Analysis of the Transportation Phase of an Innovative Foundation for Offshore Wind Turbine

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July 2019

ABSTRACT

As the global demand for energy continues to rise, renewable sources are increasingly becoming more accessible, at the expense of fossil fuels, and the oceans show an excellent possibility for the expansion and development of wind energy. In this work, we study the structural integrity and the stability during the transport of an innovative foundation for offshore wind turbines, with self-floating capability. The structure is transported to the installation site in its floating position assisted by towing vessels, where it is submerged and fixed in the marine soil through suction piles for its operational phase. Therefore, this paper focused on the development of adequate numerical models that allowed us to analyze the magnitude of the loads acting on the structure during the transport and its effects. For this purpose, the FAST and AQWA software are used to determine the aerodynamic and hydrodynamic loads. These provide the necessary input data for ANSYS to evaluate, through finite element models, the stresses transmitted to the structure, as well as its vibration modes and its stability. The entirety of the studies was carried out in compliance with the appropriate standards and specifications established by the regulating entities.

Keywords: Offshore wind energy, suction caissons, floating, transport, structural analysis, finite element model.

1. Introduction

Projections for global electricity production in the upcoming years foresee substantial growth of renewable sources with a corresponding decrease in non-renewable sources [1]. The most significant increases are observed for solar and wind, both onshore and offshore. Technological advances in the area of renewable energy production and falling costs in this sector are indicative of an industry that is maturing and is increasingly able to develop competitive projects without the need for subsidies. The levelized cost of electricity produced by offshore wind turbines has recently become lower than that of nuclear power for the first time [1], with better infrastructure and high voltage cables, and a price cut of almost half in the last two years. Larger turbines, a growing supply chain and the challenges faced by the fossil fuel industry are among several factors that have contributed to lowered costs and increased use of offshore wind energy. This shows great potential for the future development of offshore turbines, which have a number of advantages over onshore turbines. Wind is typically stronger and less turbulent on the oceans than on land [2], resulting in greater power and energy efficiency. There are also limitations to the installation of onshore turbines, with limited space for new farms and transportation logistics, and turbine noise as well as visual impact limit the construction of wind farms in residential areas.

The installation of offshore wind farms is a complex task, where one of the biggest problems lies in raising turbines and platforms above the sea level and anchoring them to the sea floor. There are different types of foundations, according to the depth at which the wind turbine will be installed. A distinction can be made between three depths of sea which require different types of foundations [3]: shallow waters, usually between 0 and 30 meters deep; transition waters between 30 and 60 meters; and deep waters, over 60 meters. For shallow waters, the structures used are quite simple, usually composed of a single steel pile that is inserted directly into the seabed. For transitional waters, more complex structures are used to increase safety levels when anchoring towers such as tripods or jackets. At the top of these foundations lies a transition piece that is connected to the turbine tower, while the legs are anchored to the sea bed with stakes or suction anchors that can be buried up to 30 meters inside the ground. For deep waters, foundations fixed to the marine soil are no longer economically viable [4], so the type of structure that is still being developed is floating platforms.

The structure to be analyzed in this work is an innovative foundation developed by Gabriel Maciel in *Development and Mechanical Design of a Foundation for an Offshore Wind Turbine* [5]. The foundation was designed taking into account the industrial needs and operating conditions in Portugal. The NREL's (National Renewable Energy Laboratory) 5 MW reference wind turbine [6] was chosen for this research, which is an upwind, horizontal-axis turbine composed of three blades. The foundation was designed to be installed in transitional waters for depths between 30 and 60 meters, and in the context of this work it was established to use a depth of 45 meters. Due to the high costs and limited availability of specialized vessels for offshore construction and installation in Portugal, the structure was also designed to have the ability to float during transportation to its site of operation [5]. For the same reasons, the foundation is fully assembled on shore, as are the tower, the nacelle, and the three blades. It is the phase of the transportation that will be studied and discussed in this document. The transportation is done using a conventional tug boat, as in the case of WindFloat (see Figure 1), that can usually reach speeds ranging from 3 to 5 knots [7]. Some boats can reach higher speeds than these, but these are specialized vessels with much higher costs and dimensions. It was then decided to use a speed of 2 m/s (7.2 km/h) for the analyses developed in this work, which is equivalent to just under 4 knots, thus using an appropriate value considering the existing capacities.

Figure 1 – Towing of the WindFloat Platform [8]

2. Model Definition

2.1. Foundation Description

The foundation developed consists of three distinct modules: a floater-suction pile assembly (number 1, in Figure 2), a metallic support (number 2) and a transition piece (number 3), all made of structural steel. The floater-suction pile assembly, as the name implies, primarily serves to enable buoyancy and stability of the structure throughout its transport, and secondly to ensure that the structure is fixed to the marine floor in the installation phase, with the three suction piles. The metallic support ensures the structural integrity of the foundation, and the transition piece allows the connection between the metallic support and the turbine tower.

