Parametric study of dynamic inter-array cable systems for floating offshore wind turbines

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Abstract

The rapid emergence of the floating offshore wind sector requires the development of new technologies such as dynamic inter-array cables. This work gives an insight into the hydrostatic predesign of such a cable system looking from side view. Numerical analyses are performed to compare two umbilical shapes, namely catenary and lazy wave shape. In a parametric study, water depth and cable length are varied. As outcome, a unique and generalized recommendation for a first umbilical design is presented. Finally, an outlook to the dynamic analysis of umbilicals in future work is given.

Keywords Inter-array cable · Floating offshore wind turbine · Hydrostatic analysis

Abbreviations

AC	Alternating current
HO	Hang-off
MAC	Max. allowable curvature
MBL	Minimum breaking load
TD	Touchdown
TSL	Target segment length

Symbols

d	Water depth
h	Height of hang-off
$l_{1/2/3}$	Lazy wave section lengths
$l_{\max/\min}$	Max./minimum length
l_{total}	Total cable length
x, y, z	coordinates

1 Introduction

Following the agreement of the 2015 United Nations Climate Change Conference to keep global warming well below 2 °C, the European Union's climate strategy aims to drastically reduce greenhouse gas emissions and continually increase

the share of renewable energy [1, 2]. According to DNV GL and EWEA¹ [3, 4], offshore wind has the potential to cover half of the European Union's power demand. Bottom-fixed turbines are already field-proven and in commercial operation for two decades, but are economically viable only in shallow water up to about 50 m [5, 6]. To unlock the wind resources from deep water sites, different floating foundations are being developed, most of them based on concepts used in the offshore oil and gas sector, see Fig. 1.

So far, no commercial size project has been realized, whereas a 30 MW precommercial project from Equinor² finished installation and is in test operation since autumn 2017. With five turbines, Hywind Scotland is world's first floating wind farm. The devices are mounted on gravity stabilized platforms. The heavy construction and the long cylindrical shape are very material intensive and limit its application to water depths over 100 m. In contrast, mooring line stabilized platforms feature a lighter construction. Due to the taut mooring, they also possess the least critical motion behavior. However, a sophisticated anchor system design becomes necessary. By now, this concept still lacks behind the other two in technology readiness without a full-scale prototype existing yet. Arguably, the most universal floating foundation currently is the buoyancy stabilized platform. An example for a proven full-scale prototype is given by the WindFloat project. Having a voluminous floater with comparatively shallow draft and catenary mooring, this concept is the most susceptible to metocean loads. The universality, the technical progress and the most challenging motion

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Fig. 1 Floating offshore wind farm foundations with according stabilization principle. Adapted from [7]

Fig. 2 Power transmission system of an offshore wind farm in top view. Adapted from [15]

Fig. 3 Power transmission system of a floating offshore wind farm in side view. From [17]

behavior are the reasons that the present work and following investigations will refer to this type of platform. For a more comprehensive overview of the strengths and weaknesses of the foundation concepts, see [4, 6, 8–10].

A big challenge for every offshore wind farm is the transportation of the produced energy to shore. A typical top view of a power transmission system is depicted in Fig. 2 with energy flowing downstream from the turbines to the grid: Presently, an inter-array voltage of 33 kV and alternating current (AC) are considered as standard electrical specification for the collection system of an offshore wind farm. However, in the last years efforts have been made to establish a new 66 kV AC standard targeting further cost

reductions for large farms [11–13]. Multiple connected turbines form a feeder. The terminal cables of all feeders end in an offshore substation which bundles the energy. It usually contains transformers for an increased export voltage which reduces losses over longer transportation distance to shore [14].

So far, this setup is valid for the transmission system of bottom-fixed and floating wind farms alike. The difference is illustrated in the side view in Fig. 3: In the classic case of fixed foundations, cables are installed on the sea bed, as shown on the right side (export) of the offshore substation, or are even buried and/or rock dumped [16]. New and characteristic for floating wind farms is the part of the inter-array cables, that is traversing the water column freely moving, as shown on the left side of the figure. Only fixed at its end

points, the cable is exposed to the motion of the floating platform, to wave excitation and currents. This type of dynamic cable is also further referred to as “umbilical.”

