Suspended cable model for layout optimisation purposes in floating offshore wind farms

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Abstract. The cable layout optimisation for floating offshore wind farms is a complex task due to the number of elements involved and their nature, such as dynamic cables with buoyant sections. The first step is defining a model of the suspended cables that connect wind turbines between them or to cables on the seabed (risers). A lumped mass model and the finite element method are used to find the static position and mechanical stresses of the cables, keeping a balance between computational time and the quality of the results. The model allows the inclusion of standard ancillary equipment such as bend stiffeners, buoyancy modules, clamps and tethers in order to simulate multiple configurations: double hanging, single hanging (catenary), lazy wave, steep wave and tethered wave. The external actions considered are marine growth and currents and the main cable properties are taken into account to calculate its weight, buoyancy, tensions, moments and drag forces. The information obtained after the simulation includes cable tensions, curvature, laid and suspended lengths and tether tension, when applicable. Next steps include the optimisation of the suspended cables and the full network in the farm.

1. Introduction
Floating offshore wind farms (FOWFs) are a reality, as many demonstrators and prototypes have been deployed and two full-scale farms are already in operation. Nevertheless, their current risks and costs prevent the technology from being profitable, with an expected LCOE for 2020 of 135€/MWh against 114€/MWh of the bottom-fixed offshore wind farms or 50€/MWh of the onshore farms [1]. One of the causes are the cable costs due to their demanding electrical and mechanical requirements, and the considerable lengths used. Moreover, suspended cables are a key point new to this technology. For these reasons, their global optimisation is crucial to bring forward the commercial development of the FOWFs.

Several optimisation models have been developed for flexible risers as well as for the cable layout of bottom-fixed offshore wind farms (BFOWFs), but no coupled optimisation has been developed to improve the complete cable system in a FOWF from a topologic point of view.

The main advantage of current models is that allow accurate dynamic analysis of dynamic cables (e.g., OrcaFlex). However, they lack optimising capabilities or these are limited (e.g., only 2D optimisation). Moreover, their simulations are too long to be incorporated into optimising algorithms, and in most of cases their integration is complex because they have been designed for other purposes. Finally, these models require inputs with a high level of detail and provide case-specific results, which is unnecessary during early stages of projects. All these issues are addressed in this new cable model.
1.1. Background
In order to understand the model, what it includes and further work, it is important knowing the cable types of FOWFs, their ancillary equipment and the standard cable configurations.

1.1.1. Electric cable classification. In a FOWF, electric cables or sections of them can be classified:
- According to their function:
  - Export: connect the offshore site to the shore connection point.
  - Inter-array: connect the elements of the offshore area (mainly turbines and substations).
- According to their structure:
  - Static: designed to withstand static stresses (including cable laying stresses).
  - Dynamic: designed to withstand static and dynamic stresses (including bending and fatigue).
- According to their position:
  - Touching the seabed (fixed): generally buried or protected under a berm.
  - Suspended: at least with one end in a floating element and subject to motions.
    - Single hanging (risers): connect a seabed fixed section to a floating element.
    - Double hanging: fully suspended cables connecting two floating elements.

Usually, the export cable is a static cable touching the seabed, except its offshore end which may be a dynamic riser. The inter-array cables can combine static and dynamic sections, and can be fully or partially suspended depending on the depth and turbine spacing.

![Figure 1. Cabling scheme of a FOWF.](image)

1.1.2. Ancillary equipment for suspended cables. Suspended cables require additional elements to work properly depending on their configuration. The different components that are usually installed are described below.
- Bend stiffeners gradually increase the bending rigidity of cables at their connection point to rigid structures or fixed sections to limit the stresses in that areas, as otherwise their curvature could be too high under certain conditions [2]. This component is recommended in the hang-off zone for any suspended cable configuration, but it is also used in some configurations at the touch down point (TDP). A bend stiffener failure can reduce the life of the cable by a factor of 20 times [3].
• Bell mouths have the same purpose as bend stiffeners. Instead of increasing the cable rigidity, bell mouths limit the cable curvature, therefore their performance may be lower under highly dynamic situations.
• Buoyant modules may be attached to a suspended cable to create a buoyant section. Their correct design and installation present the following advantages [4]: significant reduction of the effect of surface motions on the TDP or touch down region (TDR), avoidance of compression forces at the cable TDR and increased depth reachable with the same cable type.
• Buoyant arches tethered to the seabed may also be used. In this case, a cable section is laid over the arch, providing a slightly increased performance compared to the buoyant modules but with a higher complexity.
• Rigid structures are used to completely isolate the TDR from the surface motions. Although their performance is excellent, their costs and installation complexity limit their usage to special cases.
• TDR protection may be used in some configurations to reduce the damage caused by impacts and abrasion against the seabed. The protection is usually an additional external layer clamped to the TDR.
• Clamps tethered to the seabed may be attached to cables when these incorporate buoyant modules or arches. They improve the cable response against movements and loads.
• A TDP base is used in some configurations to attach the lower end of a riser to the seabed. When a base is used, a bend stiffener is required to allow a smooth transition from the suspended cable to the fixed section.