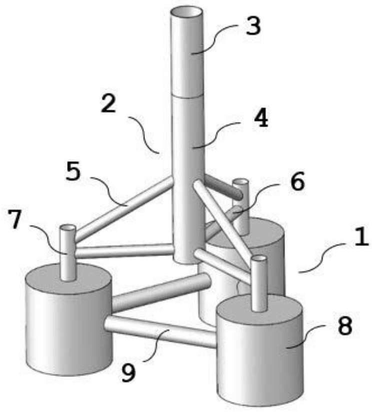

Figure 2 – Description of the offshore foundation [5]

The metallic support is formed by one main column (number 4), three legs (number 5), three braces (number 6), and also three secondary columns (number 7) that attach this component to the floater-suction pile assembly.

The floater-suction pile assembly is formed by three columns (number 8) and three cylindrical connections (number 9). These members attenuate the column's natural frequencies and ensure the foundation's structural integrity. The columns' lower part is the suction pile (number 11 in Figure 3) and is an open cylinder at the bottom, while the upper part is an enclosed reservoir called the floater (number 10).

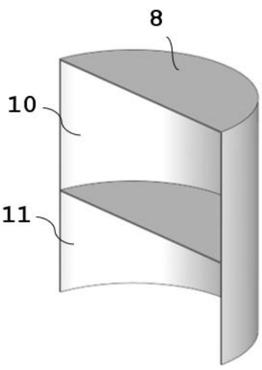

Figure 3 - Open column perspective view [5]

The structure is transported to the site of installation with the reservoirs of the columns filled with air. When the destination is reached, the three floaters are fed with water, through a pump-valve system, which causes the total mass of the structure to increase substantially. Due to the action of gravity, the structure submerges, and once reaching the seabed, the water from the suction piles is extracted. This generates a pressure drop in the piles, which, combined with gravity, allows them to penetrate the ground. For the dismantling of the structure, the reversed process can easily be applied.

The Table 1 summarizes the diameter, D, the thickness, t, and the length, L, for each member of the foundation. The material used for the three modules is a structural steel with the following properties: Young's Modulus of 210 GPa; density of 8500 kg/m^3; yield strength of 355 MPa.

Table 1 - Principal dimensions of each member

Member	D [m]	t [mm]	L [m]
3	6	120	10
4	6	120-140	33
5	2	60	20,79
6	2	60	18
7	3	80	10,18
9	3	80	23
10	8,5	80-150	9
11	8,5	80	7

2.2. Design Load Cases

Throughout the design process of a wind turbine, several loads to which it will be subjected during its life cycle must be analyzed. The main purpose in this regard is to verify that the turbine will be able to withstand such loads with a sufficient safety margin. This task is systematized by analyzing the wind turbine for a number of relevant load cases, which are the design load cases (DLC). The DLCs are established by combining relevant design situations for the wind turbine with various external conditions. These consist mainly of various operating conditions, which generally represent different wind and sea states. The various situations of the project can be divided into operational or temporary situations, and this document will focus on a temporary situation, which is the transportation. There are a number of regulating entities that are responsible for determining standards and recommended rules for offshore wind turbine projects, and here will be used the standards defined by Germanisher Lloyd (GL) [9]. For the transportation phase, there are two different DLCs defined in the GL norms, one of which has not been studied here because it is only relevant for long distance transport cases or when the turbine is transported separately. The three cases studied refer to DLC 8.1 [9], and are defined in Table 2. For this DLC, the standard stipulates that the manufacturer has to specify the different states of the wind, marine conditions and the relevant situations during transportation. It is also important to state the maximum average wind speed, and corresponding wave height, up to which the turbine can be assembled and transported. If the wind and sea conditions exceed the established limit, the transportation cannot take place and it must be delayed until the specified requirements have been met. It is further specified in the standards that the simulation time must be at least 10 minutes. The external conditions have to be chosen according to a specific installation site. For this approach, the chosen site is on the north coast of Portugal, near Póvoa de Varzim, and its transportation takes place on the outskirts of that area. It is also specified in the norms for the DLC 8.1 that no currents are to be considered and that the considered safety factor should be of 1,35. In Table 2, V_{hub} is the average wind speed at the hub height, H_s is the significant wave height, T_p is the peak period of the wave and v_{st} is the transportation speed. The determination of the external conditions for the specific location was done using a combination of different methods, including the use of long-term databases, on-site measurements and numerical models [10][11].

