HIghly advanced Probabilistic design and Enhanced Reliability methods for high-value, cost-efficient offshore WIND

Title: Design brief of HIPERWIND offshore wind turbine cases: bottom fixed 10MW and floating 15MW

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Definitions:	

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List of Abbreviations

COG	Center Of Gravity
DEL	Damage Equivalent Load
DFF	Design Fatigue Factor
DLC	Design Load Case
MSL	Mean Sea Level
RNA	Rotor Nacelle Assembly
RPM	Round Per Minute
SCF	Sress Concentration Factor
WTG	Wind Turbine Generator
FOWT	Floating Offshore Wind Turbine
FSS	Floating Sub System

1. Introduction

The use cases considered by HIPERWIND include two offshore wind cases. First one considers the DTU10MW WTG installed on a monopile, specifically designed by EDF for HIPERWIND. This system is located offshore in the North Sea.

Second one considers a floating offshore wind turbine (FOWT) located in the south of Brittany, offshore in France, wherein the IEAWIND 15 MW wind turbine/UMaine Floater is modified to reflect the site water depth and required natural frequencies.

This document details the necessary input parameters for the aero-hydro-servo-elastic engineering codes.

The engineering tools considered in the project involve three coupled aero-hydro-servo-elastic codes:

- DIEGO (Dynamique Intégrée des Eoliennes et Génératrices Offshore) is an in-house aero-hydro-servo-elastic code developed by EDF R&D (1).
- Deeplines Wind™ (DLW) is part of the marine software solutions developed by Principia and IFP Energies Nouvelles. It is a finite element code and forms an integrated solution to perform in place and installation analysis of a wide range of offshore structures (2).
- HAWC2 (Horizontal Axis Wind turbine simulation Code 2nd generation) is mainly developed by DTU Wind Energy (3).

2. Definition of large turbine bottom fixed use case: Monopile+DTU10MW

In this section, a bottom-fixed use case considering the environmental conditions of a generic offshore North Sea is presented (Figure 1:). The chosen turbine for this use case is the DTU 10 MW for which publicly available information can be found in (4). In this reference, the tower and RNA designs are given. Thus, for the use case purposes, there is a need to design the transition piece and the monopile for this WTG considering the environmental conditions. Those conditions come from an internal EDF database.

EDF has designed a transition piece and a monopile for this use case. Details of this design are presented in this section. First, the methodology used to deduce the design is briefly described, and then the results are presented.

Figure 1: The HIPERWIND bottom-fixed use: DTU 10MW on EDF monopile.

2.1. Methodology

The frequential tool DOmyMP (Design and Optimize my MonoPile) developed in-house at EDF is used to design the transition piece and the monopile considering the DTU 10 MW WTG and the internal environmental conditions. This tool presents an optimization possibility that allows providing, for given environmental and soil conditions, a design of the structure that permits verifying the various constraints while minimizing the steel mass (cf. Figure 2). The set of design variables are the parameters that define the geometry of the offshore wind turbine. The constraints are of two types: the constraints linked to design criterion and the constraints linked to the fabrication.

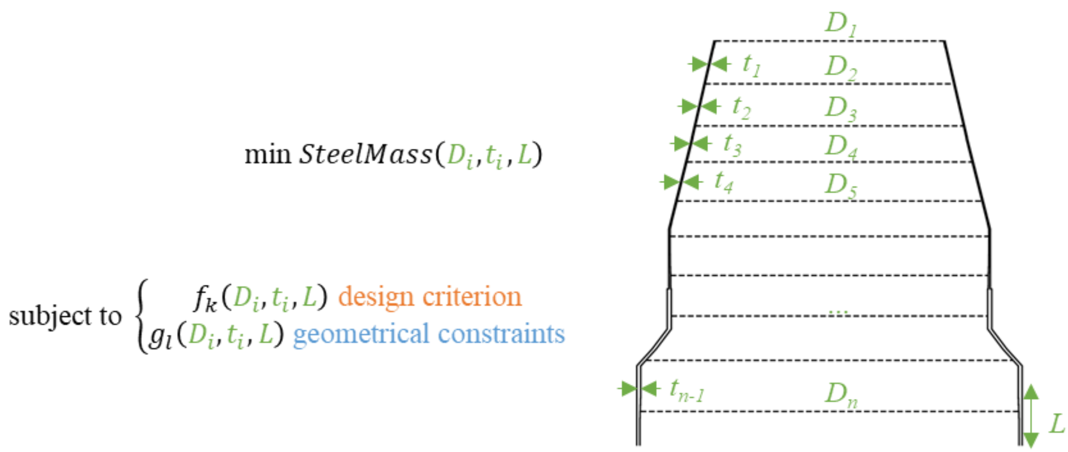

Figure 2: Illustration of the solved constrained optimization problem in DOmyMP

The optimization methodology implemented in DOmyMP is a methodology in which the design variables are always increasing. That is to say, that initially the structure is flexible (and does not verify *a priori* the design criterion) and during the procedure the structure is stiffened step-by-step where it is necessary to verify all the constraints while minimizing the overall structure mass. The choice of where to stiffen the structure at each step of the procedure is done by finding the design variable that has the most impact on the design criterion compared to its impact on the mass using a second gradient method.

The design criterion considered in this process are the following ones:

- Verification that the stresses induced by ultimate loading are allowable (i.e. below the material's yield limit)
- Verification that the first natural frequency ranges between the 1P and the 3P frequencies.
- Verification that the fatigue damage is allowable (i.e. factored damage below unity, the safety factor is given in 2.3.4).
- Verification of the geotechnical criterion

The criteria are detailed in next sections.

The geometrical constraints required by the fabrication are the following ones:

- Verification that the ratio of diameter over thickness is allowable. A value of 120 is considered as a maximum threshold (classically used in practice)
- Verification that the diameter and the thickness values range between given borders.

- Verification that the angle of variation of the diameter is allowable, a maximum angle of 3° is considered herein (classically used in practice)

2.2. Environmental conditions

2.2.1. Soil profile

The soil profile as well as the soil properties are taken from the EDF internal database. The *P-y* curves approach is used to model the soil behavior. For marine sands and Boulder Bank clay the P-y curves defined in (5) are used, and for the weak rock layers the formulation described in (6) is used.