Because floating platforms are a very recent addition to the offshore renewables sector, field experience with dynamic cables in this area is still scarce and a lot of research problems remain to be investigated [9]. The objective of this paper is to give an insight into the layout of an inter-array cable system from elevation perspective. Therefore, Sect. 2 contains an overview of literature already available on this subject. Moreover, two typical umbilical shapes are introduced. The cable specifications, the simulation setup

Fig. 4 Sketch of catenary and lazy wave umbilical shape

and the evaluation methodology applied in the present study are described in Sect. 3. Following in Sect. 4, a parametric study is conducted comparing the two umbilical shapes for different water depths and cable lengths. The hydrostatic analyses are conducted using the software OrcaFlex [18]. Finally, Sect. 5 gives a summary of the current work and an outlook to future investigations considering metocean loads and hydrodynamic behavior.

2 Umbilical shapes

The major part of publications on inter-array cabling in off-shore wind farms focuses on the cable routing layout from top view by means of finding the shortest and/or most cost efficient connection of the turbines, see e.g. [15, 19–23]. Several authors enhance their algorithms by including the optimization of turbine positions regarding the wake effect [24, 25] or by adding non-crossing [26] or geology constraints [27, 28].

The objective of the present paper, however, is to define the umbilical shape in the vertical plane. Two types of shapes are tested and compared: first, a simple catenary shape, whose outline resembles the curve of a free hanging, uniform chain under only the influence of its own weight; second, an umbilical with buoyancy elements added at an intermediate part of the cable, resulting in a characteristic shape called “lazy wave,” see Fig. 4. An overview and comparison of different variants of wave-type cable shapes is given in [29].

As first full-scale demonstrators for floating wind turbines only have emerged during last decade, field experience with dynamic umbilicals in this area is hardly available [9]. In literature, findings relating to umbilical shapes are coming from few experimental [30, 31] and some numerical investigations [30, 32–35].

Martinelli et al. [30] perform dynamic scale tests on a power umbilical connected to a floating wave energy converter model. Both catenary and lazy wave shape are

tested, however limited to one cable length and only small variation of water depth. They back their experiments with numerical simulations using an in-house code and the Flexcom software.

Taninoki et al. [31] report about the development of a dynamic cable system for Japan’s first half- and full-scale floating wind demonstrators tested close to Kabashima Island. Their lazy wave concept is supported by an intermediate subsea buoy. Apart from laboratory tests and numerical analyses, they give rare insights into field experiences with the finally installed cable.

Poirette et al. [33] present a lazy wave optimization tool based on their in-house Sequential Quadratic Approximation algorithm coupled with the software Deeplines. They examine production and storm load cases for a full-scale floating wind turbine model. Besides length also the diameter of the cable sections is varied. The water depth assumed in the studies remains unspecified.

Thies et al. [34] make use of the software OrcaFlex for their dynamic cable simulations. The simulation setup considers a floating oscillating water column plant. Catenary and lazy wave shape are tested; cable length and water depth (57 m) are not varied. In post-processing, they introduce a method for the fatigue life assessment of the cable. In a later work from 2017, they examine seven lazy wave configurations for a point absorber wave energy converter in shallow water (30 m) regarding maximum tension and minimum bend radius by varying the position of the buoyancy section.

Krügel [32] adopts the fatigue life assessment from the aforesaid authors. The innovation of his approach consists in not assuming a continuous buoyancy section for the wave shaped umbilical, but letting a genetic algorithm place small floater sections along the cable in order to minimize fatigue damage. Only one cable length and water depth (50 m) are considered.

Concluding from the above described literature, first umbilical shape analyses have already been performed. Mostly however, the examinations are limited to a predefined cable length and/or one single water depth. Depths larger than 50 m, which are considered for future commercial floating wind farms [3, 4], are hardly covered. Apart from that, it is difficult to compare the results among the authors, as various floating devices with presumably unlike motion behavior and differing load cases are considered. Under these circumstances, this work knowingly takes a step back to the hydrostatic analysis of umbilical systems. To develop a basic understanding of influencing parameters, a wider range of water depths relevant for floating wind is taken into account. For every water depth, various cable lengths are tested. The influence of metocean loads and dynamic behavior of the cable are to be investigated separately in future work. Therefore, the present paper can be understood

Fig. 5 Typical double-armored umbilical cross section. From [31]

as predesign study thereof. The methodology of the current hydrostatic approach is illustrated in the following section.

3 Methodology

Subsea umbilicals are specifically engineered to withstand dynamic loads from harsh offshore environmental conditions. A typical cross section design and the mechanical properties of the cable used in this study are subsequently presented, followed by the description of the simulation setup and the evaluation parameters.

