Design and development of an offshore wind foundation

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Abstract

Offshore wind energy is a renewable source with strong prospects of development, allowing both the reduction of greenhouse gas emissions and the promotion of technological progress. Currently, most of the offshore wind turbines use fixed-bottom foundations, in shallow, or transitional waters (depths up to 60 meters). Offshore structures' transportation and installation are usually assisted by rent expensive dedicated vessels. In this work, a foundation concept for transitional waters with self-floating capability and suction pile embedment is developed. The structure is transported in the floating position to the installation site aided by tugboats. These boats have a reduced daily cost and the logistics process is simplified. Under these circumstances, buoyancy and stability of the entire structure must be ensured. When the structure arrives at the installation site, it submerges and the suction piles guarantee the correct attachment to the seabed. The structural analysis is performed, during the turbine's operation phase, using FAST and ANSYS software. FAST computes aerodynamic and hydrodynamic loads acting on the structure and provides the input data for ANSYS. Then, the stresses transmitted to the foundation are evaluated. It was concluded that this foundation is capable of being implemented, since the minimum safety factor present on offshore standards is respected.

Keywords: Offshore wind, foundation, suction pile, product development, mechanical design

1. Introduction

Humanity has been using petroleum, coal and natural gas as its main sources of energy. Excessive emissions of greenhouse gases from these sources have led to some environmental changes such as global warming, ozone layer depletion and ocean acidification [1]. The Kyoto Protocol was signed in 1997 aiming a greenhouse gases emission reduction of at least 5% from 1990 levels in the commitment period 2008 to 2012 [2]. The European Union (EU) has been adopting legislation to promote the use of renewable energy sources, such as wind, solar and wave energy, for example. These are reliable and non-polluting sources of energy. The EU has defined a 20% global quota for renewable sources by 2020 [3]. However, the current renewable capacity is not sufficient to guarantee the accomplishment of that goal, which means that more capacity is needed.

Oceans and seas are an excellent source for the renewable energies expansion, covering around 70% of the surface of the Earth [4]. Offshore wind has been used for electricity production for, approximately, 25 years, when the first wind farm was installed along the Danish coast [4]. This has allowed the maritime economy to evolve, creating several jobs, which, directly or indirectly, will ascend to 366.000 by 2030 [5]. Nevertheless, offshore wind technologies are still at an early stage of development, facing considerable scientific challenges. The main disadvantage of exploiting this energy source is its high installation and operational costs [6].

Onshore wind is a strong asset, with 128,8 GW installed in Europe, by the end of 2014, more than the current nuclear capacity [5]. Furthermore, onshore technology for electricity production is already economically competitive, against natural gas and coal [5]. However, offshore wind potential is much higher, since the wind is stronger and consistent, with less turbulence at sea than on land [7]. The visual and sound effects can also be avoided because the oceanic area is very large [7]. By the end of 2016, the installed offshore wind capacity worldwide was around 14 GW [8]. The United Kingdom presents 36% of the total capacity. Germany contributes with 29%. They are the two leaders of offshore wind extraction [8]. China, for instance, is already the third head force, with a share of 11% [8].

The foundation is the structure that supports the wind turbine and the loads imposed by wind and sea. Currently, most of the offshore wind turbines use fixed-bottom foundations, in shallow, or transitional waters (depths up to 60 meters) – Figure 1. As the water depth increases, offshore foundations' cost rises. Nowadays the top technologic solution used is the monopile foundation, with a share of 80%, due to its low-cost and simplicity when compared to other technologies [9]. It is basically a cylindrical steel tube that penetrates the seabed. The gravity foundation developed in the 1990s represents another main solution for shallow waters, with a 9% share [9]. It is normally a hollow concrete based structure with the capacity to hold itself on the seafloor, depending only on its self-weight, when filled with water or sand. Nevertheless, these two solutions are only suitable for water depths up to 30 meters mainly due to economical and technical limitations. For higher depths other types of foundations should be used, such as the jackets or the floating solutions. Jacket foundation is used in 5% of the total number of turbines installed in Europe [9]. This structure has a lattice geometry where the tubular members are welded together. Normally, it is fixed to the seabed by four piles increasing the distribution of burden of own weight. Jacket's disadvantages are related to its high construction and installations costs [10]. Floating solutions are still in a recent stage of development, with several scale prototypes being tested. There are essentially three types of floating solutions: spar floaters, tensioned-leg platforms (TLP) and semi-submersible platforms (SSP). The spar floater structure is a long and thin cylinder that goes deep below the water surface. Since the center of buoyancy is above the center of mass this foundation exhibits a good dynamic response [10]. TLP are submerged in water by means of tensioned mooring lines. SSP rely on the displaced volume of water to support all of the structure weight [10]. This type of foundation uses, also, a catenary mooring line system to ensure that the structure remains in the same place.

