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MOORING SYSTEM DESIGN AND ANALYSIS FOR A FLOATING OFFSHORE WIND TURBINE IN PANTELLERIA

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ABSTRACT

The mooring system plays a key role in a floating offshore wind turbine: it connects the floating structure to its anchor on the seabed and it is designed to prevent the platform from drifting under the action of wind, waves and currents. The layout of the mooring system is strictly connected to the installation site: in the first place it depends on the bathymetry and the type of seabed which conditions the type of anchor that can be used; secondly by the wind and waves loads in extreme sea states.

To properly design the mooring system, three different configurations are proposed and discussed, respectively adapting catenary, taut leg and semi-taut methodologies for a floating offshore wind turbine located near the island of Pantelleria, in Sicily. For each configuration, the Hexafloat foundation, developed by Saipem, is considered. Important design constraints such as how large the nominal sizes are, how long the mooring lines are, how far the anchor points are located, are demonstrated in detail. The material used will range from steel chains and wires to polyester ropes, to grant economically viable solutions.

Keywords: Wind Energy, Floating Offshore Wind, Moorings System Design, Techno-economic Analysis, Pantelleria Case Study.

NOMENCLATURE

BEM	Boundary Element Method
FOWT	Floating Offshore Wind Turbine
LCOE	Levelized Cost Of Energy
MBL	Minimum Breaking Load
MSQS	Multi-Segmented Quasi-Static
RAO	Response Amplitude Operator
RON	National Wave Network
TLP	Tension Leg Platform
ULS	Ultimate Limit State

1. INTRODUCTION

In recent years, offshore wind has had a great development in Europe: with an average growth rate of around 30% every year, in 2020 the total installed power has reached 25 GW [1]. Although almost all the wind farms are located in shallow waters, not exceeding 60 m in depth, characterized by bottom-fixed foundations, a large part of the European wind potential is located in seas with depths greater than 50 m, such as along the coasts of the Atlantic Ocean or in the Mediterranean Sea, making the use of fixed structures economically unsustainable and the adoption of floating platforms indispensable.

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A Floating Offshore Wind Turbine (FOWT) is a system made of four main elements [2]:

1. an offshore wind turbine;
2. a floating platform;
3. mooring lines;
4. anchors.

Furthermore, from a wind farm perspective, it is important to consider an electrical grid that includes an electrical substation and marine cables.

The mooring system represents one of the most urgent bottlenecks in floating offshore wind diffusion, as they require complex installation and involve high costs. The proposed solutions derive from the Oil & Gas industry and require specific adaptations for the different operating conditions of the floating wind turbines.

2.1 Moorings and anchors classification

The state of the art classifies moorings based on:

- Mooring configuration (catenary, taut, semi-taut, single point, spread)
- Anchor type
- Number of mooring lines
- Material (chain, wire, synthetic rope)

Figure 1 shows the most common moorings configurations.

A **catenary mooring** system is a basic configuration that consists of steel chains that hang freely between the floating structure and anchor. The slack in the system allows for some vertical and horizontal movement of the anchored structure [3]**.** While the upper section of the mooring line may consist of chains and wires or synthetic ropes, the bottom section of the line lies on the seabed, thus increasing its footprint. The system usually provides long mooring lines, partly resting on the seabed, and reduces loads on the anchors. Among the advantages of this configuration, this system is relatively easy to install compared to a taut-leg mooring system [4].

Taut-leg mooring systems consist of mooring lines that are pre-tensioned until they are taut. The moorings tension participates to the floating platform stability, likes TLP floaters. The advantage of taut mooring is that the system has a small footprint and is more stable than other configurations, but the installation process is difficult and expensive crane vessels are required. A taut-leg mooring system does not allow for any vertical movement of the anchored structure. Moreover, large loads placed on the anchors require anchors which can withstand large vertical forces [3].

The **semi-taut mooring** system is a combination of the taut mooring system and catenary mooring system. They are made by synthetic fibres or wires usually incorporated with a turret system, where a single point on the floater is connected to a turret with several semi-taut mooring lines connecting to the seabed. This system allows for some vertical and horizontal movement of the structure and reduces fatigue loading while reducing mooring lengths compared to a catenary system [3].

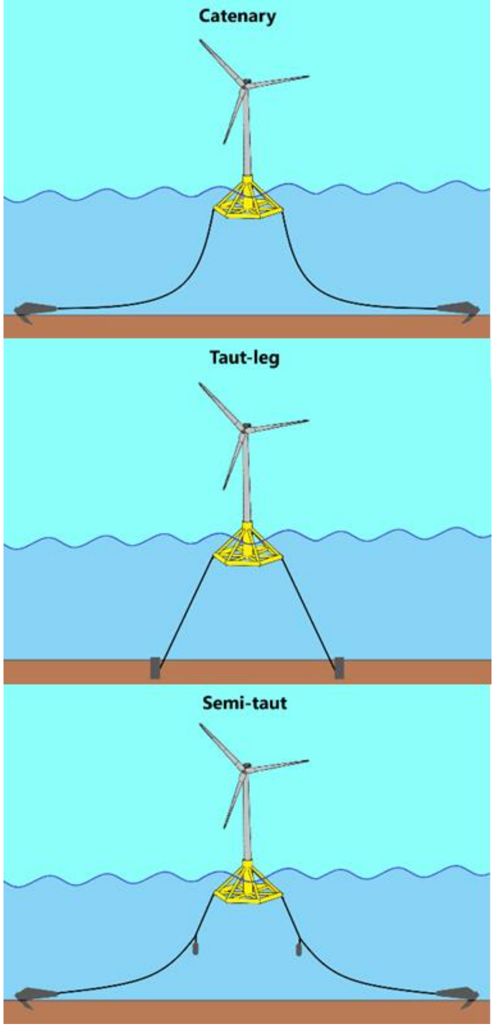

FIGURE 1: MOORING CLASSIFICATION.