2.2.2. Metocean

The scatter diagram of the directional wind speed distribution is taken from the EDF internal database of the North Sea.

2.3. Inputs data

The material properties considered in the analysis is given in Table 1. A grouted connection is considered in the analysis, with a target angle for the conic connection of 1.5° and a target grout thickness between 140 mm and 150 mm (classically done in practice).

Table 1: Material properties considered in the use case analysis

Material	Parameter	Symbol	Value	Units
Steel	Young's modulus	E	210	GPa
	Poisson's ratio	ν	0.3	-
Grout	Young's modulus	E	55	GPa
	Poisson's ratio	ν	0.2	-

Marine growth is also considered in this analysis. The profile given in Table 2: marine growth profile is considered.

Table 2: marine growth profile

Level	Marine growth thickness [mm]
Above +1 mMSL	0
+1 mMSL and -5 mMSL	180
-5 mMSL and -18 mMSL	180 to 100 (linear profile)
-18 mMSL to seabed	100

In DOmyMP, Stress Concentration Factors (SCF) are automatically computed according to the specifications described in (7) at every welded sections.

2.3.1. Geotechnical criterion

The embedded length of the pile is given by the critical length, which is defined as the length for which the relative rotation is equal to 10%. The maximum permanent rotation at seabed is set classically to 0.25°.

2.3.2. Frequency criteria

The first natural frequency is set to range between 1P and 3P frequencies. Considering the DTU 10 MW, the minimum rotor speed is 6 rpm and the maximum rotor speed is 9.6 rpm. Thus, the first natural frequency should ranges between 0.16 Hz and 0.3 Hz. Accounting for a safety margin of 15%, the target first and second natural frequencies are thus searched in the range of 0.184 Hz and 0.255 Hz.

2.3.3. Ultimate loading analysis

The considered loads in the ultimate analysis are the following ones:

- The thrust at the tower top of 4 MN (this value takes into account a safety factor by 1.35). This value is obtained with a time domain computation considering extreme turbulent wind conditions (DLC 1.3 (8)) for a nominal producing wind speed.
- The hydrodynamic loads are computed considering a wave corresponding to the above-mentioned wind condition, i.e. H_s=3.0 m and T_p=8 s.

The design criterion is to keep the stress smaller than the steel yield strength. This criterion accounts for a safety factor applied on the loads (1.35) and a resistance safety factor applied on the yield strength (1.1).

2.3.4. Fatigue analysis

The metocean table is deduced from the EDF internal database. An unavailability of 7% is considered. A design lifetime of 25 years is considered in the fatigue analysis. The design criterion is that the total damage of each connections over the design lifetime is smaller than 1.0 divided by the design fatigue factor (DFF=3.0 in the transition piece and the monopile and DFF=1.0 in the tower).

2.4. Results & design

The results of the optimization procedure are given in Table 3 and the structural dimensions are described in Table 4. The water depth considered herein is 12.52 m. The embedment length of the pile that permits verifying the geotechnical criteria equals 32 m. The distance of the blade tip from the mean sea level equals 30 m.

Table 3: Summary of the results of the optimization procedure

	Result	Criteria
First natural frequency	0.219 Hz	0.184 Hz ≤ f ≤ 0.255 Hz
Permanent rotation	0.05°	θ ≤ 0.25°
Critical length	L_{crit} = 32 m	-
ULS loading at seabed	F_x = 6.0 MN & M_y=517 MN.m	-
Maximum stress	127 MPa	< 322 MPa
Factored fatigue damage	0.7	< 1
Outer diameter at seabed	8.3 m	-
Embedded length	32 m	= L_{crit}
Tower mass	444 tons	-
TP mass	391 tons	-
MP mass	679 tons	-

Table 4: Structural dimensions of the bottom-fixed use case (results of the optimization procedure)

Location	Height	Outer diameter	Thickness	Young's modulus	Volumic mass
-	[mMSL]	[m]	[mm]	[GPa]	[kg/m^3]
Tower top	116.25	5.30	20	2.10E+11	8450
	113.82	5.40	20	2.10E+11	8450
	111.40	5.50	20	2.10E+11	8450
	108.97	5.60	20	2.10E+11	8450
	106.55	5.70	20	2.10E+11	8450
	104.12	5.79	20	2.10E+11	8450
	101.25	5.86	22	2.10E+11	8450
	98.37	5.93	22	2.10E+11	8450
	95.50	6.00	22	2.10E+11	8450
	92.62	6.07	22	2.10E+11	8450
	86.87	6.21	24	2.10E+11	8450
	84.00	6.28	24	2.10E+11	8450
	81.12	6.35	24	2.10E+11	8450
	78.25	6.42	26	2.10E+11	8450
	75.37	6.49	26	2.10E+11	8450
	72.50	6.56	26	2.10E+11	8450
	69.62	6.63	26	2.10E+11	8450
	66.75	6.70	28	2.10E+11	8450
	63.87	6.77	28	2.10E+11	8450
	61.00	6.84	28	2.10E+11	8450
	58.12	6.91	28	2.10E+11	8450
	55.25	6.98	30	2.10E+11	8450
	52.37	7.05	30	2.10E+11	8450
	49.50	7.12	30	2.10E+11	8450
	46.62	7.19	30	2.10E+11	8450
	43.75	7.26	32	2.10E+11	8450
	40.87	7.33	32	2.10E+11	8450
	38.00	7.40	32	2.10E+11	8450
	35.12	7.47	32	2.10E+11	8450
	32.25	7.53	34	2.10E+11	8450
	29.37	7.60	34	2.10E+11	8450
	26.50	7.67	34	2.10E+11	8450
	23.62	7.74	34	2.10E+11	8450
	21.31	7.88	36	2.10E+11	8450
Interface level	19.00	8.02	36	2.10E+11	8450
TP	18.83	8.00	80	2.10E+11	7850
	16.22	8.00	80	2.10E+11	7850
	13.60	8.00	80	2.10E+11	7850
	11.19	8.00	80	2.10E+11	7850