Due to increased offshore wind interest, the development and demonstration of novel solutions for deeper waters have been undertaken by several international industrial consortiums, usually with EU financial and political support.

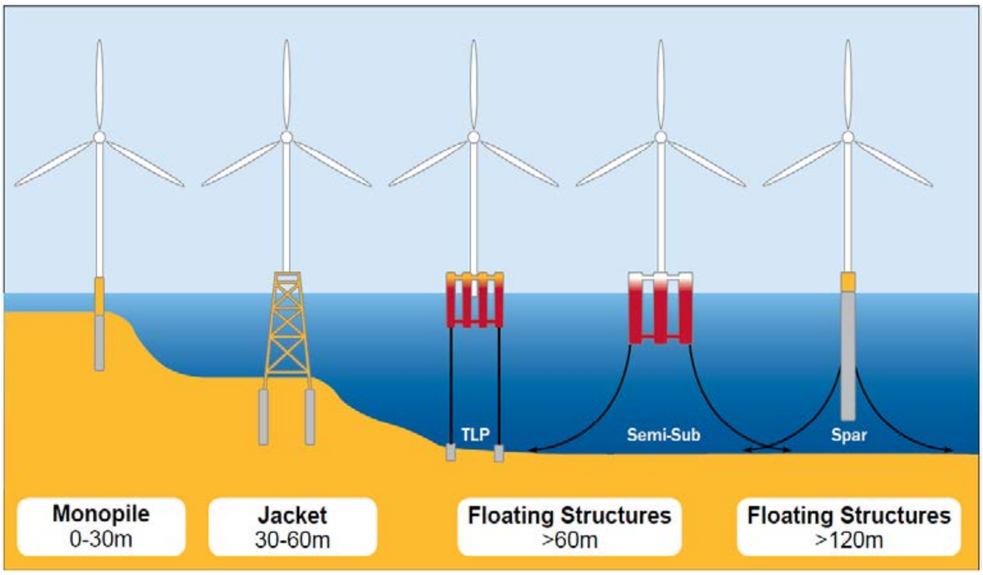

Figure 1 – Types of foundations for different water depths (adapted from [4])

Assembly of these structures may be performed at the existing shipyards and transportation and installation operations are usually assisted by dedicated vessels. They are rent-expensive and usually require anticipated reservations due to its high occupancy rates [6]. Each dedicated vessel may have a daily cost of 200.000 euros, thus it is desirable to optimize all logistic process to minimize the total time consumed [6]. Those limitations have led to the emergence of self-floating foundations using only tugboats for its transportation. They are highly available and inexpensive, with a daily cost of 900 to 5000 euros [6]. WindFloat (Figure 2) and Demogravi3 (Figure 3), for instance, are two self-floating foundations.

Figure 2 – WindFloat during transportation [11]

The WindFloat prototype was installed at the end of December 2011, 5 km off the Portuguese coast, near Póvoa de Varzim, and it is a semi-submersible foundation supporting a 2 MW turbine. This project was supported by the EU through the Demowfloat project, led by EDP (Energias de Portugal) and developed by Principle Power, in partnership with Repsol, WavEC and ASM Industries, among other companies [12]. This foundation was completely built on land, including turbine assembly, so that the structure could be transported, thus avoiding complex offshore installation operations. In July 2016, WindFloat structure was dismantled, after five years of tests [12].

Demogravi3 project began in 2016 and consists on a gravity foundation composed by three columns made of concrete connected through a metallic tripod [13]. These columns guarantee buoyancy and stability of the entire system during transportation. As soon as it arrives at the installation site, the concrete caissons are filled up with water and the structure is sunk onto the seafloor. The project, funded by the EU and leaded by EDP, is being developed by the Spanish company Typsa and includes among its partners WavEC, Universidad Politécnica de Madrid (UPM) and ASM Industries [13].

Figure 3 – Demogravi3 during transportation [13]

2. Methodology

Since it is intended to design a self-floating foundation, buoyancy and stability must be ensured, which increases the product development process complexity. FAST is used for the foundation's structural analysis. This program computes aerodynamic and hydrodynamic loads on the foundation and simulates its dynamic behaviour. Subsequently, FAST output data is introduced in ANSYS finite element software to analyse the stresses transmitted to the foundation.

