Dynamic Analysis of Fixed Offshore Structures for Wind Turbines.

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Abstract. Offshore wind power presents itself as an alternative for complementing and diversifying the Brazilian energy matrix. In this context, fixed jacket-type platforms, widely used by the oil industry, are alternatives for supporting offshore wind turbine towers. However, the large dimensions, high centers of mass, eccentricities, and the random nature of loads, such as ocean waves, winds, and currents, present significant engineering challenges. This article presents some of the main computational models for dynamic structural analysis of fixed offshore wind turbines. In the applied methodology, the sea state is modeled based on second-order Stokes wave theory, where fluid kinematics are calculated from the analysis of random waves in the frequency domain, using the Pierson-Moskowitz spectrum. The dynamic forces and interactions acting above the free surface were simplified through the adoption of values prescribed in the literature. Finally, structural analysis is carried out using the finite element method, with the jacket bars modeled using plane frame elements. The results obtained in terms of dynamic properties, as well as structural responses, were compared with those extracted from recent works, thus confirming the validity of the chosen methods and consolidating the results achieved.

Keywords: Fixed offshore wind turbine, Structural dynamics, Hydrodynamics.

1 Introduction

The energy transition from fossil fuels to renewable sources is one of the main actions to achieve global climate goals. Brazil stands out for its capacity to generate clean energy, largely due to its high national hydroelectric potential. However, as discussed by Silva et al. [1] this source, that account for 66% of the country's generation, exhibits fluctuation that can persist for months due to hydrological seasonality. There is also a trend of increasing demand for electric energy due to the socio-political-economic transformations of global economy decarbonization. In this context, offshore wind power generation emerges as an alternative for complementing and diversifying Brazil's energy matrix.

However, the still high costs of implementing and operating this technology pose a challenge to engineering, which must balance structural safety with commercially viable values. According to Moné et al. [2], the costs of the substructure and foundations account for approximately 14% of the implementation cost. Fixed jacket platforms, widely used by the oil industry, emerge as an option to support offshore wind generation towers. They have been used in relatively deep waters up to a depth of 50 meters, as noted by Kim, Heo e Koo [3]. Additionally, Gong [4] suggests that jacket structures present some advantages, such as a lower impact of wave and current loads when compared to other structures.

The maritime environment brings with it the unique characteristic of uncertainty regarding actions throughout the entire life cycle of the structure. Several processes and phenomena can lead an offshore structure to structural collapse, such as buckling, resonance, fatigue, wear, corrosion, brittle or ductile fracture, among others.

Considering this context, this work focuses its efforts on analyzing the dynamic structural behavior of fixed jacket structures. The analysis are performed considering the random nature of the environment simplified through the adoption of a wave spectrum in the frequency domain.

2 Sea State Modeling

Describing the sea state to replicate real conditions is not a simple task. Wave theories are important tools for understanding the kinematics of fluid particles. In this work, the second-order Stokes wave theory, one of the most well-known and widely used theories, was applied to model the sea state. Like the linear theory proposed by Airy, Stokes' theory assumes that the fluid is homogeneous, incompressible, and irrotational, and that the velocity field is derived from a velocity potential. The sea waves are non-linear, regular, and propagate two-dimensionally. According to Benitz, Lackner e Schmidt [5], an important consequence of the nonlinear effects considered by Stokes is that the waves have sharper ridges and shallower valleys, which more closely match the gravitational wave profile of the soft surface.