Table 2 - External conditions for the DLC 8.1 cases analyzed

Case	V_{hub} [m/s]	H_s [m]	T_p [s]	v_{st} [m/s]
1	8	2	10	2
2	11,4	2,5	10	2
3	18	4	12	2

With all the external conditions established, the resulting hydrodynamic and aerodynamic loads acting on the offshore wind platform have to be determined. For that purpose, we used the FAST (Fatigue, Aerodynamics, Structures and Turbulence) software, which is NREL's main tool of CAE (Computer-Aided Engineering) to simulate the dynamic response of wind turbines. FAST assembles aerodynamic and hydrodynamic models for offshore structures, dynamic electric control system (servo), and dynamic structural (elastic) models to allow a partially non-linear aero-hydro-servo-elastic simulation in the time domain [12]. The FAST tool enables the analysis of a wide range of wind turbine configurations, including two- or three-blade horizontal axis rotors, pitch and yaw angles variation, up-wind or down-wind rotor, jacket or tubular tower. The wind turbine can be modeled on land or at sea on fixed or floating foundations. FAST is based on advanced engineering models, derived from fundamental laws, but with appropriate simplifications and assumptions, and supplemented, when relevant, with computational solutions and experimental data. The program consists of a series of submodules, each managing a specific part of the simulation, such as the mooring system, the wind flux or the sea state [12].

2.3. Aerodynamic Loads

Aerodynamic loads depend (among other factors) on the rotational speed of the rotor (null during transportation), the average wind speed in the rotor plane, the intensity of the turbulence, wind direction, air density and aerodynamics of wind turbine components and their aero elastic effects. These parameters are all considered in the FAST submodules for the calculation of the resulting aerodynamic forces. The wind flow in the vicinity of the wind turbine rotor is quite complex, and it is therefore common to use simplified methods to calculate the loads on the rotor, to be used for the design. FAST uses the Blade Element Momentum (BEM) [13] theory that assumes the turbine blades as being subdivided into smaller elements acting independently of the surrounding elements and operating aerodynamically as two-dimensional airfoils whose aerodynamic forces can be calculated based on the local flow conditions. These elemental forces are summed along the span of the blade to determine the total forces and moments applied to the turbine. The other half of the BEM theory assumes that the loss of pressure, or momentum, in the rotor plane is caused by the work done by the airflow passing through the rotor plane on the blade elements. Using the momentum theory, we can calculate the induced velocities from the momentum lost in the flow in the axial and tangential directions. And from these induced velocities, FAST is able to calculate the resulting aerodynamic loads, like the lift and drag forces on the blades, and on the rest of the structure. FAST also uses some corrective measures to include some important unsteady flow effects, like the stall phenomenon and vortex shedding [13].

2.4. Hydrodynamic Loads

Hydrodynamic loads depend on the kinematics of the water flow, water density, water depth, the shape of the foundation and its hydro elastic effects. In linear hydrodynamics, the hydrodynamic problem can be divided into three separate and simpler problems, each solved by FAST: one for radiation, one for diffraction and one for hydrostatic [14]. The radiation problem seeks to find the loads on a floating platform when the body is forced to oscillate in its various modes of motion and no incident surface waves are present. The resulting radiation loads are brought about as the body radiates waves away from itself (i.e., it generates outgoing waves) and include contributions from added mass and from wave-radiation damping. The diffraction problem seeks to find the loads on a floating platform when the body is fixed at its mean position (no motion) and incident surface waves are present and scattered by the body. The diffraction loads are the result of the undisturbed pressure field (Froude-Kriloff) and wave scattering. The hydrostatics problem is elementary, but is nevertheless crucial in the overall behavior of a floating platform, and consists of calculating the pressure exerted by the water on the platform [14]. Hydrostatic loads, external or internal, can occur if a compartment is in contact with water. Hydrostatic forces act in a normal direction to the surface, and for large structures with empty spaces they can have considerable effects. The hydrostatic loads are independent of the incident and outgoing waves from the diffraction and radiation problems, respectively.

FAST uses the Morison equation to predict the hydrodynamic loads distributed along each member of the structure. In this equation, the horizontal force on a vertical element *dz* of the structure at level z is expressed as [15]:

$$dF = dF_I + dF_D = C_I \rho \pi \frac{D^2}{4} \ddot{x} dz + C_D \rho \frac{D}{2} |\dot{x}| \dot{x} dz \quad (1)$$

$$F = F_I + F_D = \int_{-d}^{\xi(t)} C_I \rho \pi \frac{D^2}{4} \ddot{x} dz + \int_{-d}^{\xi(t)} C_D \rho \frac{D}{2} |\dot{x}| \dot{x} dz \quad (2)$$