	10.75	8.00	80	2.10E+11	7850
	10.31	8.00	80	2.10E+11	7850
	9.87	8.00	80	2.10E+11	7850
	9.43	8.00	80	2.10E+11	7850
	8.99	8.00	80	2.10E+11	7850
	8.55	8.00	80	2.10E+11	7850
	8.06	8.03	80	2.10E+11	7850
	7.57	8.06	80	2.10E+11	7850
	7.08	8.08	80	2.10E+11	7850
	6.59	8.11	80	2.10E+11	7850
	6.11	8.14	80	2.10E+11	7850
	5.62	8.16	80	2.10E+11	7850
	5.13	8.19	80	2.10E+11	7850
	4.64	8.21	80	2.10E+11	7850
	4.15	8.24	80	2.10E+11	7850
	4.00	8.25	80	2.10E+11	11163
	4.00	7.81	69	2.10E+11	7850
	3.75	8.28	297	1.31E+11	30805
	3.50	8.29	297	1.31E+11	30857
	3.25	8.30	297	1.31E+11	30908
	3.00	8.32	297	1.31E+11	30960
	2.75	8.33	297	1.31E+11	31012
	2.50	8.34	297	1.31E+11	31063
	2.25	8.36	297	1.31E+11	31115
	2.00	8.37	297	1.31E+11	31167
	1.75	8.38	297	1.31E+11	31218
	1.50	8.40	297	1.31E+11	31270
	1.25	8.41	297	1.31E+11	31322
Equivalent TP + MP	1.00	8.42	297	1.31E+11	31374
	0.75	8.43	297	1.31E+11	31425
	0.50	8.45	297	1.31E+11	31477
	0.25	8.46	297	1.31E+11	31529
	0.00	8.47	297	1.31E+11	31580
	-0.23	8.49	297	1.31E+11	31630
	-0.46	8.50	297	1.31E+11	31715
	-0.69	8.51	297	1.31E+11	31763
	-0.92	8.52	297	1.31E+11	31810
	-1.15	8.53	297	1.31E+11	31858
	-1.38	8.55	297	1.31E+11	31905
	-1.61	8.56	297	1.31E+11	31953
	-1.84	8.57	297	1.31E+11	32001
	-2.07	8.58	297	1.31E+11	32048
	-2.30	8.59	297	1.31E+11	32096

	-2.54	8.61	297	1.31E+11	32145
	-2.78	8.62	297	1.31E+11	32195
	-3.03	8.63	297	1.31E+11	32245
	-3.27	8.65	297	1.31E+11	32295
	-3.51	8.66	297	1.31E+11	32345
	-3.75	8.67	297	1.31E+11	32395
	-3.99	8.68	297	1.31E+11	32445
	-4.23	8.70	297	1.31E+11	32495
	-4.48	8.71	297	1.31E+11	32545
	-4.72	8.72	297	1.31E+11	32595
	-4.96	8.73	297	1.31E+11	32645
	-5.20	8.75	297	1.31E+11	32695
	-5.35	8.74	80	2.10E+11	11157
	-5.35	8.30	69	2.10E+11	7850
	-5.80	8.30	69	2.10E+11	7850
	-6.27	8.30	69	2.10E+11	7850
	-6.73	8.30	69	2.10E+11	7850
	-7.20	8.30	69	2.10E+11	7850
	-7.61	8.30	69	2.10E+11	7850
	-8.02	8.30	69	2.10E+11	7850
	-8.40	8.30	69	2.10E+11	7850
MP	-8.84	8.30	69	2.10E+11	7850
	-9.27	8.30	69	2.10E+11	7850
	-9.71	8.30	69	2.10E+11	7850
	-10.15	8.30	69	2.10E+11	7850
	-10.58	8.30	69	2.10E+11	7850
	-11.02	8.30	69	2.10E+11	7850
	-11.52	8.30	69	2.10E+11	7850
	-12.02	8.30	69	2.10E+11	7850
	-12.52	8.30	69	2.10E+11	7850

Seabed is located at -12.52 meters. In the engineering code of HIPERWIND, the soil structure interaction is modeled by a stiffness matrix at the seabed.. For this reason, in those codes, the MP description is limited at -12.52 meters. The degrees of freedom of translation along the *z* axis and of rotation around the z axis are blocked at seabed. Thus, the stiffness coefficients are limited to the lateral stiffness K_L, the rotational stiffness K_R and the coupling stiffness K_{LR}, the values are the following:

$$\begin{pmatrix} K_L & K_{LR} \\ K_{LR} & K_R \end{pmatrix} = \begin{pmatrix} 1.03\ 10^9 & -1.42\ 10^{10} \\ -1.42\ 10^{10} & 3.08\ 10^{11} \end{pmatrix}$$

Figure 3 and Figure 4 illustrate the geometry of the wind turbine at the end of the optimization procedure. Figure 3 depicts the outer diameter of the tower (in blue), of the transition piece (in orange) and of the monopile (in green). Similarly, Figure 4 shows the thickness of the steel tube of the tower (in blue), of the transition piece (in orange) and of the monopile (in green). Looking the values for the diameters of the tower, it can be noted that this component is not modified during the optimization procedure as it is provided by (4).

Figure 5 and Figure 6 show the results of the fatigue analysis performed at the end of the optimization procedure (i.e. when the structure is no more modified). Figure 5 shows the damage equivalent load (DEL). The final fatigue calculation gives access to the cumulated damage field. From this field, one can deduce the DEL along the structure assuming linear Wöhler curves. This DEL refers to the bending moment that would cause the same damage if applied 10^7 times. The shape of the DEL is typical for those structures, with the maxima occurring at tower base and seabed (-12.52 m).

Figure 6 shows the utilization ratio along the structure. The utilization ratio refers to the total damage divided by the design fatigue factor (DFF). It can be seen that the utilization ratio is below unity, that is to say that the proposed structure verifies the fatigue criterion (cf. section 2.3.4).