2.1 Second Order Stokes Wave Theory

The equations derived from Stokes' theory eq. (1), (2), (3), and (4) describe the fluid kinematics. Here, h represents the local water depth, while H and L denote the wave's height and length, respectively. The wave number is given by $k = H/L$, and $\theta = kx - \omega t$, where ω represents the angular frequency. The horizontal velocity V_x and vertical velocity V_z of the velocity field $V(x, z)$ are given by:

$$V_x = \frac{\pi H}{T} \cdot \frac{\cosh[k(z+h)]}{\sinh(kh)} \cdot \cos(\theta) + \frac{3(\pi H)^2}{4TL} \cdot \frac{\cosh[2k(z+h)]}{\sinh^4(kh)} \cdot \cos(2\theta). \tag{1}$$

$$V_z = \frac{\pi H}{T} \cdot \frac{\sinh[k(z+h)]}{\sinh(kh)} \cdot \cos(\theta) + \frac{3(\pi H)^2}{4TL} \cdot \frac{\sinh[2k(z+h)]}{\sinh^4(kh)} \cdot \sin(2\theta). \tag{2}$$

The accelerations in the x directions are shown in eq. (3) and (4).

$$a_x = \frac{2\pi^2 H}{T^2} \cdot \frac{\cosh[k(z+h)]}{\sinh(kh)} \cdot \sin(\theta) + \frac{3\pi^3 H^2}{T^2 L} \cdot \frac{\cosh[2k(z+h)]}{\sinh^4(kh)} \cdot \sin(2\theta). \tag{3}$$

$$a_z = \frac{-2\pi^2 H}{T^2} \cdot \frac{\sinh[k(z+h)]}{\sinh(kh)} \cdot \cos(\theta) - \frac{3\pi^3 H^2}{T^2 L} \cdot \frac{\sinh[2k(z+h)]}{\sinh^4(kh)} \cdot \cos(2\theta). \tag{4}$$

2.2 Spectral Analysis and Sea State

From a structural engineering perspective, the primary environmental actions arising from the ocean are waves, currents, and wind, which are inherently random. Consequently, the response to these solicitations is also random and must be evaluated as a stochastic process.

A spectrum describes the behavior of a specific stochastic process in the frequency domain. The use of a wave spectrum is based on the assumption that waves are ergodic stationary processes that follow a Gaussian probability distribution. In summary, we say that a stochastic process is ergodic if we can infer its properties and statistical information from a single sample of it.

The prediction of linear and non-linear responses of structures in marine environments is obtained from the spectral representation of various sea states. According to Benitz, Lackner e Schmidt [5], predicting the response, including motion, moments, and forces, depends on accurate sea state modeling. Since the 1950s, many spectral formulations have been developed to describe the sea state. In this work, the Pierson-Moskowitz wave spectrum was used, Jr e Moskowitz [6].

2.3 Pierson-Moskowitz Spectrum

The Pierson-Moskowitz spectrum was empirically derived by , Jr e Moskowitz[6] through analysis of records obtained from fully developed seas in the North Atlantic. According to Benitz, Lackner e Schmidt [5], fully developed seas occur when there is a balance between the rate of energy input from the wind into the waves and the energy dissipation due to breaking or nonlinear interaction among them. Thus, if the wind blows steadily over a large area for a long period of time, the waves reach equilibrium with the wind.

In Pierson's experiment, Jr e Moskowitz [6], five dimensionless spectra were produced with wind speeds between 20 and 40 knots. The average of these results was taken to generate a general formula for the spectrum expressed as:

$$S(\omega) = \frac{Ag^2}{\omega^4} \exp\left[-B\left(\frac{g/U}{\omega}\right)^4\right]. \quad (5)$$

where $A = 8.10 \times 10^{-3}$, $B = 0.74$, and U is the wind speed measured at 19.5 m above the sea surface.

According to Reeve, Chadwick e Fleming [7], this value is typically considered between 5 and 10 percent above the value of U_{10}, which is a commonly used reference value. Reeve, Chadwick e Fleming [7] also suggests the following relationship $U_h/U_{10} = (h/10)^{1/7}$. Thus, the spectrum depends solely on the wind speed.

The range of wind speeds that Jr e Moskowitz [6] considers as fully developed sea states ranges from 10.28 m/s to 20.57 m/s.

