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Non-Linear Dynamic Analysis Of Spar Type Off-Shore Wind Turbine

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ABSTRACT

In order to compete with other energy industry sectors, the offshore wind turbine business is moving towards deploying wind turbines with higher power per mass ratios and higher energy harvesting capacity per unit. Due to national advocacy for green energy and sustainable development, the wind energy industry is growing quickly in response to the pressing environmental issues and the depletion of conventional energy sources. Wind Turbines are extremely dynamic and active structures. Floating offshore wind turbines (FOWTs) must be built to resist the irregular wave load that they are subjected to over the course of their lifetime. The floating base make it possible to harness the enormous potential of the wind in huge offshore areas. In this paper a finite element model of the FOWT (spar) is created using the FE simulation. The output is produced using the hydrodynamic diffraction and hydrodynamic response packages. For the analyses, a significant irregular wave with a peak duration of 10 seconds and a height of 10 m is used. The JONSWAP (Hs) wave type is considered. The results related to position, rotation and force in cable are discussed in this paper. The most recent relevant material is studied.

***Keyword:** - FOWT, Spar, Hydrodynamic, Peak period, JONSWAP*

1. INTRODUCTION

The first offshore wind turbine was installed in Denmark in 1991, giving offshore wind turbine a background of about 20 years. Offshore wind energy is produced by harnessing the force of the wind at sea, where there are no obstructions with constant and greater wind speeds. Since the wind blows faster offshore than on land, offshore farms produce more energy per installed capacity. Offshore wind electricity is clean, limitless, and renewable.

With water on three sides of its approximately 7600 km of coastline, India is fortunate to have excellent prospects for utilizing offshore wind energy. Since there is little visual and acoustic interference when offshore, much bigger areas can be utilized. Because of this, offshore wind farms usually have installed capacities of several hundred megawatts. In a similar vein, shipping is simple, allowing for much greater unit powers and masses than are feasible on land. With the increasingly prominent environmental problems and the exhaustion of traditional energy, wind energy industry develops rapidly based on the national advocacy of green energy and sustainable development.

Offshore wind farms are currently situated in shallow waters (up to 60 meters deep) far from the coast, major shipping lanes, important naval facilities, and areas of ecological interest. Some of the advancements we will witness in the upcoming years include the creation of new kinds of supports that enable these installations to be placed much further away from the coast and the constant improvement of the size and shape of wind turbines [5]. Offshore wind farms will surely have a long and successful future for sure.

Operating wind turbines are vulnerable to yielding, buckling, and failure during near-field earthquakes [1]. The final structure should have enough fatigue strength to withstand cyclic dynamic loads caused by wind and waves, be able to prevent potential resonant vibrations of the entire structure and its substructures, be able to prevent structural instabilities like flutter of the blades and rotor, and withstand extreme loads like wind gusts [2].

1.1 Types of Offshore Wind Turbines

Offshore wind turbines are constructed over the ocean with various types of foundation, depending upon the depth of seabed. The challenge lies in elevating the wind turbine above the sea level and anchoring them to the sea bed. Thus, it is a complex task. Offshore wind turbines are mainly classified into two categories, Offshore wind turbines with fixed foundations and Offshore wind turbines on floating platforms [2].

1.1.1 Offshore Wind Turbines with Fixed Foundations

These are installed on a fixed support structure on the sea bed, as shown in Fig. 1. In turn, there are different types of foundations: Monopile (the tower is installed on a large steel cylinder embedded in the seabed). This are used for depth less than 15 m. Gravity-supported (requires a high-mass, large-area concrete or steel platform resting directly on the prepared seabed). This are used for depth less than 30 m. Jackets (reticular steel structures with three or four anchor points on the seabed). This are used for depth between 30 m to 60 m. Current fixed foundation technology permits structures to be installed up to 60 meters below the surface [4].

1.1.2 Offshore Wind Turbines on Floating Platforms

This type of technology allows offshore wind turbine farms to be built in very deep waters, away from the shore, as shown in Fig.2. The floating bases make it possible to harness the enormous potential of the wind in huge offshore areas. Depending on the system used to fasten the equipment to the sea bed, they are classified as: single floating columns or spars, semi-submersible platforms, or tension-leg platforms.

