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Evaluation of dynamic effects in the response of offshore wind turbines using incremental wind-wave analysis

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Abstract

Different methods for analyzing and evaluating offshore wind turbines under combined and single wind and wind loads are discussed. In areas, where dynamical analysis is required due to high wave height and high structure height, the accuracy of the results obtained from regular models will be discussed that statically analyze the behavior of the structure. The most correct approach to investigate the dynamical behavior of offshore structures against wave and wind force is to use long-term and irregular time series of water level and wind force on the offshore wind turbine. Because of time consuming and complex interpretation of results and high data volume, there is a need for alternative methods with appropriate accuracy in short-term period. The purpose of this study is to provide a more accurate and practical method than statistical and spectral methods to evaluate the response of wind turbines under loading of both wave and wind time series. Furthermore, the incremental wind-wave analysis is used. The results show that the response of the offshore wind turbine support structure, which is a jacket platform, is more affected by the waves. While turbine tower responses are mostly affected by wind force on wind turbine blades.

Keywords: Marine Renewable Energy; Offshore Wind Turbine; Incremental Wind-Wave Analysis; Wave Force; Wind Force.

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1. Introduction

Due to the possibility of using endless marine resources, extensive research is being done in the field of energy extraction from the sea. Thus, the use of offshore wind turbines has received special attention in recent years to generate clean energy. In 2008, 3.7 GW of electricity was supplied from these renewable sources in European countries (Marino, 2011). The most correct approach to investigate the dynamic behavior of marine structures against wave force is the use of long-term and irregular time histories of water level. Furthermore, due to time-consuming and complex interpretation of results and high volume of data, the short-term alternative methods with appropriate accuracy are needed.

In this regard, Movahedinia *et al*. (2014) explained the analytical method of incremental wave and for the platform under study using the method of incremental wave analysis, the final rupture limit, collapse wave and capacity curve have been calculated. The approach used in this research was nonlinear static analysis (pushover) (Movahedinia *et al.*, 2014). In another study by Wei *et al*. (2014), two types of wind turbine support structures (jacket and monopile) in two areas with different depths in the sea was studied and compared. Moreover, wave and wind loading in two cases with the same return period (for wave and wind) and different return period were conducted (Wei *et al*., 2014). In the present study, to investigate the combined effect of these two phenomena on offshore wind turbines, two researches in 2019 are used (Dezvareh, 2019a; Dezvareh, 2019b). The aim of this study is to provide a more accurate method than static and faster than dynamic analysis of the long-term series of irregular wind and waves. In accordance with the environmental conditions of the sea and the geometry of the structure, the dynamic behavior of the wind turbine should be evaluated appropriately.

2. Materials and methods

2.1. Jacket offshore wind turbine

The offshore wind turbine platform considered in this research was designed by Rambouillet in a wind farm project. The turbine mounted on the jacket structure is known as the NREL 5 MW turbine (Jonkman *et al.,* 2009). The offshore turbine support structure is located at a depth of 50 meters of water. This four-legged jacket has four levels of cross members as well as horizontal members in the level close to the bed. Furthermore, four central piles were hammered through four bases in the bed to a depth of 45 meters. The Transition piece (TP) is the distance between the jacket and the wind turbine tower and is actually a concrete block that encloses the jacket bases at its highest point (Figure 1). The design of the jacket includes connecting members, especially in cross members, in accordance with the rules of regulations and accessories such as anodes, J-tube, and boat landing, which the total weight of the structure will be about 400 tons.