2.1. Buoyancy

In the third century B.C., Archimedes discovered that a body immersed in a fluid experiences a vertical force equal to the weight of the fluid it displaces, called buoyancy, $\boldsymbol{I}$ [14]:

$$\boldsymbol{I} = \rho_{fluid} g V_{sub} \quad (1)$$

In the previous equation, ρ_{fluid} represents the fluid density, g is the gravitational acceleration and V_{sub} is the displaced volume. The point through which buoyancy force acts is called the center of buoyancy, labelled B, that is the geometric center centroid of the submerged volume of a floating body (Figure 4) [14].

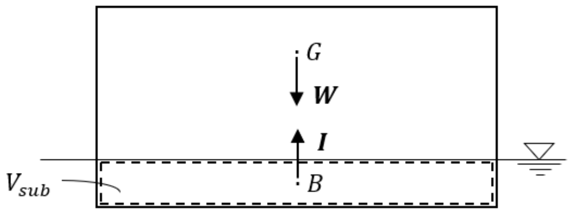

Figure 4 – Body partially submerged in a fluid

For static equilibrium, buoyancy force, $\boldsymbol{I}$, equals body weight, $\boldsymbol{W}$. These forces are collinear, so the body displaces its own weight in the fluid in which it floats [14]. Weight is computed by multiplying the body mass, m_{body} , by the gravitational acceleration, thus the displaced volume is given by:

$$V_{sub} = \frac{m_{body}}{\rho_{fluid}} \quad (2)$$

Therefore, the foundation must guarantee the correct buoyancy of the entire structure.

2.2. Stability

The only way to know if a position of a floating body is stable is to disturb it slightly and see whether it develops a moment which will return it to its original position (Figure 5) [14].

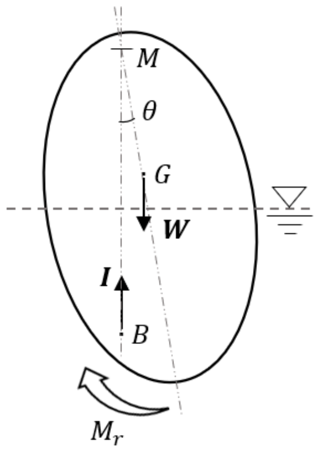

Figure 5 – Floating body is tilted at a small angle θ (adapted from [14])

In Figure 5 the floating body is tilted at a small angle θ. If an upward vertical line is drawn, from the center of buoyancy, B, it will intersect the body line of symmetry at point M, called the metacenter [14]. In the previous figure, M is above G and there is a restoring moment, M_r, which brings the body back to its original position. Consequently, the body is stable for small disturbances.

Metacentric height, $\overline{MG}$, is a property widely used in the naval industry as it provides an indication of the stability of the body. It is computed according to [14] by:

$$\overline{MG} = \frac{I_O}{V_{sub}} - \overline{GB} \quad (3)$$

I_O represents the area moment of inertia of the waterline footprint of the body about its tilt axis and $\overline{GB}$ is the distance between G and B.

For small disturbances, a negative metacentric height implies that the metacenter will be below the center of mass and, therefore, the body is unstable as an overturning moment appears. On the other hand, a positive metacentric height indicates that the metacenter will be above the center of mass and the body is stable. A zero-metacentric height means that the center of mass and the metacenter are coincident. Thus, the body remains in the new position until additional external forces are applied.

For freely floating bodies the restoring moment can be computed according to [15] by:

$$M_r = m_{body} g \overline{MG} \, sin(\theta) \quad (4)$$

Hence, for a given equilibrium position, the restoring moment equals the inclining moment transmitted by the environmental forces (mainly due to wind).

2.3. Numerical Analysis

In an offshore wind turbine, the loads are essentially of two types: aerodynamic, due to wind, and hydrodynamic, due to waves and currents.

The structural analysis is performed with ANSYS finite element method (FEM) software. The input data for ANSYS is provided by FAST program. This is a computer-aided engineering (CAE) tool developed by the National Renewable Energy Laboratory (NREL), that simulates the coupled dynamic response of wind turbines. FAST joins aerodynamic modules (aero), hydrodynamic modules, for offshore structures, (hydro), control and electrical system (servo) and dynamic structural modules (elasto) to enable coupled nonlinear aero-hydro-servo-elastic simulation in the time domain [16]. Fast input data is provided by text files associated with each of these modules. The main modules used in this work are the SubDyn, HydroDyn and InflowWind modules. SubDyn is a time-domain structural-dynamics module for multimember fixed-bottom structures that contains the foundation geometry and material information (Young's modulus and shear modulus) [16]. HydroDyn is a time-domain hydrodynamics module, that includes the foundation geometry and simulates the sea state information (significant wave height, peak period and current's velocity) in time [16]. InflowWind is a module for processing wind-inflow data in space and time (Figure 6) [16].