Fig -1: Offshore Wind Turbines with Fixed Foundations (Source-google)

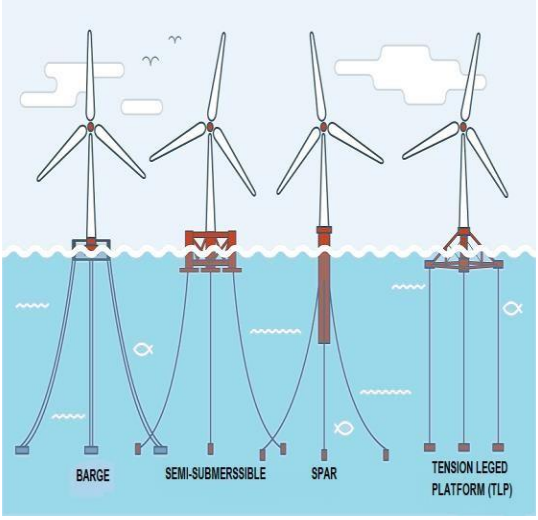


Fig -2: Offshore Wind Turbines on Floating Platforms (Source-google)

2. METHODOLOGY

Design and calculation of floating offshore wind turbine with spar support is manually carried out. A finite element model of the FWOT (spar) is generated using FE simulation. Hydrodynamic diffraction and hydrodynamic response packages are used to generate the output. Hydrostatic results are compared to numerical values to validate the model.

2.1 Structural Model

The Spar type OWT is modelled as a rigid cylinder with six degrees-of-freedom (i.e. three displacement degrees-of-freedom i.e. Surge, Sway and Heave along X, Y and Z axis and three rotational degree-of-freedom i.e. Roll, Pitch and Yaw about X, Y and Z axis) at its center of gravity, CG. The Spar platform is assumed to be closed at its keel. The stability and stiffness are provided by several mooring lines attached near the center of gravity for low dynamic positioning of the Spar platforms. At the bottom we have a fixed ballast, above it there is a flooded section tank for the variable ballast. At the top of the hull there are the hard tanks. Main parts of wind turbines are the tower, the nacelle, the hub, and the blades. The effect of the rotor-nacelle assembly is considered in the model by considering its mass and moment of inertia with respect to the upper centre of the tower [3].

The hull external diameter, total length, free board, and draft are needed. The free board is the length about sea level and draft is the length below the sea level. Displacement of the hull is the volume of water displaced by the submerged structure, this is what will produce buoyancy capacity for the hull and its center is the center of buoyancy.

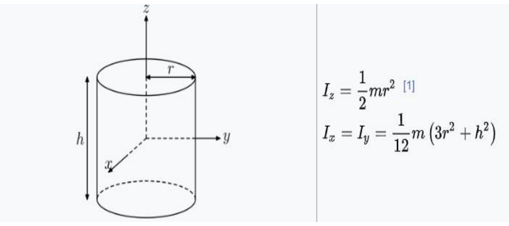
To estimate the stability of the floating hull we need to determine the overall center of buoyancy and center of gravity. In a spar hull center of buoyancy is always above the center of gravity that is why this concept is unconditionally stable. In other words, it is conceptually impossible to capsize. A coordinate system is added where Z is pointing upward.

2.1.1 Fix Ballast

Fix ballast is made up of heavy density material such as magnetite. The reasonable density for this is 5000 kg/m^3. As this volume is internal, the inner equivalent diameter is used to calculate its mass. The centre of gravity and mass movement of inertia are needed to model the rigid body in the FE simulation.

2.1.2 Variable Ballast

The variable ballast is made of seawater as it is an open tank to the ocean. The level of the ballast is controlled by pumping compressed air to the top of the tank. Again, the mass the center of gravity and the mass inertia is needed.



$$I_z = \frac{1}{2}mr^2 \quad [1]$$

$$I_x = I_y = \frac{1}{12}m\left(3r^2 + h^2\right)$$

Fig -3: Mass moment of inertia of cylinder

Where, r = radius, h = height and m = mass.

2.1.3 Hull

To calculate the mass of hull, use a simple approach of mass per unit length of 10,000 kg/m (linear mass). Add 5 bulkheads to the hull, each one weighing 80 tons. The secondary steel which is the mass of internal piping, ladder, accessories for mooring etc. will have an additional mass of 10 tons per meter as well.