Data analysis is conducted using statistical parameters. Two of the most commonly used for offshore structure design purposes are significant wave height (H_s) and peak period or frequency (f_p). Significant wave height is a reference value and corresponds to one-third of the average height of the highest ocean waves. According to Benitz, Lackner e Schmidt [5], H_s equals four times the square root of the area under the spectral density curve.

To predict wave height and peak period, Ochi [8] developed the following forms based on the Pierson-Moskowitz spectrum, eq. 6 and eq. 7:

$$H_{m0} = \frac{0.21 U_{19.5}^2}{g}. \quad (6)$$

$$f_p = \frac{0.87}{2\pi U_{19.5}}. \quad (7)$$

Equation (5) is a theoretical representation of the spectral density observed by Pierson. However, as it presents a continuous frequency domain, in order to generate a model it is necessary to discretize the spectrum, which can be done by considering a constant frequency interval (Δf). According to Gireli [9], from this discretization it is possible to define the relationship between an amplitude spectrum and an energy spectrum, as shown in eq. (8).

$$A = \sqrt{2 \cdot S(f_m) \cdot \Delta f_m}. \quad (8)$$

2.4 Hydrodynamic Force

Once the velocities and accelerations of the fluid particles are known, the hydrodynamic force exerted by sea waves was calculated using the semi-empirical Morison model, eq. (9).

$$F = C_m(\rho \cdot \frac{\pi D^2}{4})\frac{\partial u}{\partial t} + C_d \cdot \rho \frac{D}{2} u \cdot |u|. \quad (9)$$

where C_d - is the Drag coefficient; ρ is the water density; D is the diameter of the pile, u and $\frac{\partial u}{\partial t}$ are, respectively, the horizontal velocity and acceleration of the fluid particles at a point.

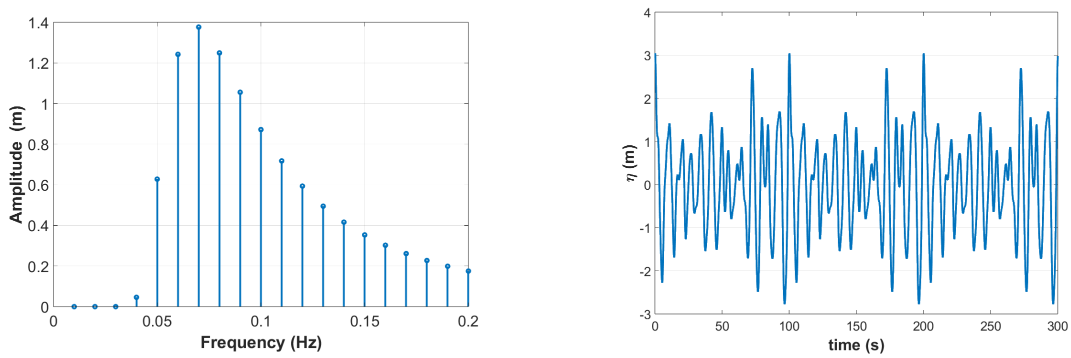
3 Computational Implementation

In this work, several methods were employed to simulate the dynamic behavior of an offshore jacket structure for wind turbines.To achieve this goal, codes were implemented using the Matlab programming language. Sea state modeling involved stochastic analysis using the Pierson-Moskowitz Spectrum to represent multiple discrete amplitude waves. The waves were then represented in the time domain using Stokes Wave Theory. Once the fluid kinematics were established, hydrodynamic loads were computed using Morison's Equation. Static and dynamic loads, including sea waves, currents, wind loads, and self-weight, constituted the external global forces. The dynamic equilibrium equations were solved using the Finite Element Method (FEM). Modal analysis was employed to determine frequencies and mode shapes. Time domain analysis utilized the Newmark integration method to calculate displacements of the discretized structure.