Where the first term is the inertial force and the second is the viscous drag force. C_I and C_D are the inertia and viscous drag coefficients, respectively, D is the member diameter, ρ is the water density, $\dot{x}$ e $\ddot{x}$ are the water horizontal speed and acceleration. The level z is measured from still water level, and the z axis points upwards. FAST joins that equation with the hydrodynamic strip theory, where the structure is divided into several elements, or strips, where two-dimensional properties (added mass and viscous drag coefficients in the case of Morison's hydrodynamics) are used to determine the general three-dimensional loading in the structure. Using the strip theory, other forces such as the impulse, $\vec{F}_B$, the marine growth, $\vec{F}_{MG}$, the forces due to the ballast, $\vec{F}_{F\_B}$, the added mass of the structure, $\vec{F}_{AM\_M}$, the mass added due to the marine growth, $\vec{F}_{AM\_MG}$, and the added mass due to the ballast, $\vec{F}_{AM\_F}$, are also counted [16]. Thus, the hydrodynamic loads distributed along the length of a member are calculated as:

$$\vec{F} = \underbrace{\overrightarrow{F_I} + \overrightarrow{F_D}}_{Morison\ equ.} + \vec{F}_B + \vec{F}_{MG} + \vec{F}_{F\_B} + \vec{F}_{AM\_M} + \vec{F}_{AM\_MG} + \vec{F}_{AM\_F} \quad (3)$$

3. Implementation

3.1. Numerical Models

In addition to FAST, another software was also used to simulate the sea state and determine the hydrodynamic loads on the structure, called AQWA. This was accomplished in order to compare results between software and because AQWA offers a numeric tool that enables us to study the stability of the floating platform during its transport. For both of these software, a number of inputs has to be specified containing all the necessary data to describe both external and internal conditions such as the foundation and turbine geometry, sea and wind conditions, and the models to be used (sea state profile, BEM theory, Morison equation and strip theory). Active controls are also implemented to determine key aspects of turbine operation during the simulations, as required. It was decided to carry out the transport with the turbine rotor in a locked state, with the brake engaged, and the blade pitch rotated to 90 degrees, to minimize the impact of the wind forces. The global coordinate system of FAST and AQWA originates from the intersection of the axis of the turbine tower with the still water line, where the wind flows on the positive direction of the X axis, and where the Z axis is vertical and positive in the upward direction (see axis in Figure 5). The visual representation of the sea profile modeled by AQWA can be seen in Figure 4.

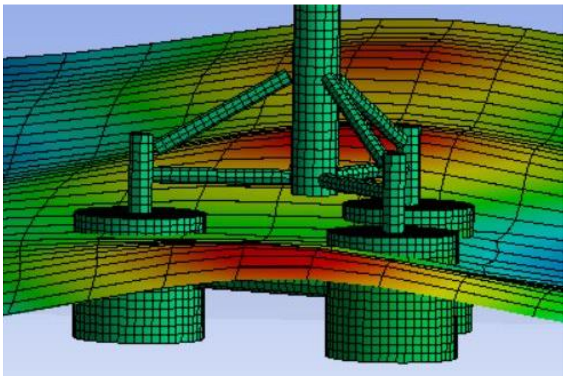

Figure 4 - Modeling of the sea profile by AQWA

Once all the simulation parameters are defined, the programs calculate the hydrodynamic pressures, perpendicular to the submerged members, for different sea states, with different wave amplitudes, frequencies and directions. As defined in section 2.2, the desired wave peak periods and significant heights are selected, choosing to use the wave direction with the most adverse effects on the structure. Therefore, the chosen direction was for incident waves at an angle of 0 degrees, that is, coming from the front of the foundation, and parallel to the X axis. For the calculation of these pressures, AQWA takes into account the incident waves, the diffraction and radiation of the waves, and the hydrostatic pressure. The output data of FAST and AQWA, that is, the pressures acting on the foundation due to the hydrodynamic and aerodynamic loads, are then retrieved. They then must be applied to the corresponding surfaces on a finite element model of the structure. The Figure 5 shows an example of the mapping of the pressures computed in the AQWA software.

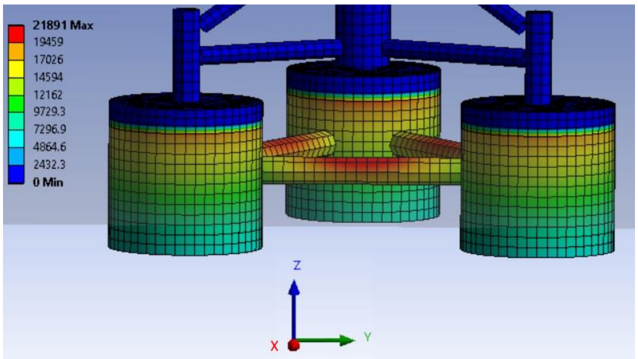

Figure 5 - Mapping of the pressures generated by AQWA (in Pa)