2.2. Aero-hydrodynamic forces

To determine the wave force, it must be possible to estimate the kinematics energy of water particles using the measured water surface profile, thus three common ways to do this can be summarized as follows:

1) The theory of the Dean Flow function can

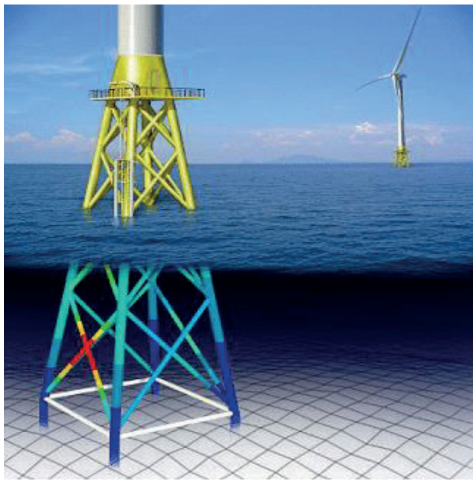

Figure 1. Support platform of the offshore wind turbine (Gagliardini *et al.*, 2014)

be applied in a slightly different way than the original form. This theory is nonlinear, but the temporal changes in the wave profile were not allowed (Dean, 1965).

2) The extended velocity potential method can be used. This method is similar to Dean's theory; The difference is that, as the name implies, the method is based on the potential for velocity. In this method, it is possible to apply temporal changes to the wave profile.

3) Linear wave overlap can be used. Using Fourier analysis, the frequency content of the water level profile can be determined. To reconstruct a given surface profile, phase angles of different frequencies must be calculated. Each frequency is expressed by a linear wave theory and the results are added together. This method can only be applied to low height waves.

Due to the presence of slanting members in the platforms and the need to calculate the forces acting on them, it must be possible to obtain the load applied to these members. To this aim. there are different approximated methods that the most common and accurate method is the one proposed by Chakrabarti (2005). In this method, the velocity and acceleration of the particles are converted into the tangential perpendicular components to the pile axis, but the components perpendicular to the axis are just used in the Morison equation (Kappos, 2001). Assuming the propagation of the wave in the positive x direction, two horizontal and vertical components of velocity (u, v) and acceleration (a_x, a_y) will be defined. The velocity of water particles perpendicular to the axis of the cylinder, U, is calculated as follows:

$$U = [u^2 + v^2 - (c_x u + c_y v)^2]^{\frac{1}{2}} \tag{1}$$

The velocity components in the x, y, and z directions can be expressed as Equations (2).

$$\begin{aligned} u_n &= u - c_x (c_x u + c_y v) \\ v_n &= v - c_y (c_x u + c_y v) \\ w_n &= -c_z (c_x u + c_y v) \end{aligned} \tag{2}$$

The coefficients c in the equations are defined as follows.

$$c_x = \sin\phi.\cos 6$$
$$c_y = \cos\phi \quad (3)$$
$$c_z = \sin\phi.\sin\theta$$

The acceleration perpendicular to the axis of the cylinder has the following components in the coordinate axes' directions:

$$a_{ny} = a_y - c_y(c_x a_x + c_y a_y)$$
$$a_{ny} = a_y - c_y(c_x a_x + c_y a_y) \quad (4)$$
$$a_{nz} = -c_z(c_x a_x + c_y a_y)$$

Using Morison formula, the force components per length of the cylinder in different directions (x, y, z) can be expressed as the Equations (5).

$$f_x = \frac{1}{2}\rho C_D D U u_n + \rho C_I \frac{\pi D^2}{4} a_{nx}$$
$$f_y = \frac{1}{2}\rho C_D D U v_n + \rho C_I \frac{\pi D^2}{4} a_{ny} \quad (5)$$
$$f_z = \frac{1}{2}\rho C_D D U w_n + \rho C_I \frac{\pi D^2}{4} a_{nz}$$

The force per length unit of the cylinder perpendicular to the axis of the cylinder will be obtained from the following equation.

$$f = \pm(f_x^2 + f_y^2 + f_z^2)^{\frac{1}{2}} \quad (6)$$

Finally, the total force on the cylinder in each direction will be calculated by the Equations (7).

$$F_y = \int_s f_y ds$$
$$F_y = \int_s f_y ds \quad (7)$$
$$F_z = \int_s f_z ds$$

which, s represents the distance on the member axis, and the integral limits are defined as to include the entire length of the member affected by the wave. It should be noted that due to changes in height and phase, speed, and acceleration will change along the member length.

