Six Degrees of Freedom Numerical Analysis of an Offshore Wind Turbine Floating on a Spar Buoys

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ABSTRACT

Application of offshore wind turbines (OWT) due to relatively clean and local energy production is increasing recentlyconsequently It is obvious in near future wind energy will get significant portion of man produced energy. One of the most important issues and updates in design of these structures is correct analysis and increasing the accuracy of the analysis so that in addition to considering efficiency and stability of structure. On the other hand, fluid and structure interaction is the most complicated issues foraccurateanalyzing of OWT. In this study, a 5 MBoffshore wind turbine located ona spar type substructure and mooredby three weighted catenary cables is investigated. Different kinds of load combinations such as wind, current, wave, dead and live loads and earthquake loading applied to OWT and structure responses have been investigated. Next step critical load combination was asset. Finally according to calculations, the most critical load combination for OWT was combination of seismic loads and specific portion of live and dead loads.

KEY WORDS: *Offshore wind turbine, Dynamic analysis, Catenary mooring lines*.

1.0 INTRODUCTION

Wind turbine is used in wind plants for transferring kinetic energy to mechanical energy, which is called wind power. Wind turbines are constructed in two kinds of horizontal and vertical axis. The small wind turbine are used to charging the batteries or alternative power in wind boats, while the greater wind turbines with rotating generator are considered one source to produce electrical energy [1]. Wind turbines in wind farms for commercial production of electricity used today, are usually three – bladed and are located by computer based systems. Wind turbines with two and even one blades are also used recently [2]. The turbine blades are usually between 20 to 40 meters and even have more longitudinal and rotational speed of about 10 to 22 revolutions per minute. If the length of a wind turbine is 40 m and rotate by 20 22 revolutions per minute, Linear speed of the blade tips will be about 84 meters per second (302Km/h). The blades are mounted on top of the tower, as a steel pipe and a height of 60 to 90 meters. Usually with a gearbox, shaft rotation speed is increased, but in some designs, the axis rotates a ring generator with same speed. Some models of wind turbines operate at a constant speed with variable speed turbines can produce more energy which moves by lift force and blades drug. In Figure 1, an example of a wind turbine is shown.

Figure 1: Offshore wind turbine floating with Spar buoys

In 2013, Kelly et al [3] studied all previous studies related to offshore wind turbines. In 2012, Karimi rad et al [4] investigated dynamic behavior of spar wind turbine floating in applying wave and wind. They conducted their study under performance and turbulent conditions on a spar wind turbine with 5 Mb. They used aero-hydro-servo-elastic simulations to analyze dynamic response in the time domain. They also used Morrison equation in advanced blade element momentum theory for aerodynamic and hydrodynamic modeling to calculate the position of the moment and panel imposed structures. Kelader et al [5] in 2014, analyzedfluid and structure interaction in coupling mode in floated offshore wind turbines. They presented a computational framework for modeling the complex interactions floating structures and waves. Finally,the ability of this method had a good agreement with the actual and laboratory tests.

Front et al [6] presented none-linear model to optimum analyses of fluid and structure interaction. Weng and Teng [7] also suggested about nonlinear method of explicit model to waves and floated structures interaction in forced and free vibration motion. The application of a submerged object method in the modeling of wave-structure interaction was presented by et al [8] in 2016. The numerical method used was nonlinear finite element. They solved the Navier-Stokes equations on the covered mesh generator on the entire range. The modeling method by changing the parameters of Beria modeling of wave-structure interaction in offshore wind turbine was presented by Sava and et al [9]. Kelleder et al [10] in 2016 remodeled fluid-structure interaction in floating structures by considering atmospheric turbulence and real waves. In the following sections of the study, governing equations, validation and investigating the effect of loading combination are presented.

2.0 GOVERNING EQUATIONS

In this study hydrodynamic forces include hydrostatic, linear excitation due to waves, linear radiation due to object movement in water and nonlinear impacts are considered. All linear hydrostatic to object is computed by:

$$F_i^{Hydrostatic}(q) = \rho g V_0 \delta_{i3} - C_{ij}^{Hydrostatic} q_j \quad (1)$$

where ρ is density, V displaced fluid volume and C is hydrostatic force matrix due to hydrostatic stiffness in water. In the above equation, the indices i and j are surge, Sway, Heave, roll, pitch and yaw. It should be noted that in above equation, the effects of objects weight in restoring farce has not considered. The first term of above equation is buoyancy force which is equivalent of displaced weight of fluid due to floating object. The second term of above equation indicates the variation of force and hydrostatic moments due to structure displacement.