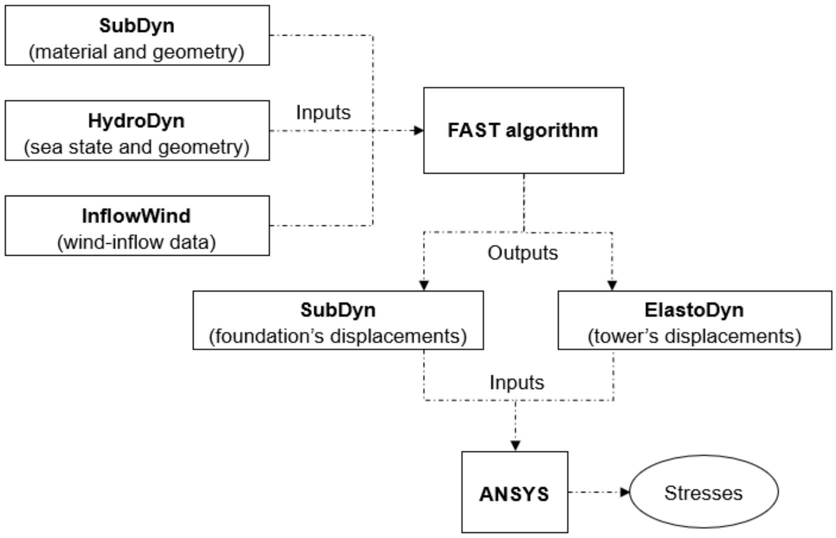

Figure 6 – Structural analysis process outline

Translational and rotational displacements at each point of the foundation and the tower – given by SubDyn and ElastoDyn modules, respectively – are used as input data for ANSYS (Figure 6). This is the simplest and the most direct methodology to define the structure loads in ANSYS. Data is provided by FAST in a matrix form, in each direction of space (X, Y and Z) as a function of time.

3. Results

3.1. Concept Development

The foundation was developed based on several needs (Table 1).

Table 1 – Needs description

Suitable for transitional waters
Support, at least, a 5 MW turbine
Easily scaled to support bigger turbines
Self-floating during transportation
Possess a modular construction
Designed in structural steel
Installed onshore
Low manufacturing cost
Simple and versatile design
Easily installed and dismantled
Movable in low deep-water ports
Low sensitivity to marine growth

Some countries such as Portugal, Spain and the United States of America, for example, possess a huge maritime exclusive zone with high sea depths, thus the monopile foundation cannot be implemented and other solutions must be used. Furthermore, monopile is the cheapest and most common solution, which makes competition hardly difficult for low-depth waters. For these reasons the foundation was designed to be suitable for transitional waters – a water depth of 45 meters was established.

Based on the available information the NREL 5 MW reference turbine was chosen for the project [17]. This power is also suitable for the current commercial needs. Over the past 10 years, the rated capacity of three-bladed turbines has increased considerably. Thus, the foundation should be flexible and adapted easily to support bigger turbines if needed.

As dedicated vessels for offshore installation are rent-expensive and require anticipated reservations due its high occupation rates, the foundation should be self-floating during transportation. Additionally, logistics process is simplified since the number of operations performed at sea is reduced.

The foundation should be designed in structural steel, to simplify its construction, since some countries, like Portugal, cannot manufacture big concrete offshore structures. In addition, the design must be simple, to minimize manufacturing costs. It is easier to produce a modular structure as well – several components can be produced parallelly rather than one at a time.

Foundation's final concept is presented in Figure 7.

