]**	**WIND DIRECTION [deg]** (No wind direction change within the simulation)	**POWER LAW FOR WIND PROFILE**	**MODEL**	**INTENSITY**	**WAVE SPECTRUM**	**SIGNIFICANT WAVE HEIGHT [m]**	**PEAK PERIOD [s]**	**WAVE DIRECTION (assuming long-crested sea) [deg]**	**CURRENT DIRECTION AT ANY DEPTH [deg]**	**SPEED [m/s]**	**DAMAGE**
1 CWL4	6.1.a	25.0	330.0	0.11	Extreme	0.11	JOSNWAP	10.5	14.3	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
2 CWL4	6.4	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
3 CWL4	6.4	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
4 CWL4	1.2	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
5 CWL4	1.2	6.0	330.0	0.14	Normal	0.20	JOSNWAP	1.2	6.3	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
6 CWL4	1.2	8.0	330.0	0.14	Normal	0.17	JOSNWAP	1.4	6.5	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
7 CWL4	1.2	10.0	330.0	0.14	Normal	0.16	JOSNWAP	1.7	6.8	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
8 CWL4	1.2	12.0	330.0	0.14	Normal	0.15	JOSNWAP	1.9	7.1	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
9 CWL4	1.2	14.0	330.0	0.14	Normal	0.14	JOSNWAP	2.3	7.6	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
10 CWL4	1.2	16.0	330.0	0.14	Normal	0.13	JOSNWAP	2.7	8.0	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
11 CWL4	1.2	18.0	330.0	0.14	Normal	0.13	JOSNWAP	3.2	8.5	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
12 CWL4	1.2	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4
13 CWL4	1.2	24.0	330.0	0.14	Normal	0.12	JOSNWAP	5.2	10.3	0.0	0.0	0.41	CLUMP WEIGHT LOSS, LINE 4

Table B.8 – Load cases BL4 (2nd upper buoy loss at line 4).

Simulation ID	DLC	WIND					SEA						DAMAGE
							WAVE				CURRENT		
		MEAN WIND SPEED AT HUB HEIGHT [m/s]	WIND DIRECTION [deg] (No wind direction change within the simulation)	POWER LAW FOR WIND PROFILE	TURBULENCE			SPECTRAL PARAMETERS					
					MODEL	INTENSITY	WAVE SPECTRUM	SIGNIFICANT WAVE HEIGHT [m]	PEAK PERIOD [s]	WAVE DIRECTION (assuming long-crested sea) [deg]	CURRENT DIRECTION AT ANY DEPTH [deg]	SPEED [m/s]	
1 BL4	6.1.a	25.0	330.0	0.11	Extreme	0.11	JOSNWAP	10.5	14.3	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
2 BL4	6.4	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
3 BL4	6.4	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
4 BL4	1.2	4.0	330.0	0.14	Normal	0.26	JOSNWAP	1.0	6.0	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
5 BL4	1.2	6.0	330.0	0.14	Normal	0.20	JOSNWAP	1.2	6.3	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
6 BL4	1.2	8.0	330.0	0.14	Normal	0.17	JOSNWAP	1.4	6.5	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
7 BL4	1.2	10.0	330.0	0.14	Normal	0.16	JOSNWAP	1.7	6.8	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
8 BL4	1.2	12.0	330.0	0.14	Normal	0.15	JOSNWAP	1.9	7.1	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
9 BL4	1.2	14.0	330.0	0.14	Normal	0.14	JOSNWAP	2.3	7.6	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
10 BL4	1.2	16.0	330.0	0.14	Normal	0.13	JOSNWAP	2.7	8.0	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
11 BL4	1.2	18.0	330.0	0.14	Normal	0.13	JOSNWAP	3.2	8.5	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
12 BL4	1.2	20.0	330.0	0.14	Normal	0.12	JOSNWAP	3.8	9.1	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4
13 BL4	1.2	24.0	330.0	0.14	Normal	0.12	JOSNWAP	5.2	10.3	0.0	0.0	0.41	2ND BUOY LOSS, LINE 4