3.1 Stochastic Waves

Once the structure is defined by its properties, it is necessary to determine the forces acting upon it. In the marine environment, the impact of waves against the structure represents a significant portion of these forces. To obtain the values of this loading, it was considered that the sea state is represented by the kinematics described by the Second Order Stokes Wave Theory, and that the waves are random and composed of a superposition of regular waves obtained through the Pierson-Moskowitz Spectrum, Jr e Moskowitz [6].

A wind speed of 20m/s was considered in a fully developed sea state. Using the eq. (6) developed by [8], the significant wave height was determined to be $H_s = 8.5627$ meters and the peak frequency as 0.0679 Hz (period of 14.72 seconds). The adopted temporal discretization was $\Delta_f = 0.01$. Thus, the discretized amplitude spectrum is shown in Fig. 1a. From the discretized energy spectrum, the amplitudes as well as the frequencies of the waves that make up the random sea state were calculated, which can now be decomposed into a finite number of regular waves. The analysis of sea waves in the frequency domain allowed for the reconstruction of the elevation of a point on the ocean surface in the time domain, as the sum of finite regular waves, as shown in Fig. 1b. All analyses from this point onward were conducted in the time domain, where effects arise from the superposition of individual wave actions that compound the wave spectrum.



(a) Discretized amplitude spectrum. (b) Elevation profile of a point on the surface over time.

Figure 1. Discretized amplitude spectrum and elevation profile. $\Delta f = 0.01$. Peak frequency is equivalent to 0.0679 Hz or period of 14.72 seconds.

3.2 Jacket Structure

In his work, Chen et al. [10] evaluated the performance of four different geometries for jacket structures. He proposed these fixed jacket structures as support for the NREL 5-MW baseline wind turbine. The NREL 5-MW is a widely studied reference wind turbine for offshore system development, described by Jonkman et al. [11]. The dynamic analysis conducted in this study considers Chen's proposed z-Braces structure, a jacket structure with a height of 70.5 m installed at a water depth of 50 m, and Jonkman et al. [11] wind offshore turbine.

The set of physical, geometric, and mechanical properties (such as dimensions, density, modulus of elasticity, support conditions, etc.) were obtained from the works of Chen et al. [10] and Jonkman et al. [11]. The adopted model considers the weight of the superstructure as well as the forces acting on the wind turbine and tower in a simplified manner. For the purpose of representing dynamic behavior, the mass of the superstructure was coupled to the global mass matrix. The analysis of structural behavior was conducted in a simplified manner using a two-dimensional representation of the platform. The dynamic equilibrium equation was solved using the finite element method.

The jacket and the tower were modeled using plane frame elements. The tower, which varies in section along its height, is divided into different elements with different cross-sectional areas. The geometric properties of the jacket are categorized based on the type of structural member (legs, horizontal braces, and diagonal braces). The mass of the rotor nacelle assembly is treated as a lumped mass at the top of the tower, while the transition piece is modeled as a rigid element. Regarding the support conditions, the columns are assumed to be perfectly fixed to the foundation, completely restricting degrees of freedom at the supports. In our analysis, the FEM mesh is composed of elements, each with an approximate length of 1 meter.

4 Results

The determination of the dynamic properties as well as the structural response was initially obtained by considering only the jacket structure. In this case, the mass of the elements that compose the superstructure acts directly on the jacket structure, as shown in Fig. 2. This is computed by including the wind turbine machine and tower self-weight and the additional mass in the global mass matrix.

The set of acting forces considers, in addition to the stochastic hydrodynamic forces, the wind forces acting on the surface above the mean water level as well as on the tower and wind generator assembly, the current forces, the self-weight of the structure, and the self-weight of the wind turbine.