To analyze a framed offshore structure by the methods such as direct stiffness method, the extensive forces due to waves on the members must be replaced by equivalent node forces and moments. In determining such forces, the moment in the wave cycle is usually selected when the horizontal wave force on the structure has its maximum value (static analysis). Of course, in this study, according to the desired time steps in dynamical analysis in the location of member points (both temporal phase and spatial phase), the speed, and acceleration are calculated in the desired points of the member and is placed in the modified Morison relation. The share of equivalent loads from each member is then calculated, assuming an ideal wave force distribution over that member. Finally, the forces of the total nodes are obtained from the total share of the members connected to the nodes (Edvardsen, 2015).

The dynamic wind load on the turbine blades is applied using the FAST software in time steps of 0.05 seconds which is equal to the time step of applying the wave force and is calculated at different velocities of these forces. As shown in Figure 2, the critical case scenario is when the average hourly wind speed at 10 meters above the sea level is 12 meters per second. The time series of the dynamic force applied to the highest point of the tower in the Tcl program is entered as a text file and simultaneously acts on the platform with the force of the waves and the response of the structure is recorded as output. It should be noted that all analysis inputs for the Fast software are obtained from the reports related to 5 MW wind turbines (Jonkman and

Buhl Jr, 2005). Since, the recorded wind speed and wave height are interrelated, so as the wave height increases, the time series of wind speed is measured every 120 seconds corresponding to the time series at a maximum speed of 12 m/s at 10m. So that, the height of Hs is equal to 14.5m, which is the maximum height of the waves up to the level below the deck, corresponding to this time series is the maximum wind, and the rest of the wave heights in the incremental approach linearly follow this wind time ratio to the waves' height.

3. Results and Discussion

The process of dynamic analysis of offshore wind turbines is as follows. After selecting the platform model and determining the initial specifications and gravitational loads and other necessary information, the platform modeling is modeled in Opensees software using non-linear beam-column elements and fiber sections (Wang *et al.,* 2018). Then, incremental dynamic analysis is performed and structural responses including displacement and base shear are presented. For this purpose, a modified Morison equation has been used to calculate the wave-structure interaction. This also indirectly takes into account the hydrodynamic damping of water, because when there is not even a wave, this coding has the ability to see the water environment, since, the calculations of the relative velocity and acceleration of the wave and the structure are performed in the equation Morison at any time. Assuming the absence of a wave and the presence of wind force, only the velocity and acceleration of the structure affect the equation as a passive force, which is the same as the hydrodynamic effect of water on the structure. Of course, the effect of the added mass due to the presence of elements in water has also been considered in the Morison equation and the initial modeling of the platform that calculates the period of the structure.

It should be noted that to calculate the dynamic wind load, the FAST software has been used in the corresponding marine status. Thus, for mean wind speed of 12 m/s at a level of 10 m, the maximum wind force is applied to the turbine blades. Wave and wind data related to the North Sea in the area where the platform was installed