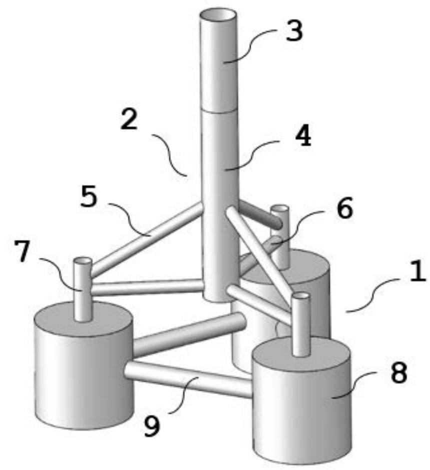

Figure 7 – Final concept

The foundation is composed by three modules, a floater-suction pile assembly (number 1, in Figure 7), a metallic support (number 2) and a transition piece (number 3). In the transition piece's upper interface will be fixed the wind turbine tower. The floater-suction pile assembly has two main functions. Firstly, it ensures the buoyancy and the stability of the entire structure, during transportation. Besides that, it anchors the structure to the seabed. The metallic support, on the other hand, provides the structural integrity.

All modules can be manufactured separately, in the same place, or at distinct locations. Afterwards they are connected through mechanical joints. Then, the wind turbine is towed together with the foundation and the structure is transported to the installation site aided by tugboats.

The metallic support consists of one main column (number 4), three legs (number 5) and three braces (number 6). There are also three secondary columns (number 7) that connect this component to the floater-suction pile assembly.

Moreover, the floater-suction pile assembly consists of three columns (number 8) and three cylindrical connections (number 9). These members attenuate column's vibration mode shapes and increase foundation's structural integrity. Columns' upper part (number 10 in Figure 8) is an enclosed reservoir called the floater while the suction pile (number 11) is an open cylinder at the bottom. Nevertheless, the number of columns can be increased (aiming a better stability, for example).

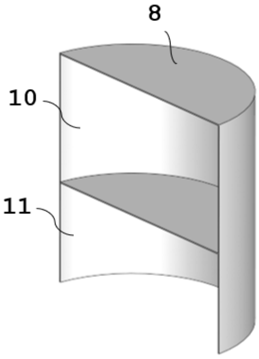

Figure 8 – Open column perspective view

During transportation, the floaters are filled with air. When the structure arrives at the installation site, the three floaters are fed with water, through a pump-valve system. So, the structure's overall mass increase, significantly, and it submerges due to gravity. Thereby, the structure alignment is accomplished by controlling air and water fluxes in the floaters.

When the foundation reaches the seabed, water is pumped from the inside of the suction pile. Afterwards, a pressure drop is created which promotes the penetration of the pile into the seafloor. Water is removed from inside the suction pile until it is fully installed in the seabed floor, thus guaranteeing a suction force which holds the foundation in its position (Figure 9). If the soil is inclined, penetration may not be equal in the different suction piles. For instance, if one suction pile is positioned in a higher plane it will penetrate deeply, compared to the others. For its installation the seabed preparation is unnecessary which is a huge advantage compared to other solutions. However, for rocky soils suction piles cannot be implemented.

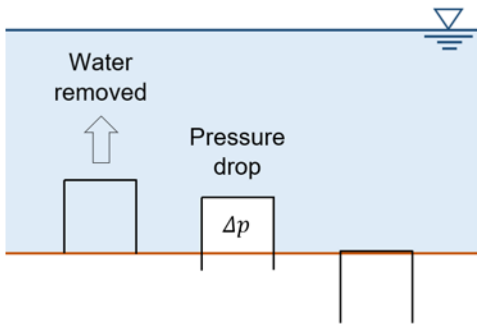

Figure 9 – Suction pile installation process.

In order to dismantle the structure, firstly water is pumped into the suction piles, so they can be detached from the seabed. Subsequently, water is removed from inside the floaters and the structure emerges.

The structure can be easily moved in low deep-water ports, improving its transportation. When the port is shallow, air can be inserted inside the suction piles through a pump-valve system, thus increasing the structure's buoyancy. Consequently, the logistics process becomes easier.

Dimensions are an essential part of the concept. To ensure that there is, at least, one self-floating and stable solution, some members' dimensions vary. Even so, most dimensions are fixed, limiting the number of solutions. Table 2 summarizes the diameter, D, the thickness, t, and the length, L, values for each member.

Table 2 – Principal dimensions of each member

Member	D [m]	t [mm]	L [m]
3	6	120	16
4	6	120	[24; 38]
5	2	40	20,79
6	2	40	18
7	3	60	10,18
9	3	80	22,97
10	[10; 24]	80	[4; 18]
11	[10; 24]	80	7

3.2. Concept Selection

The floater-suction pile assembly should ensure the buoyancy of the entire structure, during transportation. Thus, the total volume of this component should be at least equal to the displaced volume computed by equation 2. All solutions that do not meet this condition are not valid. Therefore, the green plane, in Figure 10, represents the floater-suction pile assembly total volume and the orange plane represents the displaced volume computed. Volume values vary with column's diameter and floater's height as indicated. The self-floating solutions begin once the two planes intercept. Stability is verified through the metacentric height introduced in chapter 2. Thereby, the distance $\overline{GB}$ and the area moment of inertia, I_O, are determined, for each self-floating solution. Stable concepts are represented with a blue point in both planes of Figure 10.