Nowadays, different types of **anchors** are presented in the offshore industry. Among the most common there are drag embedment anchors, anchor piles and gravity anchors [5]. Figure 2 shows the most common anchors types.

The **drag-embedded anchor** is the most common type of anchoring system thanks to the scalability of size and weight. This anchor is designed to penetrate the seabed, where the holding capacity is mainly generated by the resistance of the soil in front of the anchor. It is suited for resisting large horizontal loads, but it does not perform for vertical loads. Consequently, this anchor is well configured with a catenary mooring.

Anchor piles consist of cylindrical piles made of steel. They are used for taut mooring systems and TLP since they can hold omnidirectional loads. The installation costs are usually expensive and can be used for a range of seabed. Depending on

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the design and embedment mode can be divided into driven and suction piles.

Driven piles are relatively long, slender and open-ended steel columns. These anchors are usually installed by impact hammering, vibrating or pushing into the seabed. Suction pile anchors are caisson foundations. They penetrate the seabed to a target depth by pumping out the water, creating under-pressure inside the pile and forcing the anchor into the seabed.

The **deadweight** or **gravity anchor** consists of a heavy object placed on the seafloor to resist vertical and horizontal loads. The holding capacity comes mainly from the weight of the anchor and partially from the friction between the anchor and the soil. The considerable dimensions require specialized vessels for installation.

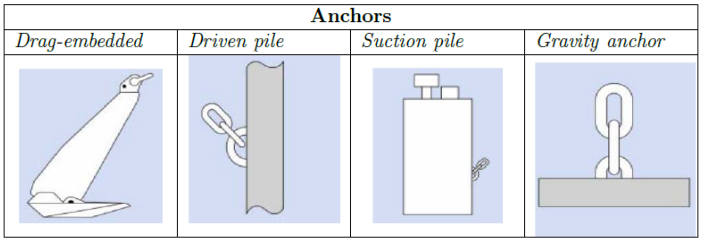

FIGURE 2: ANCHORS CLASSIFICATION, ADAPTED FROM [6].

2.1 Moorings modelling

As a matter of fact, for a correct sizing of the mooring lines, it is necessary to use a suitable numerical model taking into account not only the behavior of the moorings under waves, currents and wind loading but also the hydrodynamics of the substructure and the loads exchanged with the wind turbine. Below are some of the most used software for the design and verification of mooring lines for FOWT systems.

OrcaFlex is a marine dynamic software package developed by Orcina Ltd. allowing full analysis in time and frequency domain [7]. OrcaFlex solves tensions, bending and torsion using a discrete lumped mass approach [8]. The line is divided into a series of segments which are then modelled by straight massless model segments with a node at each end. The model segments only model the axial and torsional properties of the line. The other properties (mass, weight, buoyancy etc.) are all lumped to the nodes.

Forces and moments are applied at the nodes, with the exception that weight can be applied at an offset. Where a segment pierces the sea surface, all the fluid-related forces (e.g. buoyancy, added mass, drag) are calculated allowing for the varying wetted length up to the instantaneous water surface level. A segment can be thought of as being made up of two co-axial telescoping rods that are connected by axial and torsional spring-dampers.

The bending properties of the line are represented by rotational spring-dampers at each end of the segment, between the segment and the node. The line does not need to have axial symmetry, since different bend stiffness values can be specified for two orthogonal planes of bending [7]. Hydrodynamic and aerodynamic drag forces, represented by the drag term in Morison's equation, are applied to the line. The same drag formulation is used for hydrodynamic and aerodynamic drag forces.

Orcawave is the hydrodynamic package software developed by Orcina Ltd. that solves the hydrodynamic problem. OrcaWave always solves the potential formulation, and can optionally solve the source formulation as well. The potential formulation gives the most accurate values for the basic results that are computed directly from the values of the complex potential ϕ: added mass and damping, load RAOs and displacement RAOs. However, the source formulation gives more accurate results for the fluid velocity, $\nabla\phi$. The user can select to solve the source formulation if he wish to obtain results that depend on $\nabla\phi$, such as sea state velocity RAOs or mean drift loads [9].

For the purpose of this study, the potential formulation was adopted. In order to compute the hydrodynamic properties, the mesh of the selected substructure was obtained by mean of Salome-Meca [10].

Orcaflex always allows to remove irregular frequencies associated to the mean wetted surfaces of the substructure. The hydrodynamic solution, computed by Orcawave, considers first order linear effects and second order loads (mean drift and quadratic loads) [9].

MAP++ is a multisegmented quasi-static (MSQS) mooring model available in FAST v8.16 that was developed by Marco Masciola with both the National Renewable Energy Laboratory (NREL) and the American Bureau of Shipping. It is a relatively simple model that allows for a robust, first-pass evaluation of a mooring system by considering the average mooring line loads and nonlinear geometric restoring for both catenary and taut mooring systems [11].

Assuming a quasi-static approach, the motion of the system during a given time step is considered uniform and linear between two static positions; for every timestep, the loads on the systems are assumed constant [12]. This method ignores the dynamic effects on the mooring, omitting the motion dependency of mass, damping and fluid acceleration on the system [13]. This assumption is justified by the fact that the platform has limited movement. In fact, comparing the dynamic model with a quasi-static one, the movements of the structure are replicated quite faithfully [11]. Moreover, MAP++ does not consider bending and torsional cable stiffness and the three-dimensional shape of lines, but it accounts for the seabed friction.