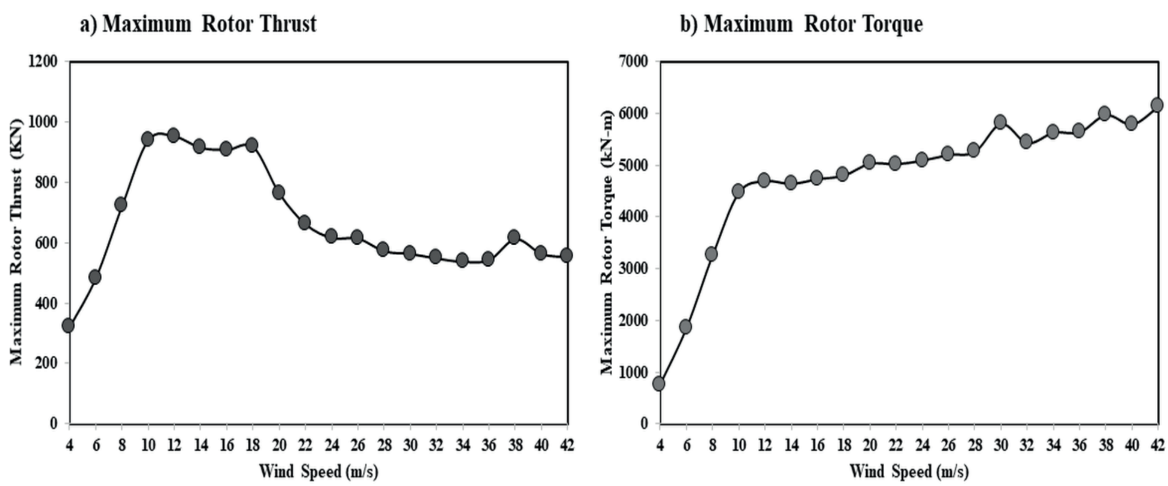

Figure 2. Maximum a) rotor thrust and b) rotor torque of offshore wind turbine based on mean wind speed

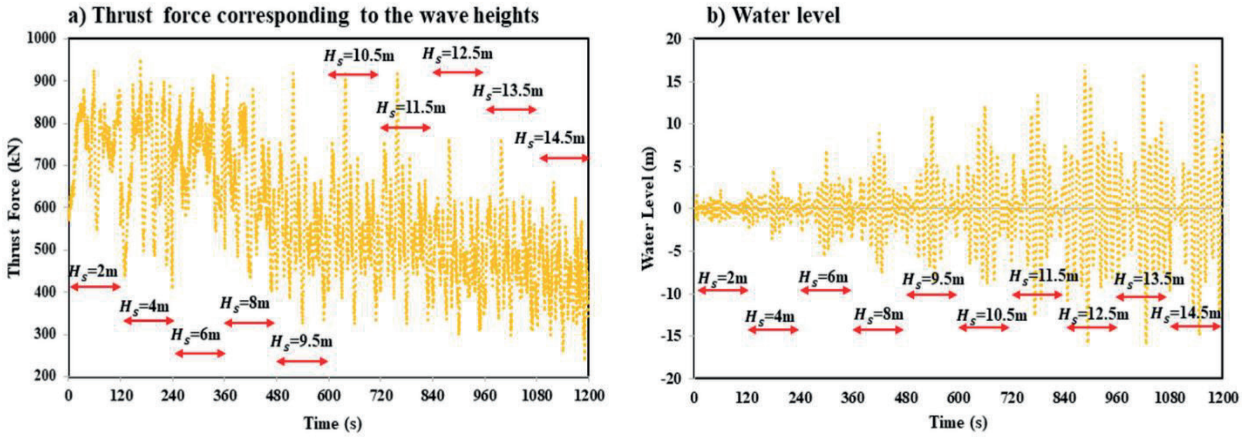

Figure 3. Time series of a) Turbine Thrust force, b) Water level changes

Table 1. Wind speed and significant wave height

$V_{wind}(\frac{m}{s})$	10	12	14	16	18	18	18	20	20	22
$H_s\ (m)$	2	4	6	8	9.5	10.5	11.5	12.5	13.5	14.5

were used to illustrate the wind profile (Weisse *et al.*, 2002). In this case, it is observed that as the wave height increases, the wind force on the turbine blades decreases, which indicates the correct design of the wind turbine (Figure 3a). It should be noted that to apply wind load to the structure every 120 seconds, the relevant section is applied to the structure separately next to the wave profile (Figure 3b). MATLAB program is used to calculate the kinematics of the waves every 120 seconds, which includes the profile output and the instantaneous velocity and acceleration of the waves. Thus, under the influence of a significant wave height from 2m to 14.5m, the wave profiles are applied to the structure separately every 120 seconds.