Only one valid solution should be chosen for modal and structural analyses, so, a weighting selection method is used. This is based on three properties: the structure's total mass, the column's height not submerged in water during transportation and the tilt angle due to a wind force. The structure's total mass was considered the most important property, since it is intended to minimize the manufacturing costs. The tilt angle is computed by equation 4, knowing the inclining moment, and should be less than 15° [15]. Additionally, the column's height not submerged in water may not be less than 2 meters and not be higher than 5 meters, for the structure to be protected from wave heights up to 4-10 meters. Considering these properties, the concept with a column's diameter of 16 meters and a floater's height of 9 meters was selected.

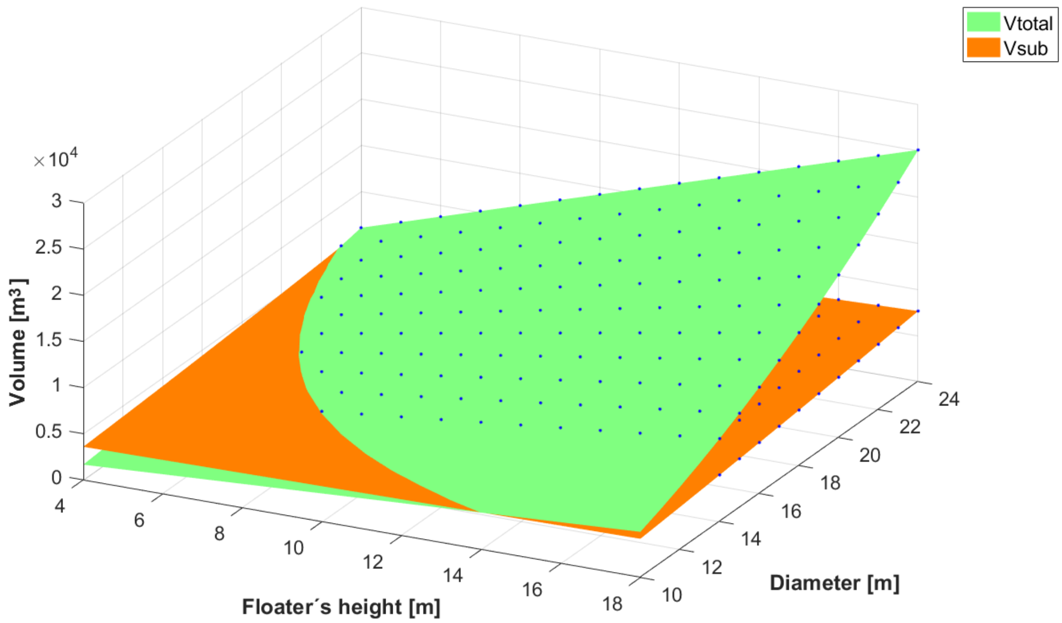

Figure 10 – Spatial representation of total and displaced volume values with the stable solutions in blue

3.3. Modal Analysis

For modal analysis, the model is composed by the foundation, a tower and a nacelle. The rotor and nacelle inertial properties are defined by a point mass coincident with this subassembly's center of mass coordinates. Therefore, the nacelle's representative block was modelled with a zero-density material. The natural frequencies are presented in Table 3.

Table 3 – Natural frequencies in Hz

Bending	side-side	1st	0,136
		2nd	0,739
		3rd	1,895
	fore-aft	1st	0,137
		2nd	0,760
		3rd	2,131
Torsion		1st	1,186

The principal excitation sources are due to [18]:

- The rotational frequency of the rotor (denoted by 1P): for the chosen turbine, this excitation frequency lies in the range [0,115; 0,202] Hz;
- Vibrations caused by blade shadowing effects (called 3P): for the three-bladed turbine selected the excitation range is [0,345; 0,606] Hz;
- Ocean wave loading: it was considered that the structure is installed off the Portuguese coast, near Póvoa de Varzim. Thus, the wave excitation frequency band is [0,05; 0,25] Hz;
- The vortex shedding induced vibrations caused by wind: it can be observed when the rotor is not operating and depends on the wind velocity and the tower and blades geometry. Hence, it is difficult to predict the exact excitation band.