MooDy differs from the other software by being an in-house code of Chalmers University and not being a complete software package. The code, compared to Map++, is merely a dynamic cable solver and needs to be combined with other codes that can solve the interaction between structure and cables [14]. A feature of MooDy is the use of the spectral/hp discontinuous Galerkin method, i.e., an arbitrary order (set by user) finite element

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method. The code uses explicit time-stepping, including the third-order Runge–Kutta scheme and a second-order leap-frog scheme.

3.1 Methods

To properly design the mooring system, three different configurations are proposed and discussed, respectively adapting catenary, taut leg and semi-taut methodologies for a floating offshore wind turbine system located near the island of Pantelleria, in Sicily. For each configuration, the Hexafloat substructure, developed by Saipem, supporting a 5 MW wind turbine is considered.

Each type of mooring is analyzed and discussed through the Orcaflex software in combination with a cost function of the whole floating wind system to evaluate the LCOE. A comparison with the different solutions is carried out in terms of stability requirements, costs and installation complexity. Finally, the most convenient mooring configuration is chosen according to the requirements cited above.

The paper is structured as follows: in section 2 a preliminary design methodology for moorings lines of floating offshore wind systems is presented and discussed; then 3 different mooring layouts are introduced in section 3 for a FOWT, made of Hexafloat foundation and NREL 5 MW wind; in section 4 the Pantelleria case study is presented, as well as the results from Orcaflex simulations for each configuration; conclusions and future works are drawn and discussed in section 5.

2. PRELIMINARY DESIGN OF MOORING LINES

There are several constraints to consider in a preliminary design of a mooring system. Among the most relevant are mentioned:

- environmental conditions (waves, wind and currents)
- seabed depth
- type of seabed, for example, if rocky, sandy, muddy, etc. as the consistency influences the type of anchor that can be installed

The methodology used to predesign the mooring configurations is shown in Figure 3.

As a first step, it is necessary to define the configuration of the mooring line, whether taut, semi-taut or catenary and the material of the line, chain or synthetic fibres. The preliminary design variables considered in this study are the line diameter, line length and anchor radius.

There are different relationships for a catenary layout between the length of the line S and the sea depth d of the installation site:

- S/d > 3 in accordance with [15]
- S/d = 4 ÷ 6 in accordance with [16]
- S/d = 4 ÷ 8 in accordance with [17]

In this paper we have decided to consider for catenary layouts a ratio S/d inferior to 3 for several reasons: first at all to reduce the moorings cost; secondly, to reduce the environmental impact on the seabed and to reduce the maritime area occupied by the system, that for a floating wind turbine can reach different Km^2.

Subsequently, based on the installation site and the meteorological characteristics, the design is carried out according to the 50 years extreme wave, as provided by the Standards.

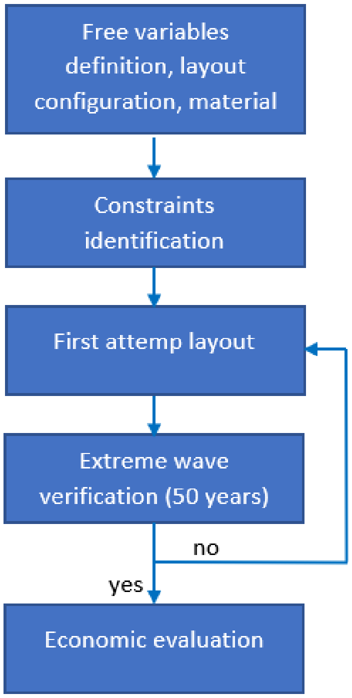

FIGURE 3: DESIGN METHODOLOGY.

Mooring constraints have a significant influence on the response of the entire FOWT system to the action of waves and wind. Consequently, limits are imposed on the displacement of the floating platform, the inclination of the turbine along with the pitch direction and the acceleration at the nacelle. Furthermore, the mooring design must respect the mechanical resistance of the mooring material: the maximum tension of the line must not exceed the minimum breaking load (MBL) of the component and it is necessary to consider a specific safety factor.

In Table 1 are reported the design constraints considered, that have been adapted from Deliverable D1.3 [18] and from Deliverable D2.1 [19]from the Corewind Project.

TABLE 1: Design constraints considered, from [18] and [19].

Design constraints	Expression
Tension	$\frac{T_d}{0.95\, S_{mbs}} < 1$
X offset	$\lvert X_{dynamic} \rvert < 60$ m
Y offset	$\lvert Y_{dynamic} \rvert < 60$ m
Acceleration	$(acc_x, acc_y, acc_z) < 2.94$ m/s^2
Pitch max	15°

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As for the excursion range in surge and sway, we have decided to consider 60 m according to [19].

If the constraints are respected by the proposed configuration, it is possible to proceed with the techno-economic evaluation of the mooring line, possibly trying to optimize it. If, on the other hand, the constraints are not respected, it will be necessary to modify the starting variables, increasing the diameter of the mooring or changing the material.

2.1 Cost analysis

A complete and comprehensive review of main costs of FOWT systems is given in [20]. For mooring lines, the price per meter depends on the minimum breaking load and the materials that compose them [21]. Typically, chains represent a large cost factor when a mooring line is designed. Synthetic ropes have a lower cost per length than steel chains or wires, but a significantly lower weight per unit of length. However, lighter components require less specialized and less costly vessels for installation.

The cost functions used to estimate the mooring system are shown below.