In this research, wind and wave loads at each time step are compatible and related to the

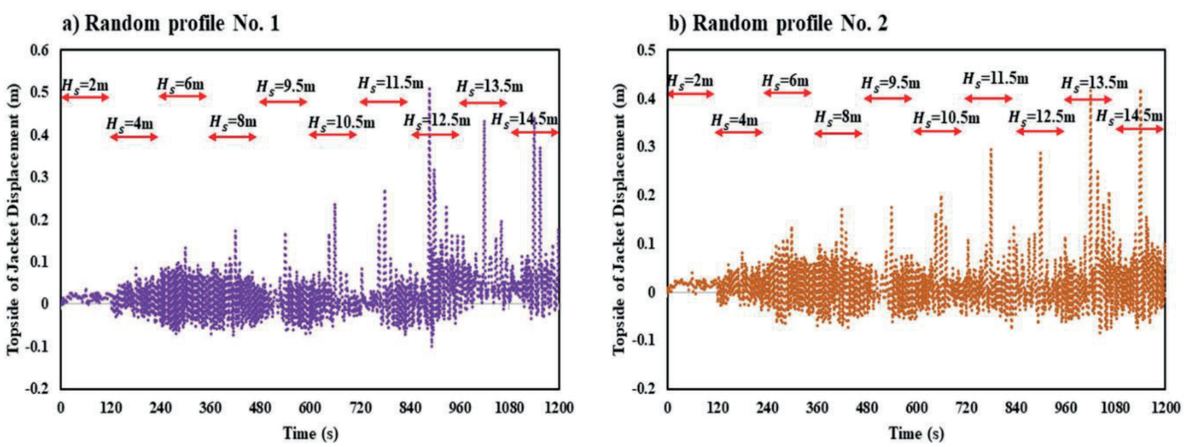

Figure 4. Displacement of the top level of the support structure a) No. 1, b) No. 2