3.1 Umbilical properties

The principal function of an umbilical is power transmission. Commonly, the inter-array transmission systems of offshore wind farms are based on three-phase AC technology. A characteristic cable cross section with three conductor cores is shown in Fig. 5. The conductors are electrically insulated and water sealed by a sheath, both made of polymer. Mechanical protection is provided by an armor of twisted steel wires. The armoring also greatly influences the dynamic behavior of the umbilical. For added stiffness and protection, a double wire armor is recommendable [14].

Mechanical cable failure modes range from tensile failure, bending failure, excessive twisting, compression (resulting in bird-caging of the armor) and fatigue to abrasive friction (on the seabed). In the following hydrostatic analysis, the first two failures are considered. Therefore, two important cable parameters are its Minimum Breaking Load and its Minimum Bending Radius, see Table 1 with the mechanical properties of the umbilical used in this work. The referenced cable with a diameter of 0.2 m is rated at 11 kV three-phase AC with a capacity of 1 MW [30]. For today's floating wind applications, these electrical specifications are rather outdated. However, mechanical properties being proprietary data of the manufacturers, there are currently no more suitable data publicly available.

Table 1 Mechanical data for double-armored umbilical. From [34]

	2-Armored cable	Buoyancy section
Outside diameter (mm)	200	306
Nominal weight in air (N/m)	706	423
Nominal weight in seawater (N/m)	390	−316
Bending stiffness (kN m^2)	10	10
Axial stiffness (MN)	700	700
Torsional stiffness ($\text{kN m}^2/^\circ$)	600	600
Minimum breaking load (kN)	100	100
Minimum bending radius (m)	2	2

3.2 Simulation setup

The hydrostatic simulations in this work are conducted using the software OrcaFlex, the world's leading package for static and dynamic analysis of offshore marine systems. It also supplies a programming interface that allows its use as library for automating calculations with the help of, e.g., Python or MATLAB. In OrcaFlex, the umbilical is represented by a finite element model using a lumped mass method. Mass and forces of the umbilical are concentrated on nodes that are connected by massless springs. For more information on the software and the modeling, see the OrcaFlex documentation [18].

For the hydrostatic calculations, the following scenario is assumed: The umbilical is hanging off a fixed point 20 m below sea level. That value corresponds to the draft of the OC4 semi-submersible test platform [36]. The height of the hang-off over the seabed therefore is $h = d - 20$ m. The water depth d is varied in the range from 50 to 200 m, which applies to roughly two-thirds of the North Sea [4]. The horizontal distance of the cable's fixation point on the sea bed is defined as $2h$. The described setup of the OrcaFlex base files is pictured in Fig. 6 for the catenary shape on the left and the lazy wave shape on the right.

As OrcaFlex models the umbilical with a finite element method, the discretization of the cable, the Target Segment Length (TSL), has to be determined in a convergence study. At the hang-off, results for tension and curvature clearly converge at a TSL of 0.1 m. This fine discretization is applied to the first 5 m of the cable. However, throughout the rest of the cable, a TSL of 0.5 m is considered to be sufficient because results deviate less than 2% from the finer discretization. Moreover, the convergence study already reveals that the cable is susceptible to overbending at the hang-off. As additional protective measure, the final umbilical setup includes a cone-shaped bend stiffener, usually molded out of polyurethane elastomer. In OrcaFlex, it is modeled with a length of 3 m, an outside diameter decreasing from 0.7 m

Fig. 6 OrcaFlex base files for catenary and lazy wave shape

to 0.38 m, a material density of 1200 kg/m³ and a Young's modulus of 45 MPa.

3.3 Evaluation procedure

The two cable shapes are evaluated regarding the maximum effective tension and the maximum curvature, latter being the inverse of the bending radius. Both criteria are combined in a fitness function, normalized by their maximum allowable value:

$$\text{fitness} = \frac{\text{max. tension}}{\text{MBL}} + \frac{\text{max. curvature}}{\text{MAC}} \quad (1)$$

with

- MBL = 77 kN: Minimum Breaking Load
- MAC = 0.38 m⁻¹: Maximum Allowable Curvature

both including a safety factor of 1.3. Using the above fitness function, an umbilical configuration with lower fitness value is considered to be better. In the following section, numerous different configurations of each shape are examined in a parametric study, with the fitness value being the central decision criterion.

4 Parametric study

The objective of the parametric study is to identify the best cable length for each shape at different water depths. The tested length intervals and additional constraint sets are specific to the shapes and described at the beginning of the respective subsection.