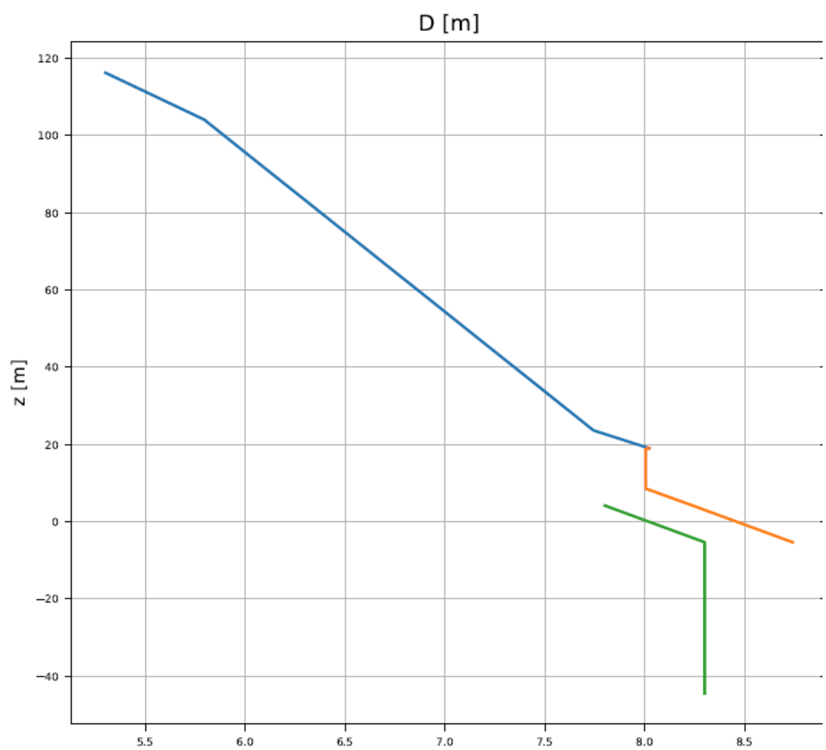

Figure 3: Outer diameter profile at the end of the optimization procedure (blue: tower, orange: transition piece, green: monopile)

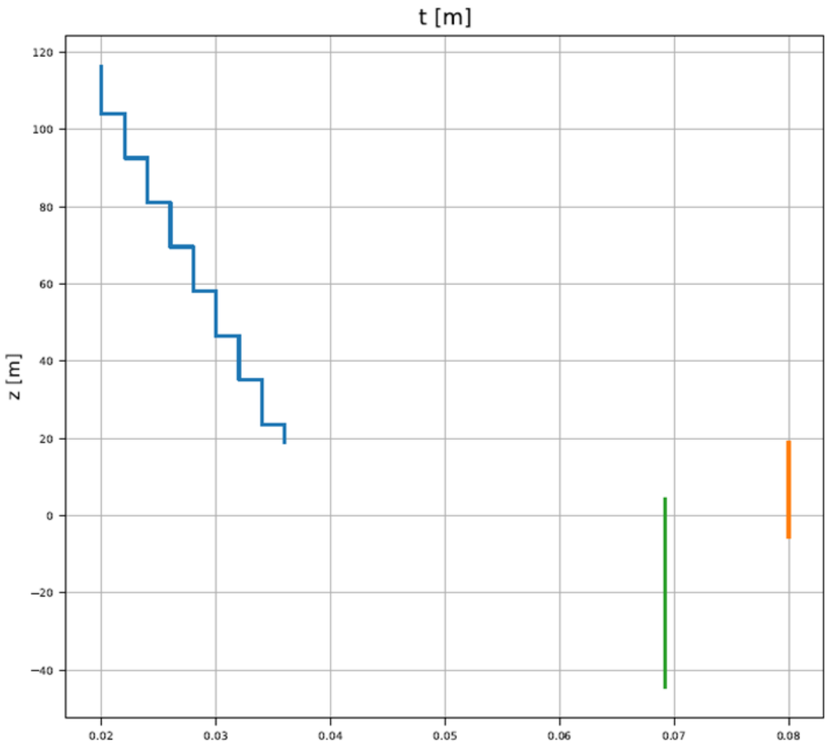

Figure 4: Thickness profile at the end of the optimization procedure (blue: tower, orange: transition piece, green: monopile)

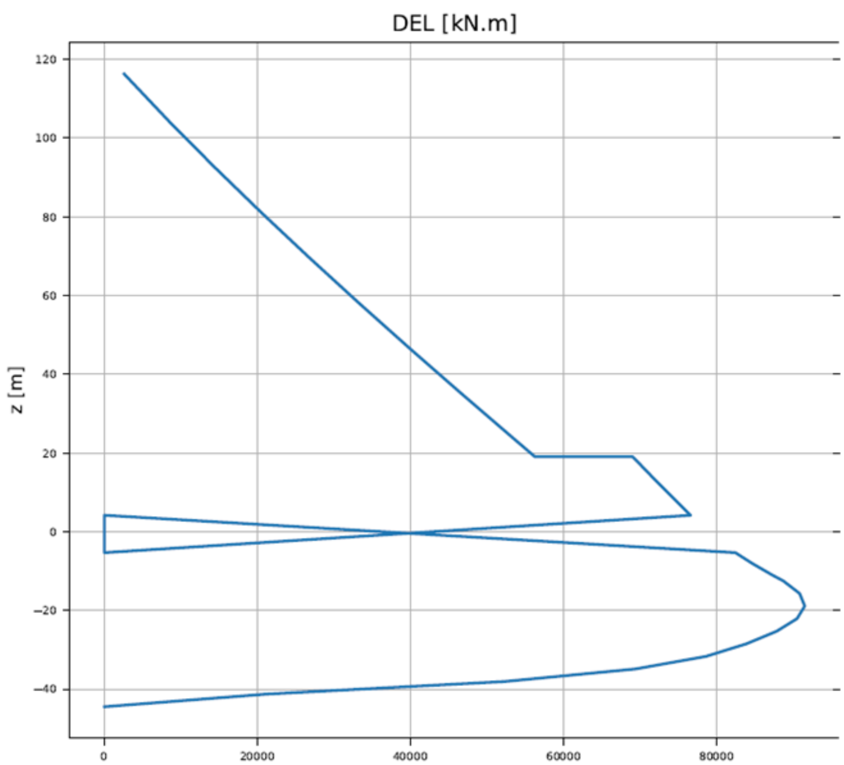

Figure 5: Damage equivalent load (bending moment) obtained during the fatigue analysis performed at the end of the optimization procedure