To avoid resonance type of failure and increased fatigue damage the natural frequencies should lie outside the mentioned ranges. Nonetheless, it is seen, for instance, that the first natural frequency is included in the 1P and wave excitation band which is not desirable. However, the tower used in this work is longer than usual for offshore conditions – the distance from sea level to hub center is 106 meters, instead of 90 meters. Therefore, the system become more flexible and heavier which makes the natural frequencies to decrease.

3.4. Structural Analysis

All components were divided into several delimited sections so that the loads could be defined. It was extracted a number of 53 nodal foundation's displacements and of 9 nodal tower's displacements from FAST to ANSYS. In addition, steel has a 355 MPa yield stress. Design load cases (DLC) are defined by GL standard [19] still, sea and wind states depend on the chosen installation site location. Three design load cases are analysed – DLC 1.1, 1.10 and 6.1 (Table 4). The first two cases are intended to study the foundation's structural behaviour when the turbine is operating under normal service conditions, producing electricity. In DLC 6.1 the turbine is not working due to a severe storm (resurgence period of 50 years). Wind velocity, V_{hub}, the significant wave height, H_s, the peak period, T_p, and the current's velocity at the surface, U_{0ns}, for each DLC, are shown in Table 4.

Table 4 – Sea and wind states for each DLC

DLC	V_{hub} $[m/s]$	H_s $[m]$	T_p $[s]$	U_{0ns} $[m/s]$
1.1	9	2	11	0,097
	11,4	2,5	11	0,12
	24	5,6	11	0,26
1.10	11,4	10,2	18	0,12
6.1	50	15	20	0,54

The maximum von Mises stress values, as a function of time, for the five DLC are shown in Figure 11. It is concluded that for a wind speed of 11,4 m/s, in average, higher stresses values are obtained (Table 5) because the rotor thrust force reaches its maximum value. However, the stress standard deviation tends to increase, usually with increasing wind speed and wave power (Table 5). Once the structure is fixed to the seabed, wind influence over the stress values is predominant compared to hydrodynamic loads. The minimum safety factor is not inferior to 1,1, so the GL standard [19] is respected. The foundation has, therefore, a good structural integrity. Intersections between braces and legs with the secondary columns appear as the critical regions, mainly due to bending caused by wind (Figure 12). The existent geometric discontinuities (fillets) promote an increase of the stress values (stress concentration regions) although, this is a localized effect. Some preventive measures may be taken to minimize this effect, such as the use of external reinforcements in that regions, or internal reinforcements in the metallic support's legs, braces and secondary columns. Nevertheless, reinforcements tend to increase overall mass and to introduce more stress concentration regions, so the process must be iterative. In the metallic support, legs and braces are subjected to higher stresses, which may justify a diameter and thickness increase. Still, this measure promotes a structure's mass increase, which is a disadvantage.

Table 5 summarizes the main results for each DLC, such as the average maximum von Mises stress, $\bar{\sigma}$, the standard deviation of the maximum stresses, s_σ, and the minimum safety factor, CS_{min}.

Table 5 – Main results for each DLC

DLC	$V_{hub}\ [m/s]$	$\bar{\sigma}\ [MPa]$	$s_\sigma\ [MPa]$	CS_{min}
1.1	9	162	11,32	1,78
	11,4	180	11,33	1,70
	24	164	17,04	1,67
1.10	11,4	184	15,99	1,63
6.1	50	173	22,78	1,39