Chain

Cost estimation depends on the steel grade that can be found for the mooring chain and the diameter.

The cost of a mooring line consisting of catenary $Cost_{chain}$ in k€ is [22]:

$$Cost_{chain} = L_{line}\ x\ W_{line}\ x\ 1.5 \quad (1)$$

Where L_{line} is the line length and W_{line} is the weight of the line per meter [kg/m].

Wire

Regarding wire rope, the cost function is given as a function of the diameter [21]:

$$Cost_{wire} = 0.03415\ x\ d^2 x\ L_{section} \quad (2)$$

Where d is the wire diameter and $L_{section}$ is the line length in metres.

Synthetic ropes

The cost function for polyester and nylon are provided from Deliverable 4.6 of DTOcean+ [17], depending on the minimum breaking load for different synthetic ropes.

$$Cost_{polyester} = (0.0138xMBL + 11.281)x\ L_{section} \quad (3)$$

Where MBL is the minimum breaking load of polyester in kN and $L_{section}$ is the line length in metres.

A similar function is available for synthetic fibres made of nylon [21]:

$$Cost_{nylon} = (0.0122xMBL + 12.116)x\ L_{section} \quad (4)$$

Where MBL is the minimum breaking load of nylon in kN and $L_{section}$ is the line length in metres.

Anchors

As for the anchors, different kinds have been considered to satisfy different layouts and seabed substrates. As for screw anchors [23]:

$$Cost_{screw} = (MBL\ x\ \frac{0.18}{9.81}\ x\ N_{anchor}) \quad (5)$$

Where MBL is the minimum breaking load and N_{anchor} is the number of anchors per mooring line.

As for drag anchors [23]:

$$Cost_{drag} = (MBL\ x\ \frac{0.052}{9.81}\ x\ N_{anchor}) \quad (6)$$

Where MBL is the minimum breaking load and N_{anchor} is the number of anchors per mooring line

As for accessories, like crickets and plates, the cost is estimated to be equal to the 17% of the total cost of the mooring line [22].

3. FOWT SYSTEM

This section describes the FOWT system considered, showed in Figure 4, which parts it consists of and the assumptions made.

3.1 Platform

Hexafloat substructure, developed by Saipem SA. is a pendulum floater connected to a counterweight with six tendons. The floater is a hexagonal steel structure, with a central column that supports the wind turbine. The counterweight is made of steel and is shaped like a cylinder to accommodate the ballast inert material: in this work, the ballast material considered is an iron powder with a density of 5200 kg/m^3.

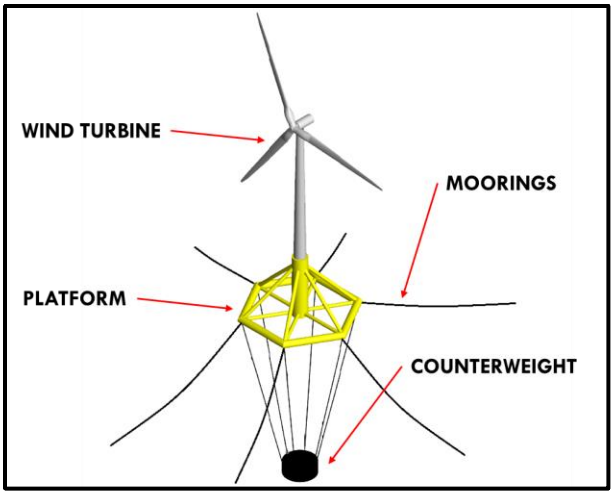

FIGURE 4: FOWT SYSTEM CONSIDERED.

The structure needs from three to six mooring lines, typically composed of chain or taut-leg moorings and a drag anchor for each line [2].

The main advantage is the floater adaptability: the diameter of the tubular structure could be slightly adapted and the ballast depth could be adjusted to suit different turbine sizes, from 2

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MW up to 15 MW. Otherwise, the overall dimensions of the structure are reported in Table 2.

TABLE 2: Hexafloat specifications for a 5 MW wind turbine.

Item	Value
Central column diameter	8.38 m
Central column height	35.25 m
Hexagon radius	26.20 m
Ballast distance above sea level	127.1 m
Steel mass	1414.4 ton
Magnetite ballast mass	2548.8 ton

During the simulation phase on Orcaflex, the Hexafloat mesh was simplified: in particular, the diagonal arms were not considered to improve the speed of execution of the simulations. These are parts that are important from a structural point of view but which have no relevance in hydrodynamic analysis.

3.2 Wind turbine

NREL 5 MW is an offshore wind turbine designed with a power rating of 5 MW, developed by the National Renewable Energy Laboratory (NREL) [23].

It is an academic turbine, not an industrial one, defined from a purely theoretical point of view and not yet built. It is has been considered for two main reasons: in the case of commercialized turbines, such information is not freely available as it is subjected to industrial secrecy, while for these all the data of interest are available, with a high degree of detail; secondly, since they have been used in numerous studies and papers, their use has allowed deeper analyzes and comparisons with other publications.

The main data are reported in Table 3.

TABLE 3: NREL offshore 5 MW baseline wind turbine specifications.

Item	Properties
Turbine rating	5 MW
Rotor diameter	126 m
Hub height	90 m
Rated wind speed	11.4 m/s
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Nacelle mass	240 ton
Tower mass	250 ton
Overall mass	600 ton

The hydrodynamic forces acting on the rotor when this is in parked condition are calculated according Morison's equation, considering its drag coefficient and its shape**.**

3.3 Moorings layouts

For each type of mooring configuration, a layout consisting of 3 mooring lines is proposed, as shown in Figure 5. The proposed configuration is closely linked to the Pantelleria installation site, as there is a strong unidirectionality of the wind and waves according to the north-west direction during most of the year. Consequently, the layout is made of two upwind mooring lines and one downwind: this configuration is also present in other previous studies, such as in [22]–[25].