4.1 Catenary shape

For every water depth, a range of different cable lengths is tested. Regarding the catenary shape, the test interval is limited by

$$l_{\min} = 1.05 \cdot \sqrt{5}h \quad (2)$$

$$l_{\max} = 0.95 \cdot 3h \quad (3)$$

with the first resulting in a close to diagonal outline (shorter scope), and the latter an almost rectangular outline (longer scope). The nautical term scope herein refers to the total cable length divided by h .

Evaluating the criteria maximum effective tension and maximum curvature separately, the following conclusions can be made: The maximum tension always is located at the hang-off point where the weight from all the suspended cable has to be supported. Choosing a longer scope results in a more rectangular umbilical outline with less free hanging cable. As a result, the hang-off tension decreases. Figure 7 shows the normalized maximum tension of the examined catenary shapes exemplarily for the water depths $d = 50$ and 100 m.

Regarding the maximum curvature, neither a very long nor a very short scope is ideal, see Fig. 8. High curvatures occur at the touchdown point for a rectangular umbilical outline and at the hang-off in case of a diagonal outline.

According to Equation (1), the fitness value is obtained by adding up the normalized maximum tension and the normalized maximum curvature. The resulting bar diagrams for the exemplary water depths are displayed in Fig. 9.

Figure 10 shows the fitness-optimized, normalized umbilical configurations for all tested water depths. Note that the curvatures as visible in the diagram are not comparable because of distortion from normalization. Corresponding numeric results are given in Table 2. Accordingly, in shallow water a slightly smaller scope is beneficial with curvature being the more important factor in the fitness function. However, in deeper water the

Fig. 7 Normalized maximum tension of all tested catenary configurations at $d = 50$ and 100 m

Fig. 8 Normalized maximum curvature of all tested catenary configurations at $d = 50$ and 100 m

Fig. 9 Fitness of all tested catenary configurations at $d = 50$ and 100 m

maximum tension quickly becomes predominant, which is why a longer scope with less free hanging cable is preferred. Nonetheless, starting from a water depth around 200 m the hang-off tension gets critical.

4.2 Lazy wave shape

The OrcaFlex model of the lazy wave shape consists of four cable sections. Precisely, those are the length invariable, fine discretized hang-off section, two sections of the standard double-armored umbilical and an intermediate section with

added buoyancy elements, see Fig. 6 right. The parametric study covers following constraint set:

$$l_{\text{total}} > l_{\min} \quad (4)$$

$$0.2 \cdot l_{\min} < l_1, l_2, l_3 < 0.5 \cdot l_{\max} \quad (5)$$

$$0.2 \cdot l_{\text{total}} < l_1, l_2, l_3 < 0.5 \cdot l_{\text{total}} \quad (6)$$

To limit the amount of possible combinations, the cable section lengths are varied in a step size of $0.1h$. Moreover, two

Fig. 10 Catenary configurations chosen regarding the best fitness value

Table 2 Results for fitness-optimized catenary configurations

d (m)	50	70	100	150	200
l_{total}/h	2.70	2.74	2.75	2.79	2.79
$\frac{\text{Max. tension}}{\text{MBL}}$	0.16	0.27	0.44	0.71	0.98 (HO)
	(HO)	(HO)	(HO)	(HO)	
$\frac{\text{Max. curvature}}{\text{MAC}}$	0.33	0.27 (TD)	0.23	0.18 (TD)	0.14 (TD)
	(HO)		(HO)		

Abbreviations for location: HO hang-off, TD touchdown

restrictions for the vertical extent of the lazy wave shape are introduced. Firstly, the sag bend must keep a clearance to the seabed of at least $0.1d$. Secondly, the hog bend must not exceed the hang-off point.

The above length constraint set leads to hundreds of possible combinations per water depth. Figures 11 and 12 show the ten best configurations regarding normalized maximum tension and normalized maximum curvature for the exemplary water depth of $d = 70$ and 150 m. The different

configurations are therein identified by the combination of their section lengths l_1 , l_2 and l_3 . The normalized tension and curvature being the two summands in the fitness function, see Eq. (1), it is concluded from the bar graphs that in shallow water the influence of curvature is more important, whereas in deeper water the tension plays a more important role. Moreover, it is seen that the configurations with lowest tension have a significantly shorter first section than the configurations with lowest curvature.

Regarding fitness, the ten best lazy wave configurations at each water depth perform only marginally different. Meanwhile, they feature significantly different total length, see Fig. 13. In the sense of an economic selection criterion, the final cable layout is chosen to be the shortest of the ten fittest configurations. Note also that the final layouts (configuration 34-34-64 at $d = 70$ m and 101-88-179 at 150 m) do not make part of the ten best configurations considering maximum tension or curvature and therefore represent a compromise between the two evaluation criteria.