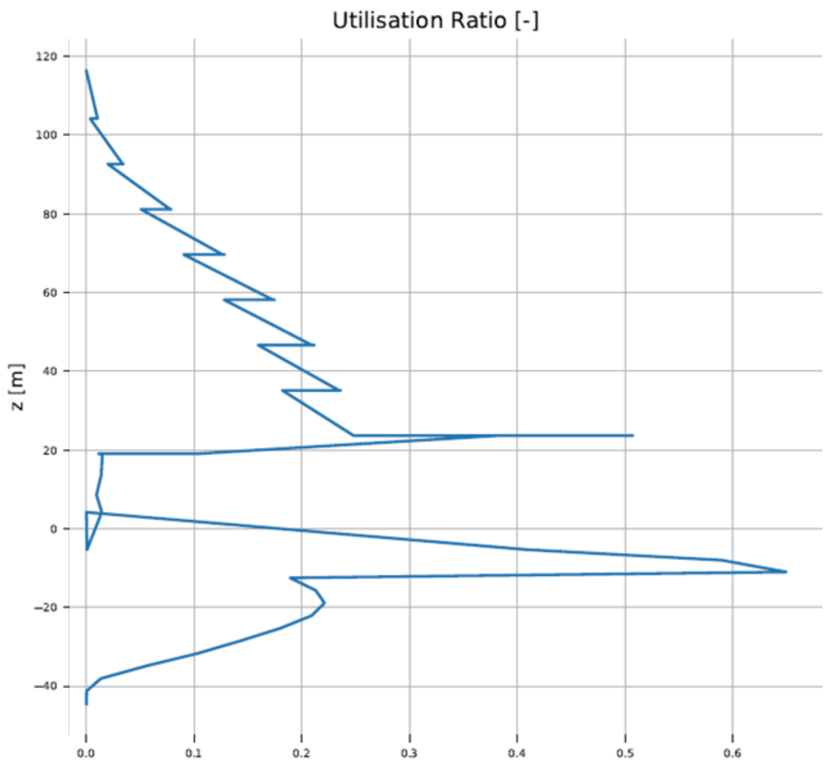

Figure 6: Utilization ratio during the fatigue analysis performed at the end of the optimization procedure

2.5. Conclusions for the bottom fixed 10MW use case

The use case presented in the document considers a fixed offshore wind cases located offshore in North Sea. It consists in the DTU10MW WTG installed on a monopile, specifically designed by EDF for HIPERWIND. This document details the design methodology, criteria and results. The frequential tool DOmyMP (Design and Optimize my MonoPile) developed in-house at EDF is used to design the transition piece and the monopile.

The design criterion considered in this process are:

- Verification that the stresses induced by ultimate loading are allowable (i.e. below the material's yield limit).
- Verification that the first natural frequency ranges between the 1P and the 3P frequencies.
- Verification that the fatigue damage is allowable (i.e. factored damage below unity).
- Verification of the geotechnical criterion.

The geometrical constraints required by the fabrication are the following ones:

- Verification that the ratio of diameter over thickness is allowable. A value of 120 is considered as a threshold (classically used in practice).
- Verification that the diameter and the thickness values range between given borders.
- Verification that the angle of variation of the diameter is allowable, a maximum angle of 3° is considered herein (classically used in practice).

3. Floating use case comparison results

3.1. Design modifications with respect to the literature

The definition of the floating use case has started by considering the FOWT composed by the VulturnUS-S FSS and the IEA 15MW. The description of this FOWT is given in (9). The IEA 15MW is firstly introduced in (10).

This floater and the mooring lines are modified in this document in order to adapt this system to the considered offshore site. Details about those modifications are listed in sections 3.4 and 3.5.

According to the industrial experience, EDF has preferred to design a new tower for this FOWT. The RNA considered in (10) is reduced in weight about 200 tons and a new design of the tower is produced verifying a set of criteria detailed in section 3.2.

In the following, the description of the components of the floating use case is reported.

3.2. Tower description

The tower is designed by EDF respecting the following criteria:

- Tower natural frequency distance from 3P higher than 15% of the 3P frequency value.
- Manufacturing constraints:
  - Diameter / thickness ratio lower than 200. This constraint also aims to avoid local buckling.
  - Maximum variation angle for the diameter of 3 degrees.
- ULS case with 4 MN of thrust and 43 m/s of wind: elastic behavior verification.

The detailed description is given in Table 5: Tower description for floating case.

The first elastic natural frequency of the system is at 0.42 Hz, considered sufficiently (~15%) far from the 3P frequency of the rotor, at 0.37 Hz. Rayleigh structural damping is considered in the model. DIEGO considers two coefficients, mass and stiffness proportional, while HAWC2 and DLW a single coefficient of linear damping to obtain an equivalent damping for tower mode is computed considering the tower mode at 0.45 Hz. Let's consider thereafter a_0 the mass proportional damping and a_1 the stiffness proportional damping.

For the tower, considering a logarithmic damping of ζ = 2.0 % and that the two first mode of the tower being 0.42 Hz and 0.45 Hz (9), one can deduce the damping coefficients using the equation:

$$2\omega_i\zeta = a_0 + a_1{\omega_i}^2 \quad (1.)$$

Thus, the values for the Rayleigh damping coefficients are:

$$\begin{cases} a_0 = 0.054 \\ a_1 = 0.0074 \end{cases} \quad (2.)$$

The structural dimensions are included in Table 5. In DIEGO, the sections are cylindrical with a constant diameter, so a refined mesh is necessary. For the other tools, conical representation is used.