1.1.3. Standard suspended cable configurations. Power suspended cables for FOWTs are a relatively new technology, but many riser configurations have already been developed for the Oil & Gas industry. Usually, flexible dynamic risers correspond to umbilical ducts in offshore platforms, although there are cases of dynamic power cables [5]. The main configurations are listed in the Table 1 [6].

| Type                | Configuration            | Buoyant modules | Buoyant arch, tether & anchor | Bottom-fixed structure | TDP base & bend stiffener | Clamp, tether & anchor |
|---------------------|--------------------------|-----------------|------------------------------|------------------------|--------------------------|------------------------|
| Double hanging      | Free (catenary)           |                 |                              |                        |                          |                        |
|                     | With buoyancy            |                 |                              |                        |                          |                        |
|                     | Single free hanging       |                 | ✓                            |                        |                          |                        |
|                     | Lazy wave                |                 | ✓                            | ✓                      |                          | ✓                      |
|                     | Steep wave               |                 | ✓                            | ✓                      | ✓                        | ✓                      |
|                     | Chinese lantern           |                 | ✓                            | ✓                      |                          |                        |
|                     | Tethered wave            |                 | ✓                            | ✓                      | ✓                        | ✓                      |
|                     | Lazy S                   |                 | ✓                            | ✓                      | ✓                        | ✓                      |
|                     | Steep S                  |                 | ✓                            | ✓                      | ✓                        | ✓                      |
|                     | Tethered S               |                 | ✓                            | ✓                      | ✓                        | ✓                      |
|                     | Fixed S                  |                 | ✓                            | ✓                      | ✓                        | ✓                      |

Table 1. Ancillary components required for suspended cables depending on their configuration. In all configurations, a bend stiffener or bell mouth is recommended at the hang-off zone(s).

1.2. Objective
The aim is to develop a model of the suspended cables with several degrees of freedom and including the main ancillary equipment as well as the relevant loads, finding a balance between realistic behaviour and moderated computation times when it comes to optimising. The existing cable configurations are assessed, plus additional configurations that may be feasible and viable for FOWFs.
2. Methodology
The position of a suspended cable, even in static conditions, cannot usually be determined analytically. The shape adopted by a free hanging cable only affected by the gravity is the catenary, but the starting information to obtain its position usually does not include its parameters, which must be obtained numerically. If any additional force, property or component is considered, a model must be developed to estimate the static position of the cable.

Despite of considering steady dynamic forces, the proposed model is not dynamic because it would slow down the optimisation process far too much. However, a dynamic analysis should be performed once the optimisation is done to validate the results.

Due to its simplicity and practicality, a lumped mass model (based on finite elements) is proposed: a series of nodes and segments that connect the nodes (see Figure 2). All cable properties are transferred to the nodes except its length, which is driven by the length of the segments. For that reason, all the considered forces are only applied to the nodes and the static position of the cable is determined imposing equilibrium of forces at each node.

![Figure 2. Cable lumped mass model.](image)

2.1. Maximum angle between segments
The model introduces an error on the cable length that can affect the results because it does not follow straight lines (the model segments) between nodes. The maximum admitted error is fixed at 0.2%, which limits the angle between segments to 12.6 deg. As the cable curvature is far from the maximum for most of the nodes in a real cable, the overall difference between the real length and the model length is expected to be always below 0.1%.

2.2. Allowed cable configurations
The selection of the configuration depends on the cable properties, water depth, floater motions and clearance requirements, among others. The following cable configurations are allowed in the model:

- Double free hanging catenary.
- Double hanging with buoyancy.
- Single hanging catenary.
- Lazy wave.
- Steep wave.
- Tethered wave.