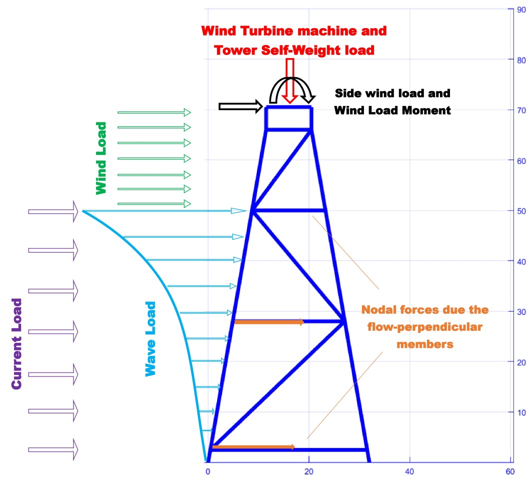


Figure 2. Environmental loads acting on the jacket substructure

The first five mode shapes of the isolated structure (without tower coupling) and their natural frequencies are shown in Fig. 3.

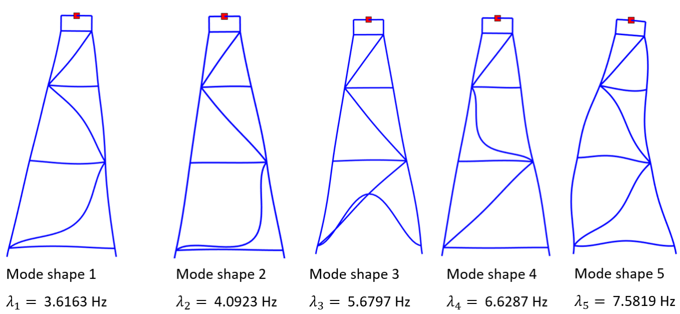


Figure 3. Mode shapes and natural frequencies

Figure 4 shows the structural response to the random dynamic loading imposed by the waves. This response is expressed by the horizontal displacement of a point located at the center of the upper horizontal bar ($x = 16m, y = 70.5m$).

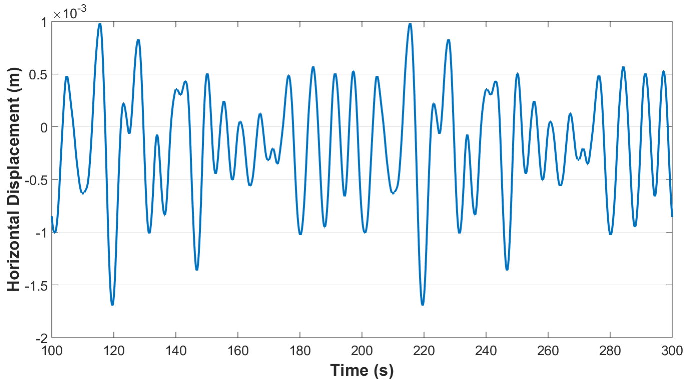


Figure 4. Horizontal displacements. Point location $x = 16m, y = 70.5m$

Partovi-Mehr et al. [12] uses tower coupling in his work to analyze the overall dynamic behavior of the jacket-type platform. Therefore, in addition to contributing through the mass matrix, the elements of the superstructure also affect the global stiffness of the structure.

The structural response to stochastic dynamic loading is presented in Fig. 5. The reference point for computing horizontal displacements is located at the upper end of the wind turbine tower ($x = 16m, y = 160.5m$). In the presented solution, displacements were shown starting from the steady-state vibration regime, with the initial moments (transient regime) disregarded. Since the modeling applied to the problem considers only the action of waves as stochastically variable over time, the displacements oscillate around a fixed value due to the assumed permanent loading, such as currents and wind.

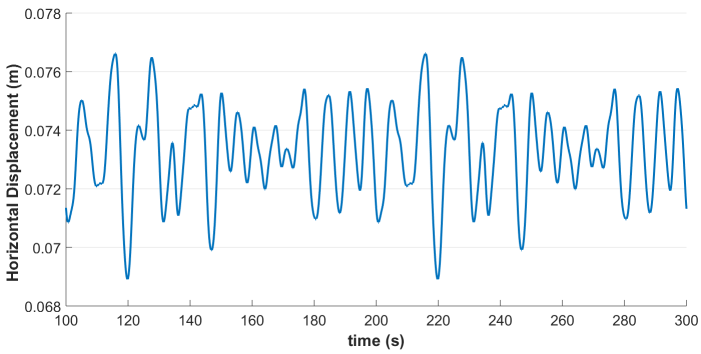


Figure 5. Horizontal displacements of the upper end of the tower. Steady-state vibration regime.