Table 5: Tower description for floating case

Height (Z)	Outer diameter	Thickness	Young's modulus	Poisson's ratio	Volumic mass
m	m	m	Pa	-	kg/m^3
15	10	0,082	2E+11	0,26103405	7850
21,5	10	0,082	2E+11	0,26103405	7850
28	10	0,078	2E+11	0,26103405	7850
34,5	10	0,073	2E+11	0,26103405	7850
41	10	0,069	2E+11	0,26103405	7850
47,5	10	0,064	2E+11	0,26103405	7850
54	10	0,059	2E+11	0,26103405	7850
60,5	10	0,055	2E+11	0,26103405	7850
67	10	0,05	2E+11	0,26103405	7850
73,5	10	0,05	2E+11	0,26103405	7850
80	9,78	0,05	2E+11	0,26103405	7850
86,5	9,34	0,0489	2E+11	0,26103405	7850
93	8,9	0,0467	2E+11	0,26103405	7850
99,5	8,42	0,0445	2E+11	0,26103405	7850
106	7,78	0,0421	2E+11	0,26103405	7850
109,5	7,41	0,0389	2E+11	0,26103405	7850
113	7,08	0,0370	2E+11	0,26103405	7850
122,5	6,5	0,0354	2E+11	0,26103405	7850
132	6,5	0,0325	2E+11	0,26103405	7850
138,291	6,5	0,0325	2E+11	0,26103405	7850
144,582	6,5	0,0325	2E+11	0,26103405	7850

No secondary equipment is considered.

3.3. Rotor-nacelle assembly

As compared to the IEA 15MW reference turbine, the RNA mass is reduced in the HIPERWIND case : the global RNA mass is 860t. In DIEGO the hub and the nacelle are considered to be rigid bodies. Masses and inertias are applied in their center of gravity and linked to the tower top by a rigid connection, the shaft is also considered as a rigid body with lumped mass and inertias. In DLW and HAWC2, hub and nacelle are also modeled by lumped masses applied in their center of gravity, but the shaft is considered to be flexible.

The RNA general properties are resumed in Table 6.

Table 6: RNA description for floating use case

Mass and inertia at RNA			
HubMass	190000	kg	Hub mass (kg)
HubIner	1382171	kg.m²	Hub inertia about rotor axis (kg m^2) at COG of Hub
GenIner	6950316	kg.m²	Generator inertia about HSS (kg m^2) at COG of generator
NacMass	430000	kg	Nacelle mass (kg)
NacYIner	10046187	kg.m²	Nacelle inertia about yaw axis (kg m^2) at COG of the Nacelle
Drivetrain			
GBoxEff	96,55	%	Gearbox efficiency (%)
GB	1	-	Gearbox ratio (-)

Some of these values are taken differently by the codes:

- For the GenIner: in DLW, the value of 3.22E+06 is used instead. It is a small mistake and it should have negligible influence on the results.
- For the NacMass: in DLW, this mass is distributed between the shaft and the nacelle.
- For the GBoxEff: in DLW, this efficiency is on the generator instead of the GearBox which efficiency is at 100%. This should not modify the results.

Blade properties are described in the NREL report (10). No changes are considered for this component and the reader can refer to the source, except for the damping coefficients because a more realistic value for blades has been proposed by DTU (logarithmic damping of ζ = 3.0 %): $\begin{cases} a_0 = 0.11 \\ a_1 = 0.008 \end{cases}$. The hub height is 150 mMSL and the rotor diameter is 240 m.

3.4. Floater description

The floating system used is based on the IEA 15MW turbine defined in (10) and the foundation proposed by University of Maine and detailed in the NREL document (9). All the geometrical parameters have been kept unchanged and only the ballast has been added for HIPERWIND purpose, mostly for sake of consistency. The reasons are the following:

- The site used for the HIPERWIND reference case is located offshore Brittany in 150m water depth. The site considered by University of Maine in the original design is 200m deep, meaning the mooring system cannot be used. . The mooring system was adapted to fit the new water depth, resulting in a lower vertical pretension on the floater at rest position.
- The tower original design proposed by University of Maine (9) has not been considered, the HIPERWIND tower being heavier by 252t (see section 3.2).
- The mass of the RNA mentioned in (9) has been changed according the new tower design, necessary in order to have a consistent FOWT. The RNA mass considered for the HIPERWIND floating case is 860t.

To keep the draft unchanged it has been necessary to add 54t of ballast in the original University of Maine semi-sub. This amount of ballast is regarded as negligible compared to the system mass (>20 000t) or even to the mass of ballast of the original floater (13 840t). Thus, 18t of ballast are added on each of the 3 side columns, 5.06m above the floater keel. The vertical location was chosen to keep the floater CoG constant, for sake of clarity when referring to the original report figures (9).

Figure 7: Geometry of the University of Maine floater considered for the HIPERWIND project. Source (9). Geometry kept unchanged for the Hiperwind floating case. Global Frame definition.