The proposed solutions are configured for a sea depth of 200 m. The 0 degree direction of the wave is along the x axis of the turbine and all the other directions are relative to it, as shown in Figure 5.

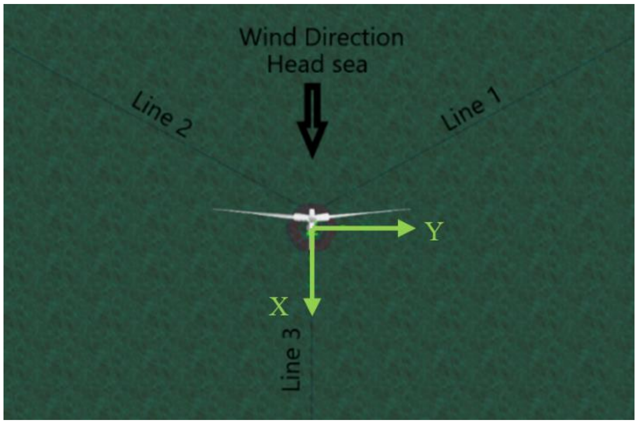

FIGURE 5: MOORING LINES LAYOUT.

Layout 1 – Catenary

The first configuration, reported in Figure 6, involves the use of 3 catenary lines, arranged at the vertices of the hexagonal platform and connected with 3 drag-embedded anchors. All the specifications are reported in Table 4.

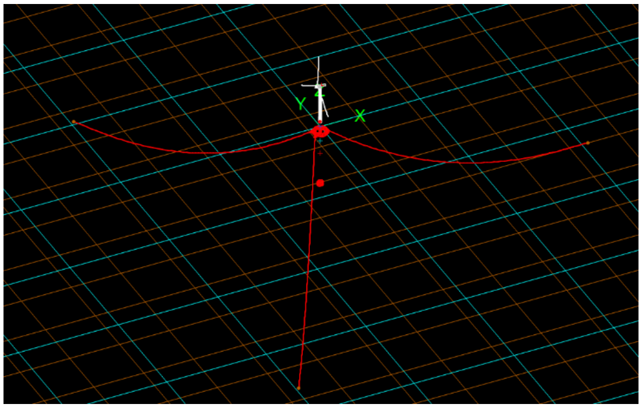

FIGURE 6: LAYOUT 1 CONFIGURATION.

TABLE 4: Catenary layout specifications.

Item	Properties
Chain type	R3
Chain nominal diameter	135 mm
Chain outer diameter	238 mm
Unit weight	347.7 kg/m
Axial stiffness (EA)	1.60 E06 kN
MBL	10.55 E03 kN
Lines length	569 m

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Layout 2 – Taut-leg mooring

The second configuration, reported in Figure 7, involves the use of 3 lines of taut-leg cables, made of polyester and fixed to the backdrop using suction anchors. To avoid the contact between the polyester and the seabed, which could quickly wear the cable, an initial part of the overhead line of 50 m length has been added. All the specifications are reported in Table 5.

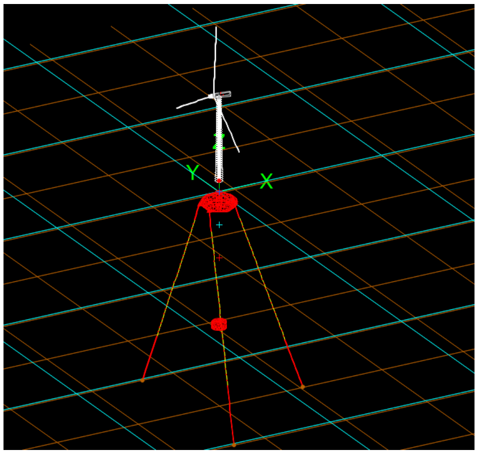

FIGURE 7: LAYOUT 2 CONFIGURATION.

TABLE 5: Taut-leg layout specifications.

Item	Properties
Material	Polyester (8-strand Multiplait)
Diameter	117 mm
Axial stiffness (EA)	20.16 E03 kN
Unit weight	13.3 kg/m
MBL	3420 kN
Lines length	200 m (50 m catenary, 132 m polyester, 18 m catenary)

Layout 3 – Semi-taut mooring

The last configuration, reported in Figure 8, involves the use of a section of catenary, placed between the drag anchor and the intermediate clump weight and a final part made of chains. All the specifications are reported in Table 6.

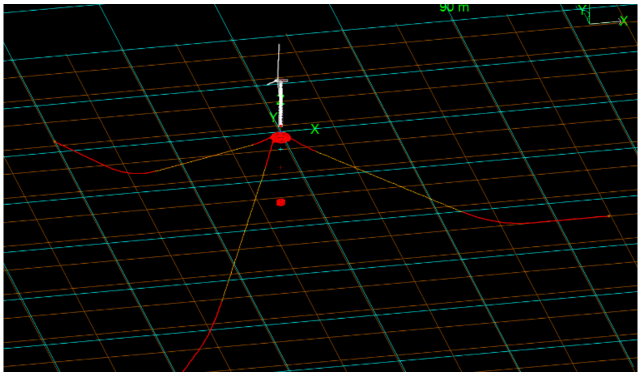

FIGURE 8: LAYOUT 3 CONFIGURATION.

TABLE 6: Semi-taut layout specifications.