Other hydrodynamic forces are dependent on the occurrence of separation of flow from the structure. For this problem, the Klugan Carpenter and Reynolds number are two decisive numbers and defined by [11]:

$$K = \frac{VT}{D} \quad (2)$$

$$Re = \frac{VD}{\nu} \quad (3)$$

which disc cylinder diameter, v fluid viscosity, T wave period and V is flow speed of the flow. The D/λ is a significant factor in the equations. In linear regular waves, wavelength and the amplitude of wave's displacement are as follow:

$$V = \frac{\pi H}{T}\frac{cosh[k(Z+h)]}{sinh(kh)} \quad (4)$$

$$k\,tanh(kh) = \frac{4\pi^2}{gT^2} \quad (5)$$

$$\lambda = \frac{2\pi}{k} \quad (6)$$

where Z is local height and k is wave number. The additional damping equation is considered by [11]:

$$F_i^{Additional\ Damping}(q^{\cdot}) = -B_{ij}^{Linear} q_j^{\cdot} \quad (7)$$

That Bij is the additional damping matrix of structure. The indices i and j indicate 6 degree of freedom of structure in the direction of surge, Sway, Heave, roll, pitch and yaw. The following equation is used to consider the stiffness and damping effects of Platform braces:

$$F_i^{Lines}(q) = F_i^{Lines} - C_{ij}^{Lines} q_j \quad (8)$$

where C is the stiffness of connected braces and F is the overall force of bracing system.

3.0 VALIDATION

Considered wind turbine for verification, includes tower, turbine, Spar substructure and mooring system is defined by NERL [11]. The base of the tower is located 10 meters above the still water level (SWL) with a diameter of 6.5 m and thickness of 0.027 meters, started in cone shape. The top of the tower is coincident with the yaw bearing and is located at an elevation of 87.6 m above the SWL and at the end has a diameter of 3.87 meters with 0.019 m thickness. In the following Table, the tower properties are shown [11]:

Table 1: Tower Properties

Elevation to Tower Base (Platform Top) Above SWL	10 m
Elevation to Tower Top (Yaw Bearing) Above SWL	87.6 m
Overall (Integrated) Tower Mass	249,718 kg
CM Location of Tower Above SWL Along Tower Centerline	43,4 m
Tower Structural – Damping Ratio (All Modes)	1%

The tower at a height of 10 meters above sea level is connected to 120 m cantilever floating platform. The platform given is a spar buoy which is composed of two cylinder parts and is connected by a cone. From a height of 10 meters to 4 meters below the water surface the buoy diameter is considered 6.5 m. The original height of 12 meters below the surface buoy with a diameter of 9.4 meters startsand goes to a depth of 120 meters below the water level. Water depth of 320 meters is considered in all analyzes. In the following Table, the general characteristics of the spar platform are shown.

Table 2: Structural properties of floating platform

Depth to Platform Base Below SWL (Total Draft)	120 m
Elevation to Platform Top (Tower Base) Above SWL	10 m
Depth to Top of Taper Below SWL	4 m
Depth to Bottom of Taper Below SWL	12 m
Platform Diameter Above Taper	6.5 m
Platform Diameter Below Taper	9.4 m
Platform Mass, Including Ballast	7466330 kg
CM Location Below SWL Along Platform C.L	89.9155 m
Platform Roll Inertia about CM	4,229,230,000 kg.m^2
Platform Pitch Inertia about CM	4,229,230,000 kg.m^2
Platform Yaw Inertia about Platform C.L	164,230,000 kg.m^2

In addition, the forces applied from the sea, the regular wave with height and the period given in Table 3 is considered and finally hydrodynamic characteristics of structures are considered in Table 4.