The finite element model was created in the ANSYS software, where the rotor and nacelle assembly was simplified and modeled as a simple zero density block with a point mass applied at the location of its center of mass and with its inertial properties. The mesh, made of solid elements, was generated considering a coarse mesh for the global model and a refined mesh in the stress concentration regions, usually near the welded joints. As the structure is floating, and is not fixed to the marine soil during transportation, it was necessary to define constraints to simulate the mooring lines that attach it to the tug boat. This was done using linear springs in ANSYS, which act somewhat like the cables used for the mooring [17]. The properties of the springs defined in the ANSYS were identical to those modeled in the FAST software, with an axial stiffness of 7.536E8 Newton per meter.

3.2. Methodology used

The methodology used throughout this project is an iterative process, where the several analyses have to be repeated in an attempt to obtain a geometry capable of withstanding the external loads. Using the wind and sea state data established, the FAST and AQWA software determine the aerodynamic and hydrodynamic loads, which are then applied to the structure geometry inserted in the ANSYS software. As long as the geometry is not verified, that is, while presenting stresses above the maximum allowable stress, it must be refined and strengthened. The maximum allowable stress (σ_{max}) is determined from the safety factor (n) and the yield strength (σ_y) of the steel as follow: $\sigma_{max} = \frac{\sigma_y}{n} = 262{,}96$ MPa. The methodology used is represented in Figure 4.

Two types of structural analyses are performed in ANSYS, static and transient. A static analysis only applies the loads for an instant in time, so they do not present valid results, since the standard defines that 10-minute analyses have to be performed. However, because transient analyses are computationally heavy, static analyses are used to obtain approximations of the stress states for a given geometry. If the static analysis is not validated, the foundation geometry is improved, and once it is validated, a transient analysis is performed on the entire time domain (10 minutes). The transient analysis is expected to display higher stress values, due to the consideration of the inertial and damping effects [18]. And then, the iterative process restarts for the transient analysis, until finally a foundation geometry is verified for all wind and sea states considered. Static analyses are useful to simplify and speed up the iterative process because, in general, when stresses are not validated in these analyses, they will not be validated in transient ones either.

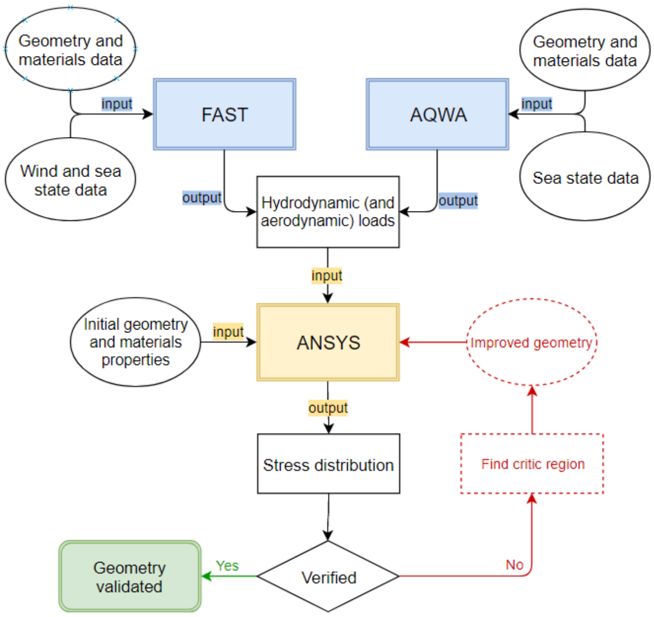

Figure 6 - Flowchart of the iterative process

4. Results

To verify the geometry of the foundation, a number of different analyses has to be performed in order to identify all the expected responses of the structure to external loads. This includes, determining the natural frequencies of the structure, study its stability and structural integrity.

4.1. Modal Analysis

A modal analysis allows determination of the vibration characteristics of a structure, that is, the determination of its natural frequencies and modes of vibration [18]. These two characteristics are important in the design of a structure subjected to dynamic loads. All physical structures have natural frequencies, which are frequencies at which the structure tends to vibrate in resonance when subjected to certain external forces, and which depend on its stiffness, the mass of the structure and the way this mass is distributed [19]. Resonance is the phenomenon that occurs when the frequency at which a force is applied to a system is equal to, or very similar to, one of the natural frequencies of the system. This causes the system to oscillate at higher amplitudes than when the force is applied at other frequencies. These large oscillations can result in important deformations and structural damage, mainly due to fatigue [20]. It is therefore crucial to avoid that the main sources of excitation transmitted to the structure include frequencies of vibration close to their natural frequencies.