Item	Properties
Chain	
Chain type	R3
Chain nominal diameter	135 mm
Chain outer diameter	238 mm
Unit weight	347.7 kg/m
Axial stiffness (EA)	1.60 E06 kN
MBL	10.55 E03 kN
Fibre ropes	
Material	Polyester (8-strand Multiplait)
Diameter	116.96 mm
Unit weight	13.3 kg/m
MBL	3152 kN
Lines length	569 m (245 m catenary, 273 m polyester, 51 m catenary)

4. PANTELLERIA CASE STUDY

Pantelleria, which location is shown in Figure 9, is a small Italian island located in the Sicily Channel, 110 km southwest from Sicily and 65 km northeast of Tunisia, in one of the windiest areas of Italy.

FIGURE 9: ANNUAL WIND ENERGY PRODUCTIVITY IN ITALY, ADAPTED FROM ATLANTE EOLICO RSE [28].

However, this energy potential has not yet been exploited, as there are not both onshore and offshore wind farms on the island. In fact, the electricity requirement, quantified as about 37.6 GWh per year, is completely provided by a thermoelectric power station (Smede) and some small photovoltaic parks [29]. Consequently, as the island is not connected to the national electricity grid and electricity must be produced on-site, the cost of electricity is higher than in the rest of Italy.

This study aims to design and test different mooring layouts of a floating offshore wind turbine, able to completely satisfy the island's electricity needs.

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4.1 Site identified

The site identified for the installation of the FOWT system is located at a sea depth of 200 m, approximately 32 km from the coast of Pantelleria (37° 06' 11" N, 11° 48' 14" E), as visible in Figure 10. Among the criteria considered for the identification of an optimal site, there is the wind resource availability, the bathymetry, the remoteness from sea routes and the distance from fishing activities.

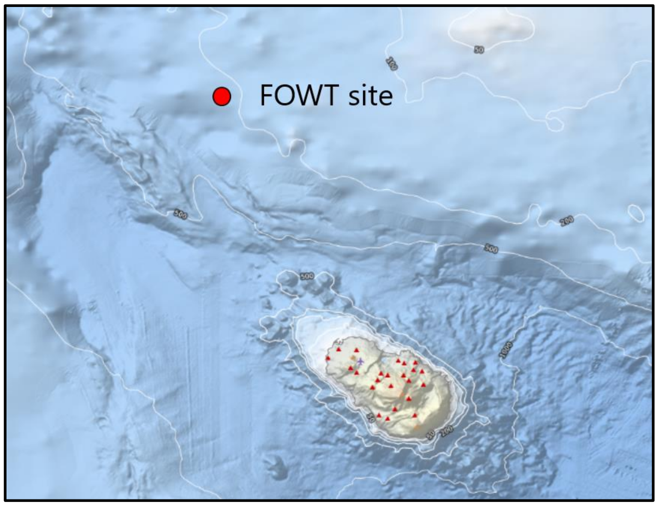

FIGURE 10: THE SITE FOR FOWT IN PANTELLERIA, ADAPTED FROM EMODNET BATHYMETRY [30].

4.2 Meteomarine analysis

The island's climate is characterized by dry temperate with strong winds that come mainly from NW and S-SE. Therefore, the orientation of the floating platform will take place with the bow in the SW - NE direction, orthogonal to the prevailing wind direction to maximize the efficiency of the wind turbine.

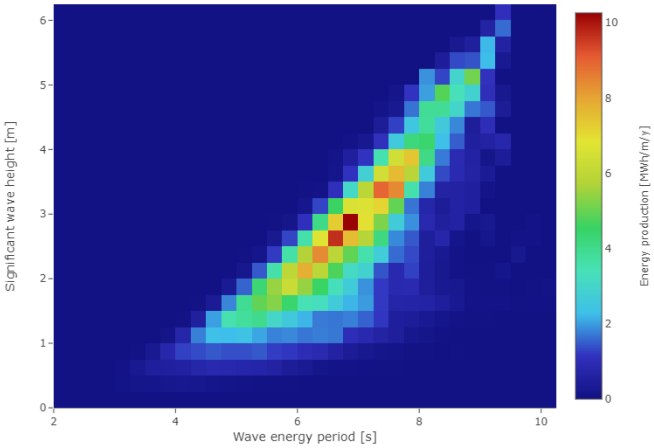

FIGURE 11: PANTELLERIA WAVE SCATTER.

The Global Wind Atlas estimates an average annual wind speed measured at a height of 100 m to be approximately 7.9 m/s, which guarantees excellent performance in terms of electricity production [31]. Regarding the wave energy potential, in Figure 11 it is reported Pantelleria scatter, with the energy production in function of wave energy height and wave period.

The simulations are made in extreme waves considering 4 main directions: at 0°, 30°, 60° and 90° measured in front of the floating platform, as reported in Table 7.

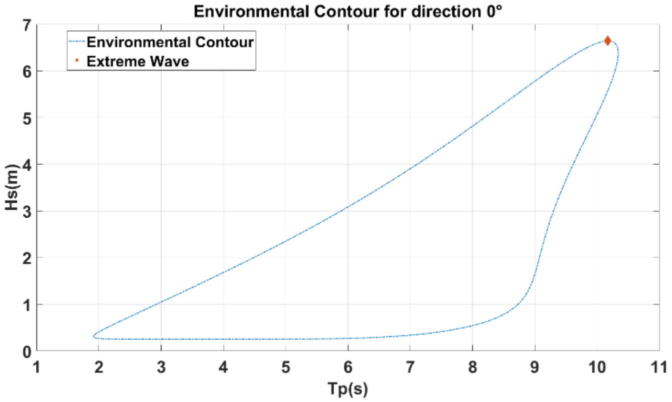

FIGURE 12: ENVIRONMENTAL CONTOUR.