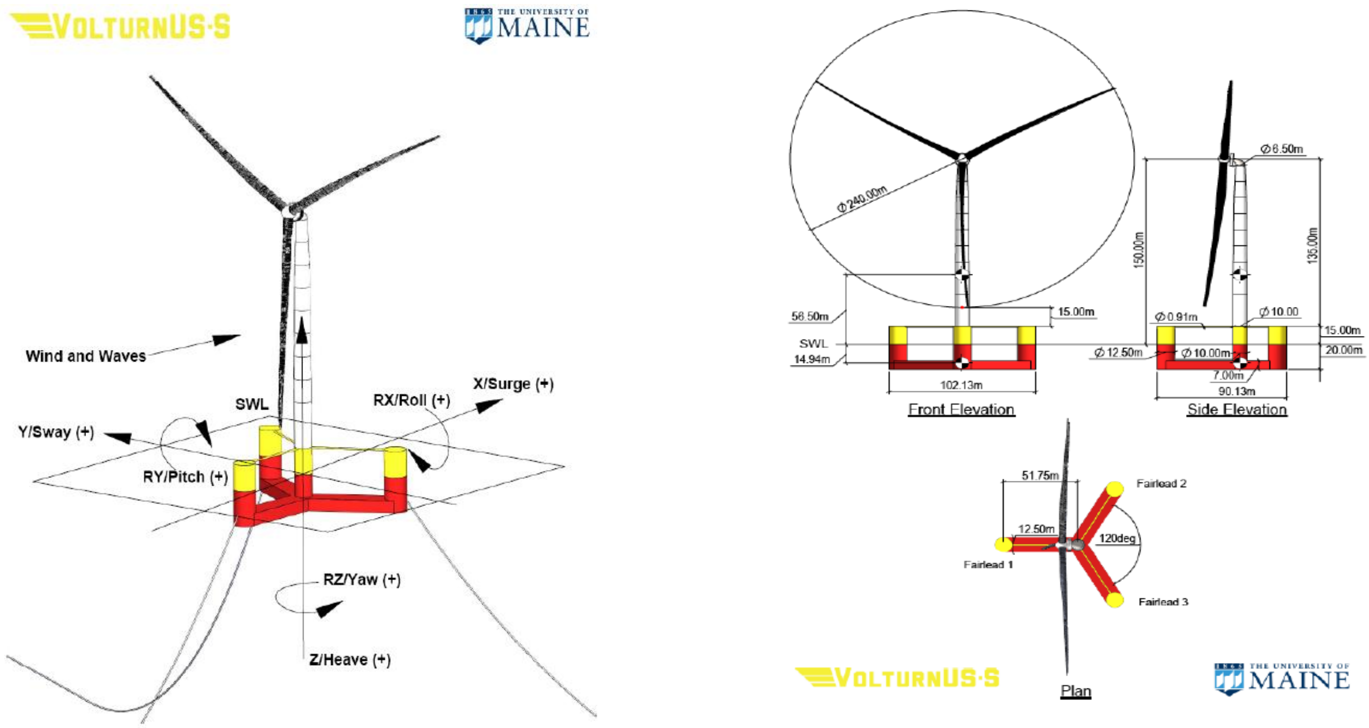

Table 7: Geometry of the University of Maine floater used for the HIPERWIND project

Draft	20	**m**		
Distance Centre-Side columns	51,75	**m**		
Side columns diameter	12,5	**m**		
Central column diameter	10	**m**		
Columns height	35	**m**		
Pontoons height	7	**m**		
Pontoons width	12,5	**m**		
Mass of the initial Umaine Floater	17854	t (including 100t for the tower interface)		
Additional ballast (@z=-14,94, distributed on the 3 col.)	54	t (to keep the same draft while SKS differs)		
Global Mass of the Floater used within HIPERWIND	17908	t		
CoG of the Floater wrt keel (x,y,z)	0	0	5,06E+00	m
Inertia of the Floater around floater CoG (Ixx, Iyy, Izz)	1,258E+07	1,258E+07	2,381E+07	t.m2
Mass of the Tower	1515	t		
Mass of the RNA	860	t		
Global Mass of the FOWT system	20283	t		
Vertical mooring lines load	428	t		
Total vertical weight (including mooring vertical loads)	20711	t		
Displacement	20711	**t**		

Except the global mass of steel, (9) provides no information about the structural aspects of the floater. Therefore HIPERWIND partners chose to work under the rigid floater assumption, with 6 degrees of freedom. The linear potential flow theory is used to derive added masses, radiation damping and load RAOs for a large range of wave frequencies, in order to feed the time domain aero-hydro-servo-elastic tools. The frequency domain data are called "Hydrodynamic Database" in this document, and include the first order loads transfer functions, the frequency dependent added mass and radiation damping matrices. There are several existing tools able to solve the diffraction-radiation problem and to generate hydrodynamic databases. EDF R&D uses the open source solver NEMOH , developed by Ecole Centrale de Nantes ; IFPEN DeepLines Wind model relies on DIODORE ; DTU HAWC-2 model get its hydrodynamic database from WAMIT. The hydrodynamic database are limited to first order in the present benchmark, meaning that the second order wave loads from the diffraction-radiation (QTF) have not been computed and used for the time domain simulations. However, the drag forces coming from the Morison elements are expected to produce a small level of nonlinear loads. These loads could be able to generate second order contribution, depending on the strategies used by the different partners for drag. At the end, this difference in the drag excitation is regarded as negligible in most of cases (when going to 50-y storms AND neglecting the wind forces, drag becomes a significant contributor). The consistency of the hydrodynamic databases obtained by each partner is checked before the start of the time domain comparisons.

The drag coefficients were defined for the benchmarking exercise:

- For the vertical columns, Cd=1
- For the pontoons: The choice was based on (11) experimental data. Unfortunately, the drag coefficient values measured are strongly dependent on the Keulegan-Carpenter number, and could vary from ~3 to ~100 depending on the sea state considered. To avoid input errors in the code-to-code comparison, it was proposed to use the same value for all the cases and in the 2 directions (vertical and horizontal) : Cd=5

The drag coefficient values are summarized in (Table 8).

Table 8: Drag coefficients

Drag coefficients (proposed values for code-code comparison	
Columns	1
Pontoons - vertical drag	5
Pontoons - Horizontal drag	5

Depending on the modeling tool, it can be necessary to define a global surface on which the pontoons drag coefficient applies. The surfaces exposed to drag are listed in Table 9. Within a realistic design procedure, it would be expected to modify the drag coefficient associated to the bottom of side columns as the flow can be quite different close to the side buoys compared to what it is close to the horizontal pontoons. In the present code-to-code comparison, the Cd value of the pontoons is used under the side columns and on the central section as well. Again, the influence of the choice and adaptation of drag coefficients will be investigated further in HIPERWIND project.

Table 9: Surfaces submitted to drag loads.

Drag Surfaces		
Pontoons - Horizontal surface	1519	**m2**
Central section - Horizontal surface	79	**m2**
Bottom of side buoys - Horizontal surface	368	**m2**
Pontoons - vertical surface	851	**m2**

Depending on the modeling tool, it can be necessary to define a quadratic damping matrix as the floater geometry is not given to the time-domain solver. In agreement with the drag coefficients given above, the following diagonal matrix was extracted from time domain imposed oscillation simulations.

Table 10: Quadratic damping matrix (units are : N, m, rad, s).

1,42E+06					
	1,42E+06				
		3,87E+06			
			4,77E+10		
				4,77E+10	
					1,10E+11

3.5. Mooring system description

The original mooring system defined in (9) has been designed for 200m water depth, verifying the ULS case (no FLS addressed). For the HIPERWIND project, modifications have been made is order to make the mooring system compliant with the 150m water depth on the site offshore Brittany. Due to time constraints of the code-to-code comparisons, it was not possible to fully redesign the lines so the modification has been made trying to keep unchanged:

- the line section
- the static offset at rated wind speed
- the surge period, so the horizontal motion dynamic will be comparable
- the maximum horizontal offset without uplift force at anchors, so the maximum allowable offset is comparable.