Table 3: Sea state definitions

Sea State	T (s)	H(m)
1	2	0.09
2	4.8	0.67
3	6.5	1.40
4	8.1	2.44
5	9.7	3.66
6	11.3	5.49
7	13.6	9.14
8	17	15.24

Table 4: Hydrodynamic Properties of structure

Water Density ($\boldsymbol{\rho}$)	1.025 $\boldsymbol{kg/m^3}$
Water Depth (h)	320 m
Buoyancy Force in Un_Displaced Position ($\boldsymbol{\rho g V_0}$)	80,708,100 N
Hydrostatic Restoring in Heave ($\boldsymbol{C_{33}^{Hydrostatic}}$)	332,941 N/m
Hydrostatic Restoring in Roll ($\boldsymbol{C_{44}^{Hydrostatic}}$)	-4,999,180,000 Nm/rad
Hydrostatic Restoring in Pitch ($\boldsymbol{C_{55}^{Hydrostatic}}$)	-4,999,180,000 Nm/rad
Added-Mass Coefficient ($\boldsymbol{C_A}$in Morison's Equation)	0.969954
Viscous-Drag Coefficient ($\boldsymbol{C_D}$in Morison's Equation)	0.6
Additional Linear Damping in Surge ($\boldsymbol{B_{11}^{Linear}}$)	100,000 N/(m/s)
Additional Linear Damping in Sway ($\boldsymbol{B_{22}^{Linear}}$)	100,000 N/(m/s)
Additional Linear Damping in Heave ($\boldsymbol{B_{33}^{Linear}}$)	130,000 N/(m/s)
Additional Linear Damping in Yaw ($\boldsymbol{B_{66}^{Linear}}$)	13,000,000 N/(m/s)

Three catenary cables used at height of 70 meters below the surface are connected to substructures and their radius is 5.2 m from the central axis. This brace is located with 902.2 m upstretched length to seabed at a depth of 320 m and are in 853.86m distance from the central axis of structure. Table 5 consist of mooring lines properties. Figure 2, illustrate the schematic shape and the considered geometry.

Table 5: Mooring Lines Properties

Number of Mooring Lines	3
Angle Between Adjacent Lines	120 deg
Depth to Anchors Below SWL (Water Depth)	320 m
Depth to Fairleads Below SWL	70.0 m
Radius to Anchors From Platform Centerline	853.87 m
Radius to Fairleads From Platform Centerline	5.2 m
Upstretched Mooring Line Length	902.2 m
Mooring Line Diameter	0.09 m
Equivalent Mooring Line Mass Density	77.7066 kg/m
Equivalent Mooring Line Weight in Water	698.094 N/m
Equivalent Mooring Line Extensional Stiffness	384,243,000 N
Additional Yaw Spring Stiffness	98,340,000 Nm/rad

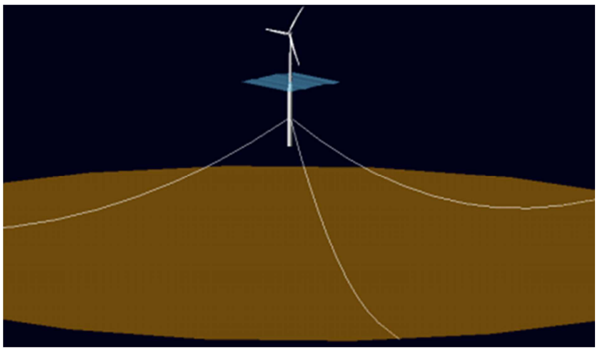

Figure 2: Computational domain of geometry

For investigating the accuracy of solving above model by AQWA ANSYS, force-displacement results are compared to the reference results [11]. Accordingly Figure3 is good agreement with NERL [11] result. The computed error for the force in the direction of the surge vibration is %5.2 and in the direction of sway vibration is %6.81.