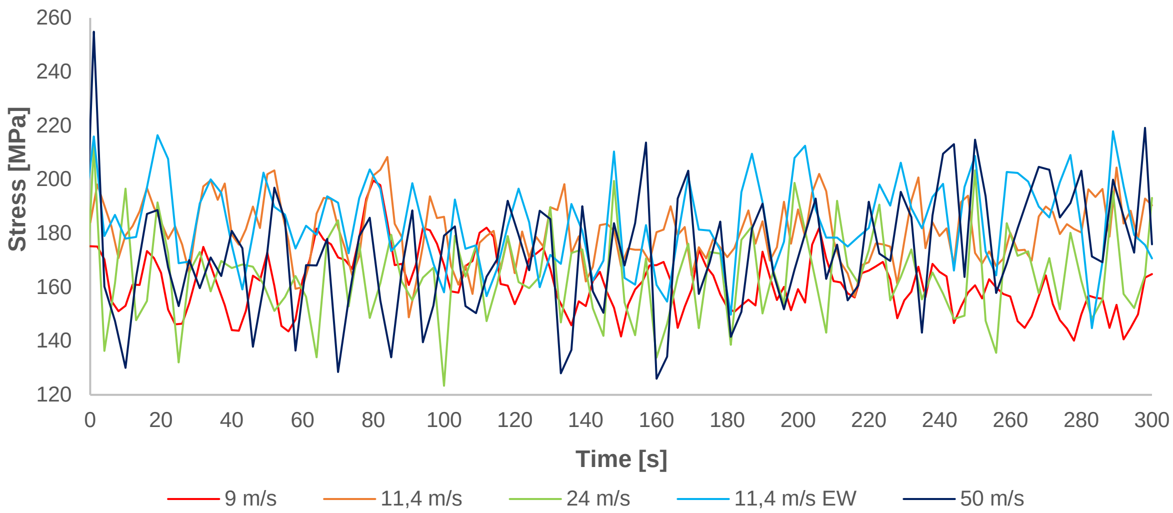

Figure 11 – Maximum von Mises stress values, in time, for all DLC

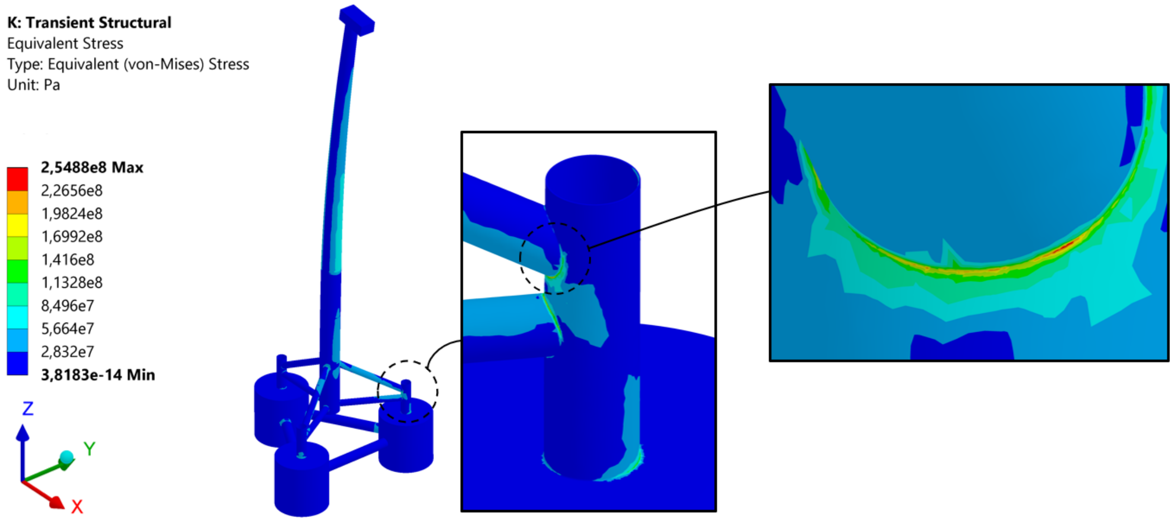

Figure 12 – Stress distribution for $V_{hub} = 50\ m/s$ and $t = 1$

4. Conclusions

Self-floating foundations have emerged to facilitate transportation's logistics process and, consequently, to reduce installation's total costs. Nevertheless, the concept development phase is more complex since the buoyancy and the stability must be ensured.

The foundation was developed based on several needs and is composed by one metallic support, one floater-suction pile assembly and one transition piece. All structure is transported aided by tugboats and then, is attached to the seabed through suction. This anchoring method is very versatile. For instance, bigger turbines will require foundations with the capacity to sustain bigger loads. This would require heavier structures, scaled-up for the bigger turbines. Instead, a bigger suction pile may be used to counteract these loads acting on the foundation. The metallic support provides the structural integrity of the foundation and the transition piece ensures waves do not reach the tower.

The first natural frequency is within the 1P as well as the wave excitation band, which may lead to unwanted structural resonance. From the structural analysis it was concluded that the foundation is possible to be implemented. The maximum stresses are never higher than the yield stress of the material and the standard is respected, since the minimum safety factor is never inferior to 1,1. Intersections between braces and legs with the secondary columns appear as the critical regions, mainly due to bending caused by wind. Although, the design analysis should be continued for other load cases, such as start-up procedures, failure occurrence and transportation process.

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