For offshore wind supporting structures there are four principal sources of excitation vibrations [20]:

- The lateral loads in the hub from the rotating blades produced by the turbulence in the wind. These excitation frequencies depend on wind speed, and the blades configuration and size;
- The loads caused by the waves crashing against the foundation caused by incident waves, that depend on the wave height and period;
- The load caused by the vibrations in the hub due to the mass and aerodynamic imbalances of the rotor. This load has a frequency equal to the rotational frequency of the rotor, and is referred to as 1P in the literature. Since the turbine rotor can rotate at a variable speed, 1P is not a single frequency, but a frequency band;
- Load in the tower due to vibrations caused by blade shadowing effect. The blades of the wind turbine passing in front of the tower cause a shadowing effect and produce a loss of wind load on the tower. This load has a frequency equal to three times the rotational frequency of the turbine in the case of a three-blade turbine and is designated as 3P. Similarly to 1P, the velocity of the turbine is variable, and 3P is also a frequency band.

It was defined in the implementation that the rotor is locked, to minimize the wind loads, which means that 1P, 3P and turbulence vibrations are not induced in the structure. Remaining only the frequency band caused by the incident waves, which can be calculated from the peak periods of the waves. Thus, for the specified location, the values of the most frequent peak periods of the waves are between 4 and 18 seconds [11], which corresponds to frequencies ranging from 0.0555 Hz to 0.25 Hz. The first natural frequencies of the structure were calculated in ANSYS, and are shown in Table 3.

Table 3 - First natural frequencies of the structure

Mode description	Frequency [Hz]
1st Tower Side-Side	0,475
1st Tower Fore-Aft	0,478
1st Tower Torsion	1,248
2nd Tower Side-Side	0,988
2nd Tower Fore-Aft	1,023
3rd Tower Side-Side	2,087
3rd Tower Fore-Aft	2,202

And from Table 3, we observe that none of the natural frequencies of the structure lie within the frequency band of the incident wave loads, which means that the structure is not at risk of resonating during transport.

4.2. Response Amplitude Operator

The response amplitude operators (RAO), are a set of parameters used to determine the likely behavior of a floating structure in the sea [63]. The RAOs can then determine the motion of the floating structure as a complex combination of its six degrees of freedom, which are the three displacements (X, Y, Z) and three rotations (RX, RY, RZ) along each axis, and are obtained in units of amplitude (meters for displacements and degrees for rotation) by wave height (in meters), as a function of the peak period of the wave. The response amplitude is proportional to the wave amplitude and depends on its direction and peak period [49]. The graphs of Figure 7 represent the displacement responses and Figure 8 the rotational responses for the six degrees of freedom, considering incident waves at 0º in the foundation, which is the direction with the most adverse effects on the structure. We can observe from this figures that the most prominent parameters are the displacements in X and Z, and the rotation along the Y axis. Each of them has peaks, where the effect of the waves is more important and more prejudicial to the transportation. The values of the RAOs read in the graphs are calculated for a wave height of 1 meter, and knowing that they are proportional to the wave amplitude, the values for the three cases studied here (section 2.2) are presented in Table 4 .

Table 4 - RAO values for the three cases studied

Case	X[m]	Y[m]	Z[m]	RX[º]	RY[º]	RZ[º]
1	0,04	3,72E-5	0,26	2,61E-5	0,21	7,46E-5
2	0,05	4,66E-5	0,32	3,26E-5	0,26	9,33E-5
3	0,17	4,73E-5	0,74	3,27E-4	0,08	2,95E-5