In Figure 12 it is represented the directional environmental contour generated from Pantelleria scatter according to [33]. The environmental contour is created using a two-parameters Nataf distribution considering 50 years RON data and the wind decoupled from Hs and Tp. According to DNV [34], the wind speed considered is the maximum registered in Pantelleria and it is 26.5 m/s.

TABLE 7: Waves summary.

Wave	Direction	Hs [m]	Te [s]	γ
1	0°	6.64	10.17	3.3
2	30	6.46	10.06	3.3
3	60	5.27	9.23	3.3
4	90	4.33	8.53	3.3

4.3 Simulation results

All the results obtained from the Orcaflex simulation are fitted in an "extreme value distribution" and the 90th percentile is considered as the reference value. The simulation setup is realized according to DNV [34]. The simulations length is equal to 3 hours storm and each simulation is repeated 10 times randomly varying the seed number.

The parameters to be considered are tension at each fairlead line, forces at the anchors (total and vertical), surge and sway, pitch and nacelle acceleration (x, y and z component).

The Orcaflex simulations are done considering the rotor parked and blades feathered.

All the maximum values for each simulation (4 waves for 10 realizations/seeds) have been placed in the app data fitter of MATLAB and according to DNV suggestion, they have fitted

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using a generalized extreme value distribution. Each 90th percentile of each distribution (one distribution for each controlled parameter) is the design parameter [27].

In Figures 13 and 14 are reported two examples of extreme value distribution relative to fairlead loads and nacelle acceleration for layout 1, the catenary mooring.

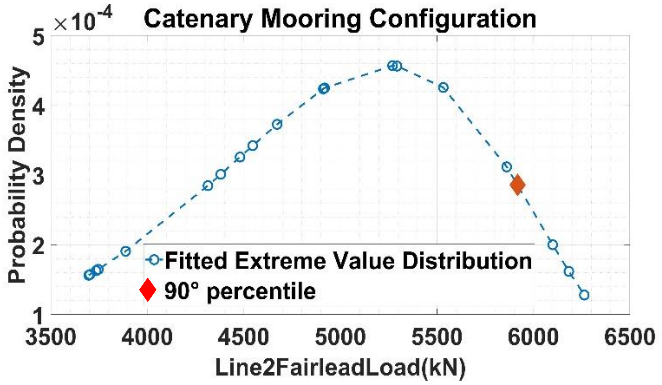

FIGURE 13: PROBABILITY DENSITY OF LINE 2 FAIRLEAD LOAD.

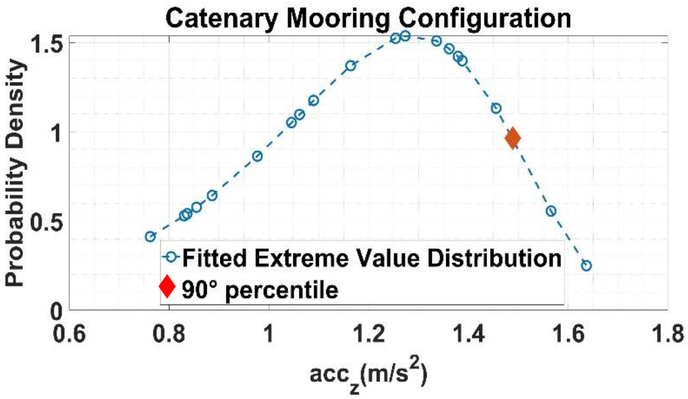

FIGURE 14: PROBABILITY DENSITY OF NACELLE ACCELERATION ALONG Z-DIRECTION.

To understand the main differences among the 3 mooring layouts, the 90th percentile of motions, nacelle accelerations and lines loads are reported in the bar plots shown respectively in Figures 15, 16 and 17.

Particularly, in Figure 15 the degree of freedoms of pitch, roll, sway and surge are monitored since the pitch angle and translations are design parameters.

The same considerations can be done in Figure 16 for the nacelle accelerations.

In Figure 17, instead, are shown the fairlead loads, which should be inferior to the MBL of the lines material, and the vertical and total anchor load, in order to understand which anchor should be used for each mooring layout. For the taut leg configuration, due to high vertical loads drag anchor are not suitable and screw or suction anchors should be used. Only line 1 and 3 have been reported, since line 2 is specular to line 1.

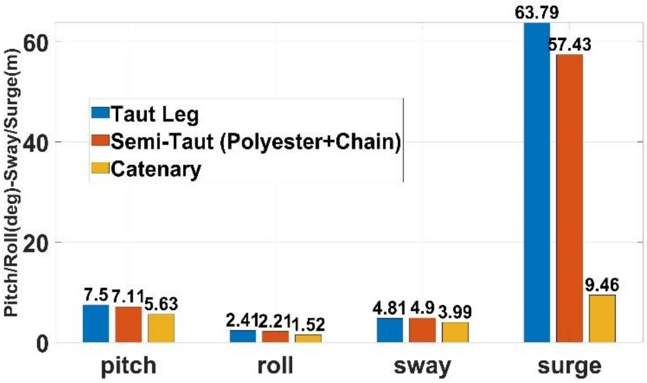

FIGURE 15: FLOATING PLATFORM DISPLACEMENTS AND ROTATIONS FOR THE 3 LAYOUTS.