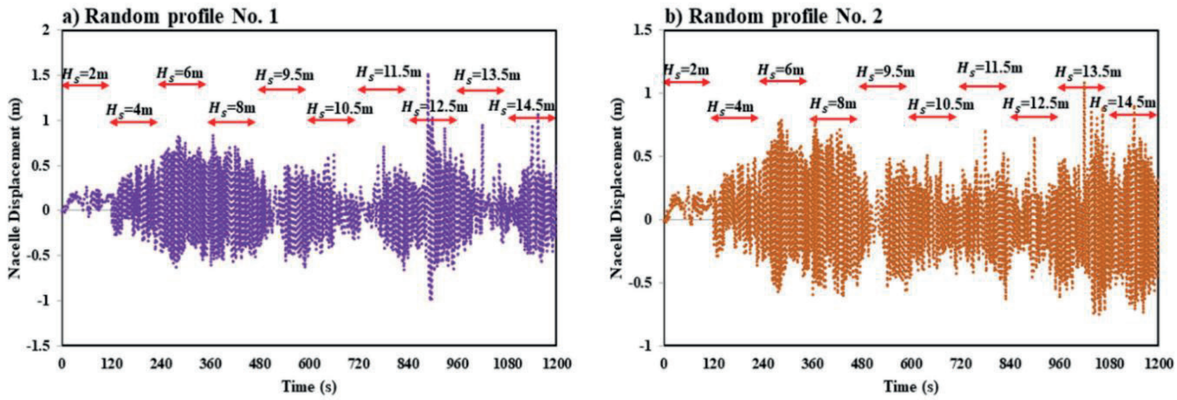

Figure 5. Wind turbine nacelle displacement a) No. 1, b) No. 2

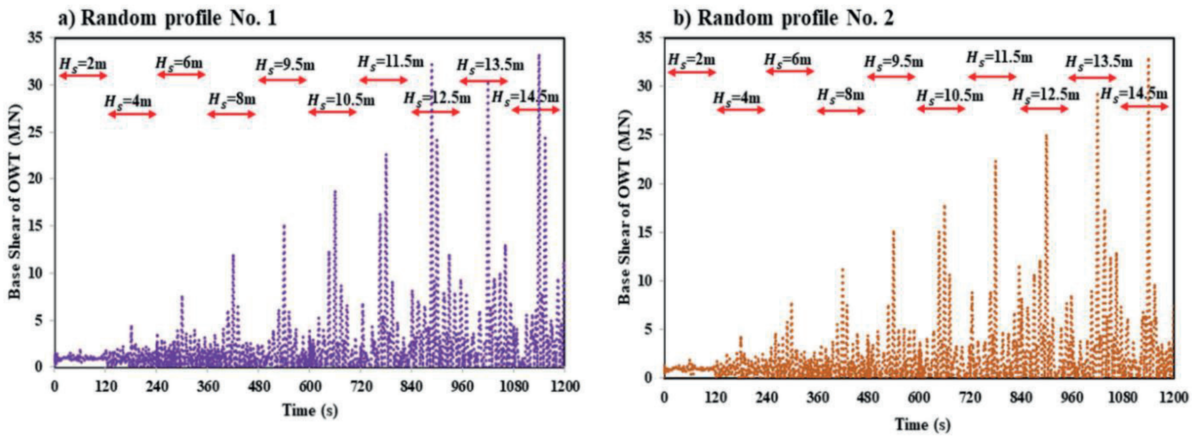

Figure 6. Offshore wind turbine base shear diagrams a) No. 1, b) No. 2

local conditions of the platform. Table 1 is the adapted wave and wind data for the turbine. The table was prepared for the platform in accordance with the information in marine conditions table in the Offshore Engineering Book by Chakrabarti (2005).

In the following figures, using MATLAB software, two incremental profiles are illustrated. The function of each case is that the random combination of single-wave phases produces an irregular wave in a specific format. Since the support structure or jacket is separate from the turbine tower structure, so their diagrams were drawn separately to better investigate the effect of wave and wind force on both structures. (Figures 4 to 6).

The time series of structural responses for each of these combinations of random loads is very close to each other at maximum response values, and at other times it takes smaller but different values depending on the type of load combination. As it can be seen, the structural responses for profiles 1 and 2 in Figure 6 are very similar (especially at maximum points for each time interval). The graphs show that the farther away from the maximum wave height, the more the result tends to be zero, and the responses are mostly a function of the irregular wave which was bounded to it. Moreover, by comparing the diagrams, it is understood that the supporting structure here, which is of the jacket type, is less sensitive to the incoming loads, but the structure of the turbine tower, which is a separate cylinder, is subject to the interaction of the entered wind and waves. Therefore, it can be seen that the response of the jacket structure is more affected by the waves entering the structure.

Conclusion

In this paper, in order to investigate the wind - incremental wave analysis on offshore wind turbines, first the platform modeling in Opensees software was performed accurately. Then in the definition of structural nodal masses, the mass includes the growth of marine plants, the mass of water inside the members, and added mass applied to the model. It should be noted that the mass of the deck, includes a concrete block with dimensions of 4 × 9.6 × 9.6 meters, which is applied centrally on the bases of the jacket, and furthermore the mass of the rotor and turbine nacelle assembly, is calculated and applied at the highest point of the wind turbine tower.

In defining the nodal loads on the structure, the dead load of marine plants, buoyancy, and the dead load of the members' weight were applied to the nodes of the structure. It should be noted that the concentrated load due to the weight of the concrete block of the deck and the concentrated load due to the weight of the turbine blades and its engine along with the moment due to its eccentricity are applied at the highest point of the structure. After modeling by creating a combination of different wave and wind loads in incremental mode, the aero-hydro dynamic force due to the combined application of these two phenomena was applied into the structure. According to the figures of time structural responses in the incremental dynamic analysis method, the followings have been achieved for offshore wind turbines under both wave and wind excitations:

- The effect of the irregular part of the wave is insignificant as long as the structure is nonlinear and the responses of the structure are mostly affected by the maximum wave height. The reason is that at each time interval, the maximum wave height is applied and the other oscillations are around it.
- The results show that the turbine supporting platform is less sensitive to wind loads and is more affected by the wave. But on the other hand, the offshore wind turbine tower is under the influence of wind and wave forces.
- This study also showed that the degree of randomness of wind-wave increment profiles does not have much effect on the response of the structure. Therefore, this kind of dynamic analysis method can be a good alternative to static pushover methods due to the shorter time of analysis.

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