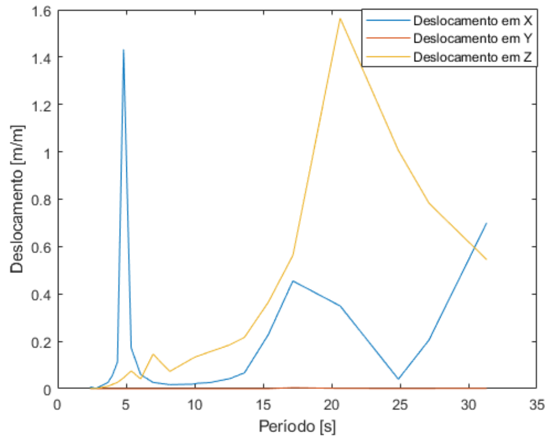

Figure 7 - RAOs for the displacements of the structure

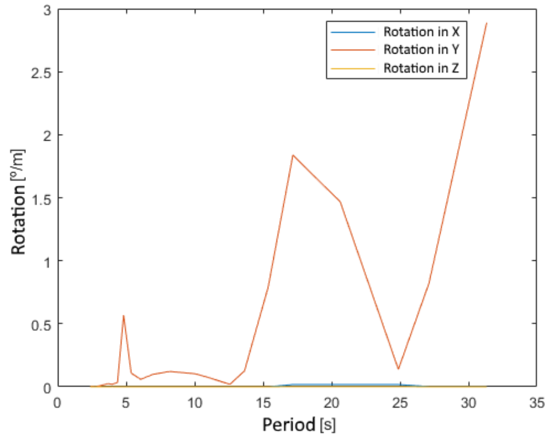

Figure 8 - RAOs for the rotations of the structure

We can identify two main critical periods for T_p = 5 s and T_p = 17 s, and it is apparent that the transport of the structure under these conditions would be less appropriate. The RAOs can be used to evaluate the stability and sensitivity of floating structures to the sea state, determining if they have large inclinations or large displacements induced by the waves [21]. However, since the values obtained here are small, we can deduce that, for the specified sea states, the structure exhibits a very stable dynamic behavior.

4.3. Structural Analysis

After the initial static and transient analyses, which were part of the iterative process described, the final geometry (section 2.1) was reached, whose transient structural analysis are studied here. As stated by the norms, the analyses are performed for 600 seconds, and the value set for the ANSYS time steps is 3 seconds. Decreasing this value would allow a more accurate stress distribution, however, it would also substantially increase the computational time required.

The final geometry was then analyzed for the three cases defined in section 2.2 for the DLC 8.1 and the von Mises stresses were calculated, as recommended by the GL norms

[9]. The von Mises stress is a value used to determine whether a given material will yield or fracture, and is mainly used in ductile materials, such as metals. The von Mises yield criterion states that a given material will start yielding when the von Mises stress reaches the value of the yield strength of that material. The von Mises stress is used to predict yielding of materials under complex loading from the results of uniaxial tensile tests [22]. Figure 9 represents the evolution of the maximum values of the von Mises stresses for the three different cases, using the loads calculated by FAST. Table 5 shows the corresponding main results of the von Mises stresses.

Table 5 - Main results for each case

Case	Maximum von Mises stress [MPa]	Average von Mises stress [MPa]	Safety factor
1	247,19	235,43	1,43
2	249,62	235,60	1,42
3	260,89	237,73	1,36

The maximum stress value that is observed for the three different analyses is 260.89 MPa (case for wind speed of 18 m/s), which gives a minimum safety factor of 1.36 for the project of this structure. Recalling that the safety factor stated by the standards is 1.35, with a maximum allowable stress of σ_{max} = 262.96 MPa, the yield criterion is thus verified for the three cases. The standards further state that the manufacturer must determine the maximum wind speed to which the transport may occur and, with the maximum value of the stresses at 18 m/s being very close to the maximum allowable stress, it is estimated that this wind speed value serves as a safety limit for the transport.

The stress distribution on the structure, as well as the maximum value of these stresses, for the wind speed of 18 m/s is shown in Figure 10. In this case, the maximum value occurs in a region of stress concentration, at the intersection of the main column with one of the support braces. A change in the critical region of stresses can be found for the other two cases, and it may be due to the randomly generated loads by FAST. As we can see in this figure, the regions that show the highest stresses are the regions surrounding the connections between the several structural members, and are located in the lower part of the non-submerged structure. Considering the low stress values for the tower and submerged section, it is presumed that the increase in stresses is mainly due to the inertial and gravitational forces, rather than the aerodynamic and hydrodynamic forces.