The Chinese lantern configuration may be useful for the oil & gas industry, but for an inter-array cable is not preferable as it increases the overall cable length and requires very precise calculations to ensure its durability. On the other hand, the S configurations are more complex than the wave configurations and are only used in specific scenarios, therefore they are not considered in the model.
2.3. Marine growth
Marine growth is a relevant issue in ageing submerged elements such as cables, as it increases their weight and drag. The organisms are classically classified in two categories with different drag coefficients and removal methods: hard fouling organisms (e.g., barnacles, molluscs and zebra mussels) and soft fouling organisms (including seaweed, algae, and biofilm slime) [7].

To determine the marine growth layer (MGL) density, it can be used the marine growth density and the volume occupied by water in the MGL, but no solid information was found. Alternatively, it may be calculated using the marine growth dry density, 1400 kg/m$^3$ [8], and water content. Following a conservative criterion, the water content has been selected from the typical range [9] as the one that maximises the MGL density. As a result, the model MGL density is obtained: 1115 kg/m$^3$.

The marine growth profile depends on the time since the cable was installed or last cleaned, water currents, nutrients distribution, water temperature and submerged surfaces tilt and material, among others. Consequently, the use of site-specific information is recommended, which is typically available in areas where deep substructures have been placed for years, such as the Gulf of Mexico, the North Sea or the Gulf of Guinea. These substructures are usually related to the oil & gas industry. A conservative generic profile is proposed for these regions in Figure 3, being stepped to reduce the computation time.

Marine growth surface roughness is between 5 and 50 mm [10]. For that reason, the proposed roughness corresponds to half of the MGL thickness, being its upper and lower bounds 50 mm and the lowest between 5 mm and the MGL thickness, respectively.

2.4. Currents
The effect of currents on the risers is a relevant factor when it comes to determine their final position and tensions. There are many categories of ocean currents such as wind generated, tidal, circulation, loop and eddy, soliton and longshore. Consequently, there is a great variability and site-specific data is recommended. However, when field measurements are not available, the current profile can be estimated as the sum of two generic profiles: tidal and wind currents [10]. An example can be seen in Figure 4.
2.5. Considered forces
The considered forces allow a balance between the computation time of the model and the quality of the results, assuming a 2D problem where all force vectors are coplanar. The discarded forces include torsion, shear forces and dynamic forces.

2.5.1. Seabed reaction. Seabed force is applied to nodes under the seabed. The seabed stiffness is adjusted to obtain realistic results: nodes located more than 10 cm below the seabed are not admitted.

2.5.2. Weight. The weight force applied to each node is calculated as the sum of the cable submerged weight, the marine growth submerged weight and the clamp submerged weight, where applicable. For the end nodes all the forces are halved as the considered cable length corresponds to half segment. The marine growth submerged weight per unit length depends on the marine growth layer density, the seawater density, the cable geometry and the marine growth layer thickness at each node.

2.5.3. Buoyancy. Buoyant forces are applied to nodes in buoyant sections.

2.5.4. Tensions. Cable tensions are calculated according to the elasticity of the segments depending on the axial stiffness, the segment strain and the unstressed segment length.

2.5.5. Moments. Moments depend on the cable curvature and the bending stiffness. In turn, the bending stiffness at each node depends on the cable bending stiffness and extra stiffness in sections with bend stiffeners. The properties of bend stiffeners are automatically calculated based on a simplified non-dimensional bend stiffener design [2]. The cable curvature at a certain node is estimated as the curvature of an arc passing through the node and its contiguous nodes.

In order to consider the bend stiffness, but only applying forces at the nodes to keep the model simple, the calculated moments cannot be applied directly. Instead, an equivalent force is applied to each node to simulate their straightening effect [11] as it can be seen in Figure 5.

2.5.6. Drag. The generic current profile described in chapter 2.4., adjusted to the specific seabed depth, is used to calculate the drag forces. Other factors involved are the seawater density, the drag coefficient, the cable diameter including the marine growth, the angle between the cable axis and the current direction and the tangential drag coefficient.
2.6. Algorithm

The algorithm determines the static position of the cable, its tension and curvature, as well as the single effect of the forces and properties considered. To that end, the position calculation is split in several steps, each one including additional forces compared to the previous step. As the analysis is nonlinear, it is required an initial guess for each step, therefore the solution of the previous step is used and an additional calculation is carried out to serve as first initial guess. Finally, the results are validated.