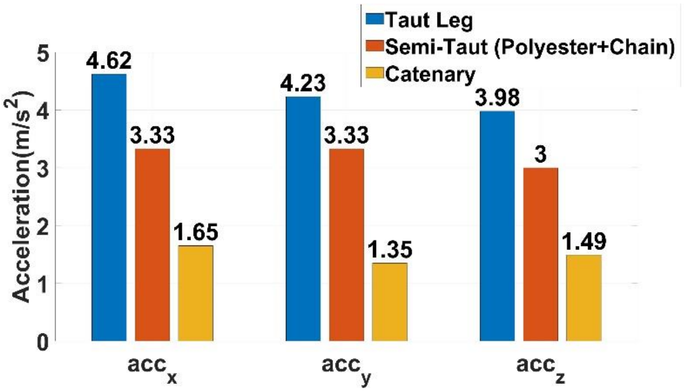

FIGURE 16: NACELLE ACCELERATIONS FOR THE 3 LAYOUTS.

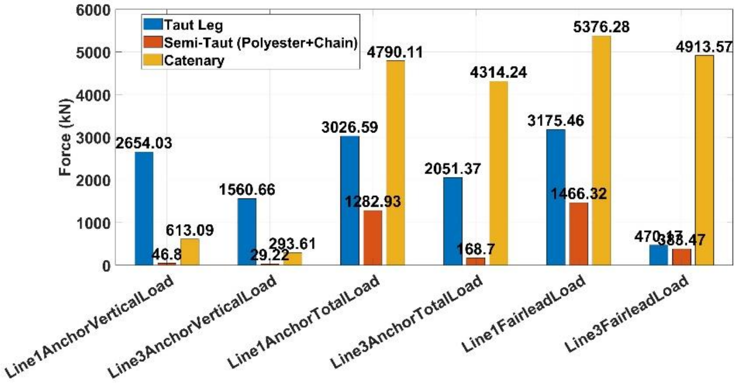

FIGURE 17: FAIRLEADS LOADS, VERTICAL AND TOTAL ANCHOR LOADS FOR THE 3 LAYOUTS.

4.4 Techno-economic evaluation

Based on the cost functions previously introduced, each configuration was evaluated from an economic point of view, considering the cost of the moorings, anchors and the costs of the accessory parts. In the following Figures 18, 19 and 20 the main costs are reported: in particular the lines costs, the anchors costs and accessories costs.

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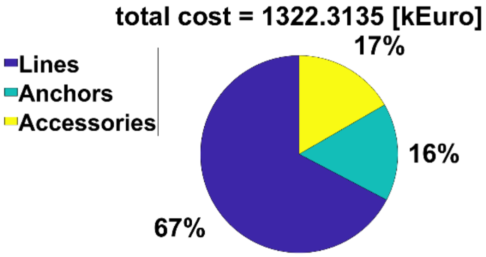

FIGURE 18: COST EVALUATION – LAYOUT N.1

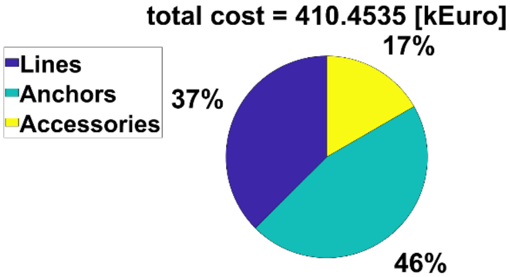

FIGURE 19: COST EVALUATION – LAYOUT N.2

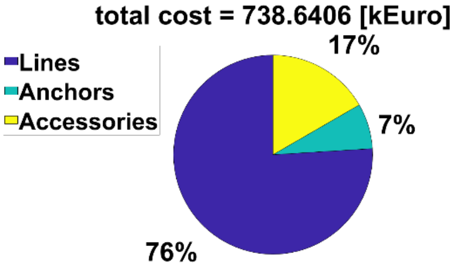

FIGURE 20: COST EVALUATION – LAYOUT N.3

5. CONCLUSION AND FUTURE WORKS

Among the three layouts considered in the analysis, only the **catenary** configuration respects the limits suggested in literature, in particular in [18] and [19]. It is important to underline that these limits are not imposed by Standards but they are suggested as reference values to keep limited maintenance costs and high safety features. Even if the catenary configuration satisfies all the constraints, its cost is higher than the other two configurations, respectively about the triple of layout n.2 and the double of layout n.3.

On the other hand, **taut leg** mooring layout guarantees a lower mooring cost as well as lower tensions, but nacelle accelerations are unacceptable. Moreover, special effort should be given to the pitch motions that occur for this case as well as the screw anchor installation. More than half of the lines loads are represented by its vertical component. Screw anchors present difficulties of installation according to the seabed characteristics thus the cost function can strongly vary.

Finally, the **semi-taut** layout represents an acceptable compromise in terms of economic investment and design constraints acceptability. However, this solution should be still improved and refined to achieve the desired design parameters at a minimum cost.

This paper aims to introduce and describe a methodology for choosing the most convenient mooring layout that satisfies design parameters. The results are strongly influenced by initial parameters, such as the anchor radius, lines stiffness, mass and diameters. A challenge of this methodology is to identify a mooring layout that with a minimum investment guarantees the survivability of the FOWT in extreme events.

Some improvements that can be brought to the presented methodology concern the environmental contour definition, considering a 3 parameters distribution to account for the jointed wind - wave height - wave periods probability. Moreover, an additional analysis will be added to the one proposed in this paper since it only consider ULS design. The operative condition, in which the rotor thrust is maximum should be analyzed in order to understand the worst situation, characterized by the highest loads or accelerations. Furthermore, the cost function could be implemented considering the specifics for mooring installation in the chosen site.

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