Given these constraints, some 50-y storm conditions (DLC6.1 only) have been simulated to ensure the tensions were compliant with the MBL.

The final mooring system proposed is summarized on Table 11:

Table 11: Mooring system properties

Type	Catenary Chain – Studless	
Grade	R3	
Diameter	185	**Mm**
MBL (Minimum Braking Load)	22,29	**MN**
ml in air	685	**kg/m**
ES (axial stiffness)	3270	**MN**
rho Steel	8000	**kg/m3**
S (Surface)	0,085625	**m2**
E (Young)	38190	**Mpa**
rho in water	6975	**kg/m3**
ml in water	597	**kg/m**
unstretched length	835	**m**

The position of the fairleads and anchors are given in Table 12 and Table 13, in the global frame as defined on Figure 7.

Table 12: Fairleads positions in the global frame (m)

Fairleads			
	X	**Y**	**Z**
L1	-58,00	0,00	-14,00
L2	29,00	50,23	-14,00
L3	29,00	-50,23	-14,00

Table 13: Anchor position in the global frame (m)

Anchors			
	X	Y	Z
L1	-837,60	0,00	-150,00
L2	418,80	725,38	-150,00
L3	418,80	-725,38	-150,00

The total vertical loads applied by the mooring system on the floater at rest are 4,20 MN, and the total pretension per line is 1,63MN. Note that 4.20 MN of Table 14 corresponds to the equivalent 428t given in Table 7.

Table 14: Vertical loads and line pretension

Total vertical tension @rest	4,20	**MN**
Line Pretension	1,63	**MN**

The modification of the mooring design leads to the following comparison between the original University of Maine and the HIPERWIND systems:

Table 15: HIPERWIND mooring system compared to the original University of Maine design.

	WD (m)	Line Length (m)	Vertical tension (MN)	Horizonal stiffness (N/m)	Surge Natural Period (s)	Yaw Stiffness (Nm)	Yaw Natural Period (s)	Offset @ Rated (m)	Offset @first Uplift (m)
Base Case	200	850	6,1	73100	143	2,54E+08	91	24	47
HIPERWIND - Britany	150	835	4,2	58300	157	1,56E+08	113	24	45
HIPERWIND / Base Case	*75,00%*	*98,24%*	*68,85%*	*79,75%*	*109,63%*	*61,30%*	*124,15%*	*100,00%*	*95,74%*

As one can see, a significant decrease in the vertical tension at fairleads is obtained (-31%, highlighted in red in the previous table), so as a decrease in the yaw stiffness (-39%, highlighted in red in the previous table). The other parameters are less impacted. The total pretension moves from 2.45 MN to 1.63 MN which lower the yaw stiffness, resulting in an increase in the yaw natural period. At the time of writing this report, no specific verification has been made in case of severe yaw misalignment or wind/wave misalignment to see how critical can be this modification. We believe the central position of the turbine mitigates this risk.

For models using a dynamic finite-element modelling of the lines, it is necessary to agree on the coefficients used in the hydrodynamic loads calculation. It was decided to keep the values proposed by University of Maine in (9):

Table 16: Hydrodynamic coefficient for mooring lines. (source: (9))

Mooring Line Coefficients	Relative to Chain Nominal Diameter	Relative to Volume-Equivalent Diameter
Normal Added Mass	1	0.82
Tangential Added Mass	1	0.27
Normal Drag	2	1.11
Tangential Drag	1.15	0.20

3.6. Controller

HIPERWIND participants agreed for the use of ROSCO controller with differences in the final controller configuration (12). Differences in simulation results, for wind steps and turbulence load cases, has to be considered in the light of those differences in the control strategy.

3.7. Environmental conditions: south Brittany database information

This database is public. It is extracted by ANEMOC (Digital Atlas of Ocean and Coastal Sea States). The goal of ANEMOC project is to disseminate the sea state conditions obtained along the French coasts and to organized it on a website with the associated database.

Website : http://anemoc.cetmef.developpement-durable.gouv.fr/

ANEMOC was built from retrospective simulations over a period of 23 years and 8 months, from 01/01/1979 to 08/31/2002, to the Atlantic, Channel, North Sea and 30 years old, from 01/01/1979 to 12/31/2008, for the Mediterranean coast.

The simulations were carried out with the TOMAWAC sea state modeling software, developed by EDF - LNHE with the support of CETMEF. TOMAWAC is a so-called "third generation" model which solves the equation of evolution in space and time of the spectro-angular density of wave action.

Warning on the use of data:

The results contained in the ANEMOC database come from numerical simulations. They must in no case be used directly for the sizing of structures. They are therefore provided for information only. It is strongly recommended to supplement with in situ measurement campaigns. CETMEF and EDF-LNHE cannot, under any circumstances, be held responsible for the use that will be made of this information.

The extraction from ANEMOC is performed at coordinates: -4.59250688553 46.8014068604.

Let note the following information:

- Files named HIPER_date_3.dat contain data about waves (frequency 30 minutes) :
-
    - TIME, WAVE HEIGHT HM0, MEAN DIRECTION, WAVE SPREAD, MEAN PERIOD TMO, MEAN PERIOD TM0, PEAK PERIOD TPR, WAVE POWER

- Files named CUR_HIPER_date_3.dat contain data about current (frequency 15 minutes) :
    - TIME, VITESSE U, VITESSE V, HAUTEUR D'EAU
    - VITESSE means SPEED
    - HAUTEUR D'EAU means WATER DEPTH

- Files named WIND_HIPER_date_3.dat contain data about wind at 10 meters (frequency 60 minutes = 1 hour)
    - TIME, PRESSION, VENT_X, VENT_Y
    - THE MEASURE UNIT FOR TIME IS DENOTED S, BUT IT IS HOUR !

First 11 days from year of the data has to be removed. This part of the data are in the transitory part of the simulation, they are not to be considered.

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