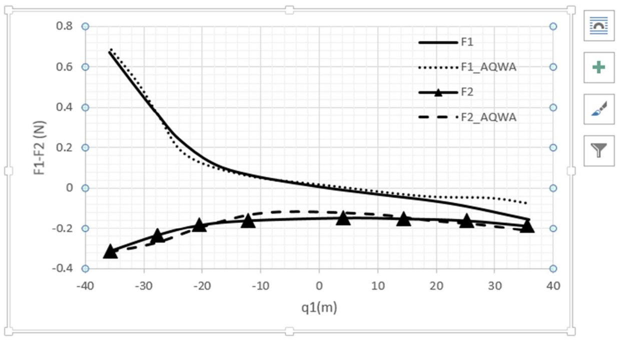

Figure 3: Force-displacement for surge and sway motions

4.0 LOADS COMBINATION

After verification of the modeling procedure, critical load combinations has been investigated. As mentioned in [12, 13, and 14], the critical combination of applied loads for analyses and design in offshore structures are presented as following:

$$COMB1 = DEAD\ Load + LIVE\ Load + Wind\ Load + Wave\ Load + Current\ Load \quad (9)$$

$$COMB2 = DEAD\ Load + 0.5 \times LIVE\ Load + Earthquake \quad (10)$$

$$COMB3 = DEAD\ Load + Wind\ Load + 1.32 \times Wave\ Load \quad (11)$$

In the above equations dead load is the weight of system, live loads consist of those which will vary in the period of utilization of system, which us set to be zero because no accidental or live load are applied here. For wave Pierson Moskowitz- Sea State 2 is used and current set to be constant by velocity of 1 m/s. Finally time history of earthquake also is:

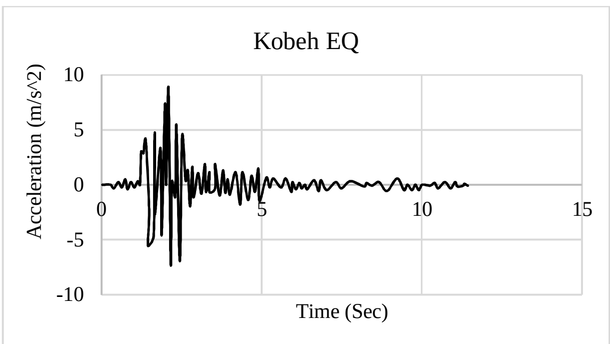

Figure 4: Time History of Kobe Earthquake

5.0 RESULTS

After analysis, the following results were observed. In the Figures 5 and 6, the samples of the waves applied to structure and the established stress are observed. Also the response of structure for the above loading combinations is shown in the Figures 7, 8 and 9. All data are estabilished in full scale, and results are calculated in full scale operating conditions. The wind turbine is assumed as source term, means that turbine torque is inputed in the calculations.

In Figure 5 the sea state 2 can be observed and also the maximum shear stress which is located at sea level is presented in Figure6. By applying 3 different combination loads, Figure7 shows the heave response of OWT in different frequencies. Combination 1 in freq. 0.353 rad/sec has the maximum heave displacement 2.68 m while combination 3 the maximum heave response is 2.3 m in freq. of 0.23 rad/sec. Finally as it can be observed combination 2 has the maximum heave displacement equal to 4 m which is the highest among all other combination loads. This heave response for combination 3 is in freq. 0.2 rad/sec.