2.6.1. Step 1: initial calculation. In the first initial guess, the basic cable position is determined and the segmentation is done. It must be calculated rapidly, and set a good starting point for the next step in the algorithm. This is achieved in two ways:

- Adapting the initial guess to the selected cable configuration. If the initial guess is close to the solution, the algorithm speed will be higher and numerical solver errors are less likely to occur. The different initial guesses are shown in Figure 6.
- Working only with the basic forces: submerged weight, seabed interaction and buoyancy. This implies that the cable shape can be divided in concatenated catenary and straight sections, therefore the unknowns are just curve parameters and not node positions. In other words, the algorithm performance is improved regardless of the lumped mass segmentation.

The general procedure is identical for all initial guesses: first, the specific initial guess is selected according to the inputs, then the curve parameters are determined and finally the nodal positions and main algorithm variables are calculated for the second step.

![Figure 6. Initial guesses: (a) double hanging catenary; (b) single hanging catenary; (c) triple catenary, note that end B may be on the seabed; (d) lazy wave.](image-url)
2.6.2. *Steps 2 to 7: using the lumped mass model.* Once the initial calculation is finished, the nonlinear solvers can be used in the remaining steps. The different forces can be seen in Figure 7.

- **Step 2:** considering the cable weight, buoyant forces, seabed reaction and tensions. This step validates the initial calculation since the properties and forces considered are the same.
- **Step 3:** including the effect of the cable bend stiffness and bend stiffeners.
- **Step 4:** considering the tether (optional).
- **Step 5:** including marine growth.
- **Step 6:** including currents (optional).
- **Step 7:** considering the axial stiffness. The cable position is recalculated until its strain error is below 0.02%.

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**Figure 7.** Lumped mass force model.  
\( n, l, T, B, S, H, W \): node, segment length, tension, buoyant force, equivalent force due to moment, drag force, weight.  

2.7. *Results validation*

Some elements are checked once the cable position is determined to validate the results:

- **Quality of the model:**
  - No angle between segments is greater than 12.6 deg. according to chapter 2.1.
  - The seabed stiffness is enough to prevent the cable from being deeper than 10 cm below the seabed.
  - There is no vertical tension at the lower end if there is not a TDP base.
- **Cable position:**
  - The cable is completely under 20 m depth to avoid any problem with ships.
- **Cable resistance:**
  - The cable maximum tension is under yield tension.
  - The cable maximum curvature is under the curvature limit.

3. *Outcomes & case study*

The following findings are highlighted:

- A good initial guess saves time and prevents the algorithm from reaching wrong solutions – or not finding any solution. Variable scaling is equally important.
- Buoyant sections should be below the euphotic zone: shallow depths where the marine growth layer thickness is greater. This way, marine growth weight is reduced.
- Bend stiffness is usually negligible due to the low cable bending, but it is relevant under extreme bending because its straightening effect reduces the maximum curvature.
- Site-specific marine growth and current profiles are important to avoid additional uncertainty, as their effect is relevant
- Axial stiffness can be neglected almost always.
The following example illustrates the model behaviour and outputs for a cable of 380 m length in a tethered wave configuration (includes upper bend stiffener, buoyant section, clamp and tether).

In Figure 8 it can be seen that two initial guesses are calculated; the reason is that depending on the cable length, the initial guess may be a steep wave or a lazy wave and the first assumption failed. These initial calculations are fast because few parameters related to the catenaries must be determined.

![Figure 8. Numeric outputs of the model in the example.](image)

Figures 9 and 10 show the relevant components and final tensions. Furthermore, the model generates figures to visualise the final curvature and the position of the cable for each step.

The model has been validated accurately reproducing the mean results achieved in [12] for the intermediate lazy wave configuration, using the same input data. Additional validation will be performed in order to test other configurations that are allowed by the simplified model.

![Figure 9. Example main components.](image)

![Figure 10. Cable tensions in the example, being 200 kN the yield tension of the cable.](image)
4. Conclusions

The presented cable model has shown excellent convergence and speed, considering the properties and actions that have the highest influence on the cable position, tensions and curvature. Although the code may be expanded to allow additional configurations, the model is ready to be used as part of an optimising algorithm, which is a major advantage compared to other models. Simplicity is a key point of the model, as it is to be used in early design stages of FOWFs or to test innovative configurations. For that reason, the final outputs should be validated using a dynamic simulation, which is out of the scope of the model.

Further development includes, as a first step, the utilisation of the model to optimise single cable configurations. As a second step, the model will be used in a 3D cable layout optimisation of full floating offshore wind farms.

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