The final fitness- and length-optimized configurations for all tested water depths are displayed in Fig. 14 and the corresponding numeric results are given in Table 3. Throughout all water depths, the maximum tension is again located at the hang-off. However, as hinted by the above bar graphs, the hang-off tension can be effectively reduced by decreasing the length of the free hanging first cable section. That is why for deep water, a lazy wave shape with higher position of the sag bend is preferable. In shallow water, where the maximum curvature plays a dominant role, a flatter umbilical outline with lower sag bend position is chosen.

Regarding the ratio of the cable section lengths, converging values are observed starting from a water depth of 70 m. Thus, a generalized recommendation for a first umbilical design is deduced with a length ratio of $l_1 : l_2 : l_3 = 1 : 1 : 2$ and a scope of around 2.8 . The discrepancy in the case $d = 50$ m is likely due to the maximum curvature as limiting factor and also occurs for a water depth of 30 m in case 2 of the investigations from Thies et al. (2017) [35].

Fig. 11 Ten best lazy wave configurations considering normalized maximum tension at $d = 70$ and 150 m

Fig. 12 Ten best lazy wave configurations considering normalized maximum curvature at $d = 70$ and 150 m

Fig. 13 Ten fittest lazy wave configurations at $d = 70$ and 150 m

Table 3 Results for fitness- and length-optimized lazy wave configurations. Abbreviations for location: *HO* hang-off, *SB* sag bend

d (m)	50	70	100	150	200
l_{total}/h	2.67	2.74	2.79	2.87	2.84
l_1/l_{total}	0.34	0.25	0.24	0.27	0.24
l_2/l_{total}	0.23	0.25	0.24	0.24	0.27
l_3/l_{total}	0.38	0.47	0.49	0.48	0.48
$\frac{\text{max. tension}}{\text{MBL}}$	0.12	0.15	0.23	0.42	0.48 (HO)
	(HO)	(HO)	(HO)	(HO)	
$\frac{\text{max. curvature}}{\text{MAC}}$	0.40 (SB)	0.38 (SB)	0.35 (HO)	0.28 (HO)	0.36 (HO)

4.3 Discussion

When comparing catenary and lazy wave shape, two cases should be distinguished concerning the water depth. In deep water well above 100 m, the catenary shape is not feasible due to the critical tension at the hang-off. Meanwhile, with the lazy wave shape optimized by the same fitness function, it is possible to cut the tension almost by half. Technically, even larger water depths than 200 m are accessible.

In the case of shallower water, the hydrostatic calculations produce well-performing results for both shapes. However, with an outlook to future dynamic analyses, it is

Fig. 14 Lazy wave configurations chosen regarding good fitness value and minimum length

understood from the references cited in Sect. 2 that the catenary shape is far more susceptible to platform movements. Accordingly, for catenary moored floating platforms with larger movement radius, a catenary umbilical has a high risk of overbending and faces new threats such as compression and excessive fatigue at the touchdown point [37, 38]. In

contrast, the lazy wave shape decouples platform and cable movement and is therefore expected to handle the aforesaid problems better [32]. A special case in which a catenary umbilical may be sufficient is for a rather stationary tension leg platform in comparatively shallow water.

In conclusion, in most cases a lazy wave shape is preferable to a catenary shape. Interestingly, for the presented optimized configurations this decision results in almost no difference of the total cable length. The only downside of the lazy wave shape is its buoyancy elements that represent an additional capital cost factor. However, a sophisticated umbilical design can help to lower the cable failure rate and therefore prevent expensive repair and downtime of the array.

5 Summary and future work

The hydrostatic analyses of the umbilical shapes revealed that the lazy wave shape is technically superior to the catenary shape. Moreover, a recommendation for a first umbilical design has been found, applicable in the water depth range from 70 to 200⁺ m. A scope of 2.8 and a ratio of the cable section lengths of 1:1:2 result in a configuration with well-balanced tension and curvature. Additionally, the use of a bend stiffener at the hang-off is strongly recommended.

In ongoing research, the umbilical analysis is to be extended regarding the dynamic behavior. Hence, future work will consider metocean loads, the resulting platform movement and an in-depth fatigue analysis. First dynamic simulations already show that the direction of the cable in respect to the metocean loads is a crucial factor to consider [37]. If becoming available, the simulations will be performed using a more state-of-the-art cable data set.

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