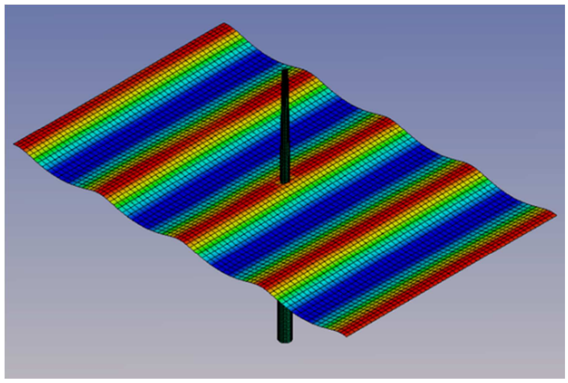

Figure 5: The applied waves on the structure

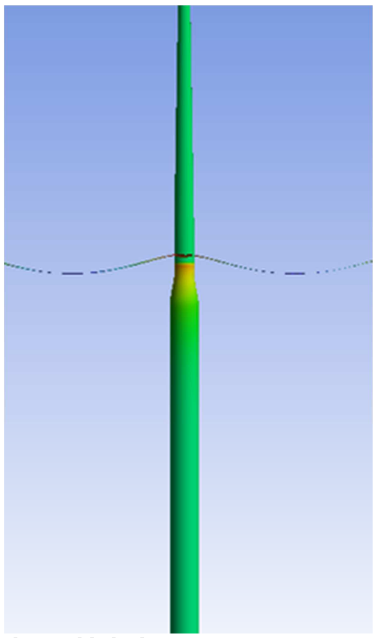

Figure 6: The established stress in structure in one time step

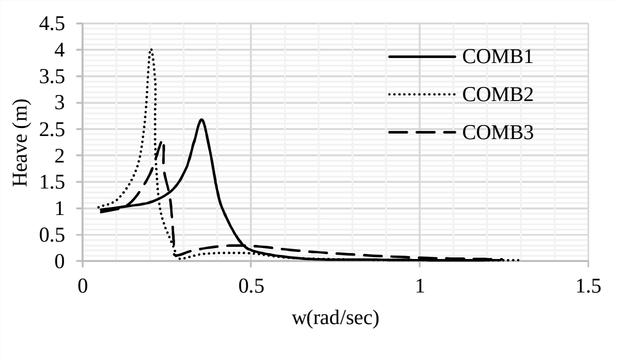

Figure 7: Heave response of OWT

Also, the most critical load combination comparing maximum shear stress is second one. In this load combination, there are two local maximum values 3.99 Mpa and 2.55 Mpa and the frequencies are 0.08 and 0.22 rad/sec. The other load combinations maximum shear stress are 3.66 and 2.4 Mpa respectively belong to Comb 3 and Comb 1. Finally Maximum deformation of total structures occurs in first and second load combination as it is illustrated in the Figure 9.

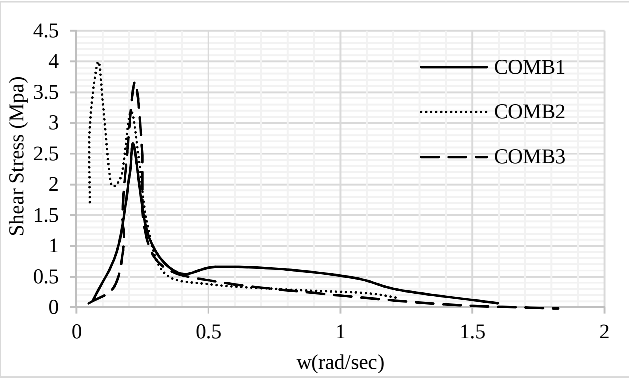

Figure 8: Maximum Shear stress at sea level

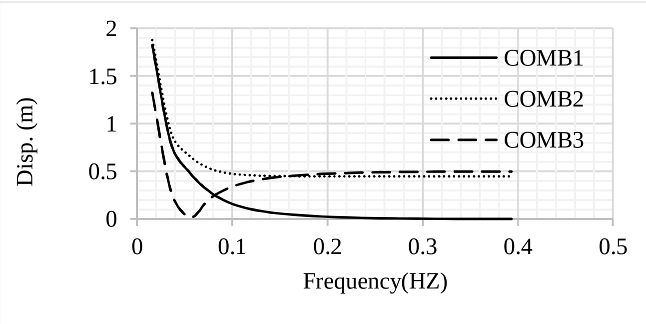

Figure 9: Maximum deformation versus Frequency

5.0 CONCLUSION

In this study, a previous study in the field of dynamic analysis of offshore wind turbine is studied. Then one of the 5 MW offshore wind turbines designed by NERL floating on a Spar buoys moored by three catenary cables harness was selected. The results in validation part of study are shown acceptable accuracy in the structural response. In the next step the existing load combination declared in different references were studied and three critical load combinations appropriate for our problem were selected and after structural and hydro dynamic analysis, the most critical case is computed. In the next step the response of structures are investigated. For comparing these three combinations heave response, shear stress and maximum deformation were computed. The combination of dead load, part of live load and earthquake was the most critical load combination. For future study it is worthwhile to study two way interaction of OWT. Also effect of different seismic loads along the other dynamic and static load can be considered for different types of OWT.

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