In his work, Kim [3] analyzes the dynamic response of an offshore wind turbine, the NREL 5-MW, supported by a jacket structure. The maximum horizontal displacement response to irregular waves and wind found by Kim [3] is on the order of 2 cm. The values found in our work for horizontal displacement are on the order of 7 cm. However, in this work, the wind and current loads were assumed to be prescribed deterministic static loads, as proprosed by Chen et al.[10], which justifies the oscillatory response around a fixed value.

The modes shapes for the model with the tower coupled to the jacket, as well as the natural frequencies, are shown in the Fig. 6.

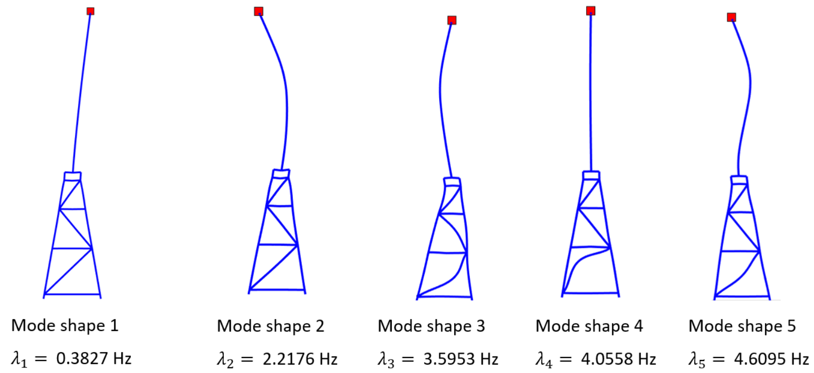


Figure 6. Mode shapes and natural frequencies

The first natural frequency is one of the most important modal parameters for the design of offshore wind turbines. To avoid the resonance phenomenon, it is mandatory that this frequency is outside the wave and rotor-induced excitation ranges. The first natural frequency obtained, shown in Fig. 6 is associated with a bending mode shape and is 0.38 Hz. The natural frequencies found by Partovi-Mehr et al. [12] and Kim [3] are also associated with bending mode shapes and are 0.29 Hz and 0.32 Hz, respectively.

The displacements found as the natural frequencies are consistent with those found in fixed jacket structures used to support wind turbines, as shown by Partovi-Mehr et al. [12] and Kim [3]. The lower frequencies are mainly associated with bending modes. Frequency domain analysis of the modeled sea state reveals that the frequencies of higher energy waves are in the range between 0.05 Hz and 0.20 Hz. These values are lower than the lowest natural frequencies, which is a desirable condition for offshore structure design. It is also noteworthy that the tower and the wind turbine generator contribute significantly to reducing the overall structure's natural frequency. This analysis of the influence of superstructure elements on the structure's dynamic behavior, coupled with the study of stress variations and fatigue, is crucial for comprehensive analysis, design, and verification of offshore structures.

5 Conclusions

This paper has explored computation modeling to achieve structural behavior of fixed jacket platforms for supporting wind turbines. To address these goals, the paper presented an overview of key computational models for dynamic analysis of fixed offshore wind turbines and employed a second-order Stokes wave theory for sea state modeling and relied on established literature values for aeroelastic-dynamic forces. Finally, the finite element method with plane frame elements was used for structural analysis. The obtained results on dynamic properties and structural responses were validated through comparison with existing research, demonstrating the effectiveness of the chosen methods and paving the way for further development.

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