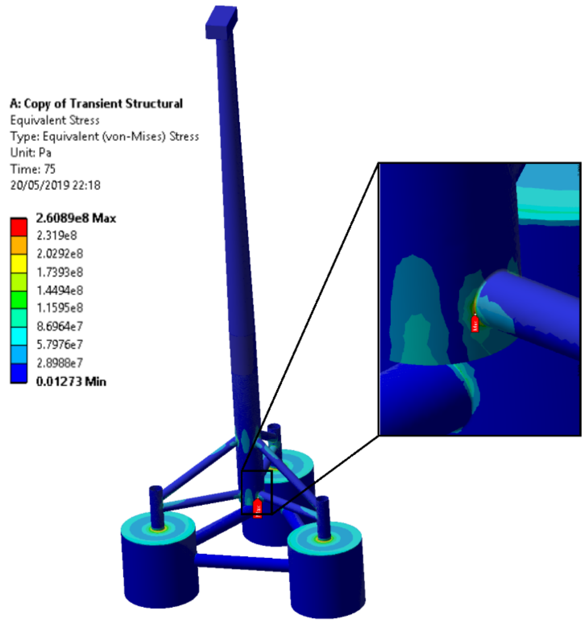

Figure 10 - Global von Mises stress distribution for the case 3

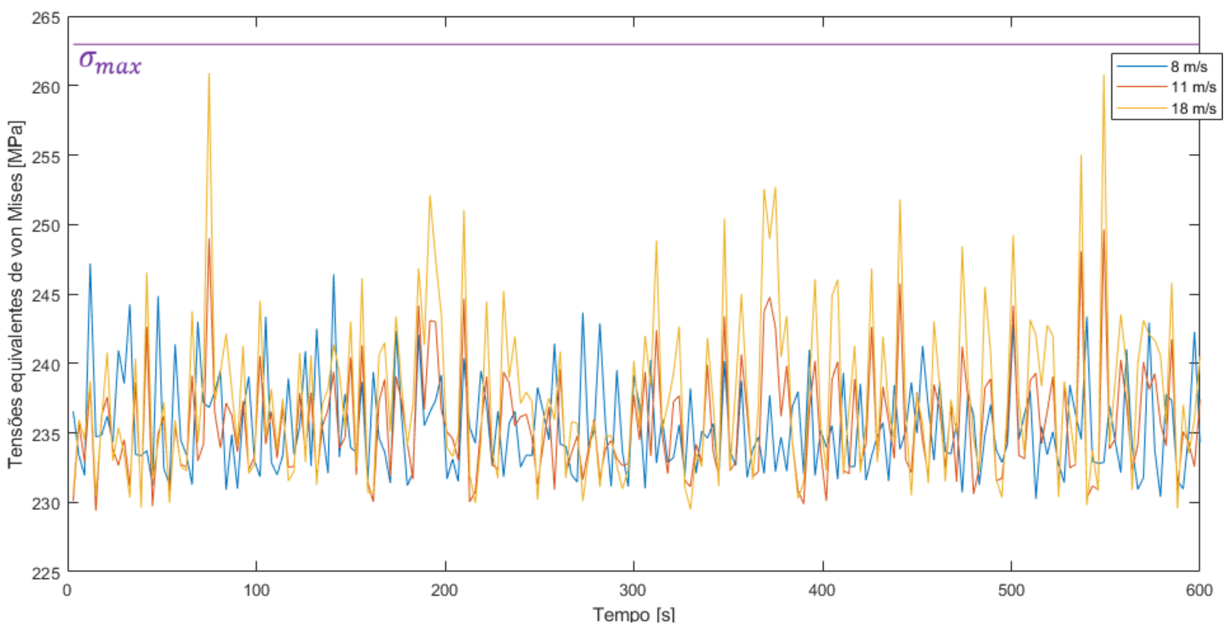

Figure 9 - Maximum von Mises stresses for the three cases

5. Conclusions

In this work, the study of the transportation phase of an innovative foundation for an offshore wind turbine along the Portuguese coast was carried out, analyzing several parameters, including the state of the sea and of the wind. For this project to be viable, the structural integrity of the structure has to be guaranteed throughout its entire life cycle, from the assembly to the operating phase, and therefore its study during transportation is crucial. To ensure its viability, modifications of the initial geometry were necessary, throughout the iterative process. To study the dynamic behavior of the structure, several analyses were performed using numerical and finite element models in ANSYS, for which the external loads were determined from the FAST and AQWA programs.

By the modal analysis, it was verified that the natural frequencies of the structure do not lie within the frequency band of excitation vibrations, which prevents it from resonating. It should be noted that during the transportation phase, immobilizing the rotor of the turbine reduces considerably the number of external vibrations acting on the structure. Doing so decreases the frequency band of excitation and minimizes the consequent risk of resonance, which is an additional safety precaution.

As for the analysis of response amplitude operators, these allowed the understanding of the response of the movement (translations and rotations) of the structure, when subjected to the action of the sea. These responses are important in order to have an overall idea of the stability of the structure, depending on the height and peak period of the waves, when it is established that high inclinations or large displacements can cause the structure to destabilize during the transportation. However, since the values obtained are inconsequential, it was concluded that, for the specified sea states, the structure exhibits a stable dynamic behavior. Nonetheless, it is important to be aware, during the transportation, of the critical wave peak periods. For these periods the response amplitudes are magnified, which could turn the structure more vulnerable.

Finally, from the transient structural analyses it is observed that an increase of the wind speed, and the consequent the increases of the height and peak period of the waves, leads to an increase of the stresses in the structure. The maximum von Mises stresses found for each case considered were used to calculate the corresponding safety factor. The safety factor specified by standards [9] (1.35) was respected for the three cases, for the entire time domain of the simulations, using the loads originated by FAST. The maximum wind speed for which the transport can then be carried out was established to be 18 m/s. It was also observed that the stresses are maximum in the zones near the connections between structural members in the non-submerged part of the foundation. From that, it can be considered that during the transport phase of the offshore wind turbine, the inertial and gravitational forces represent a bigger factor for the limitations of the project, when compared to the hydrodynamic and aerodynamic forces.

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