2.1.4 Wind Turbine -5 MW And Tower

A wind turbine is being considered with a hub height of 100 m. Hub inertia and blade inertia are not considered as they are very flexible and may not contribute much. To consider blades it may be more complicated as their properties depend on the pitch angle. Tower with diameter of 7.5m and height 83 m is considered.

Stability of hull: A spar stability is a simple calculation of the distance between center of buoyancy and center of gravity. The BG length should be always positive and the higher it is the more stiff the structure is against overturning moments or in other words stronger against the forces of the environment. For more stability one can increase the draft, the diameter and play with the fixed ballast as well reasonable ratio between cost and benefit must be considered. BG value greater than 3m or 5m is considered as good.

Table -1: Mass summary

MASS SUMMARY					
PART	MASS (kg)	$I_{XX}=I_{YY}$ (kg/m^2)	I_{zz} (kg/m2)	COG (m)	MOMENT (kg.m)
Hull	2.40E+06	2.03E+09	6.75E+07	-35	-8.40E+07
Var.ballast	5.31E+06	4.83E+08	1.43E+08	-61.74	-3.28E+08
Fixed ballast	6.79E+06	1.28E+08	1.83E+08	-81	-5.50E+08
Nacelle + rotor	2.30E+05	1.70E+09	4.50E+06	100	2.30E+07
Tower	6.70E+05	3.87E+08	4.71E+06	56.5	3.79E+07
Total	1.54E+07				-9.01E+08
Global COG	-58.50	m			

2.1.5 Mooring Lines And Power Cables

The platform is kept in place by the mooring system, which also prevents drift brought on by nonlinear hydrodynamics, weather, and currents. The mooring lines are attached to the hull at the fair leads [6]. Which can be 50 or 40% of hull draft. An angle of 45° to the vertical axis is adopted for a taut leg mooring system type. Deep water offshore platforms can use a mixture of chain and polyester lines.

2.2 Finite Element Model

To model and analyze the structure hydrodynamic diffraction and hydrodynamic response system is used. Z axis is selected as the normal axis to sketch a wind turbine. Hull of diameter equal to 15 m and draft length of 85 m is created using the geometry tools. Free board of 15 m is kept above the sea level. You need a closed volume for the submerged part to get analyzed. A tower of diameter 7.5 m and height of 83 m is created on top of the freeboard. Nacelle is sketched on top of the tower, as shown in Fig. 5. Check was conducted to ensure that the hull has normal pointing outwards, this is to ensure that the hydrodynamic model does not fail to calculate the hull displacement, if they point inward calculated volume will be negative. Use share geometry tool to share nodes in between two faces from different parts.

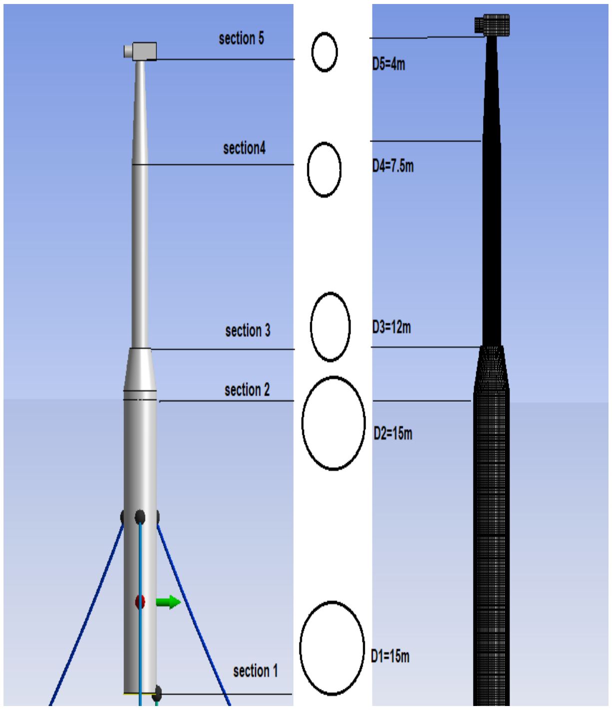


Fig -4: FE Model

2.3 Hydrodynamic system

Create a domain size of suitable parameters. Add the point masses for each part of the wind turbine. Each point mass needs to have the mass, COG, and mass inertia. Global combined mass and inertia of the structure is taken care of by the FE simulation. If the bottom of a spar hull is flat it offers large hydrodynamic drag in the vertical direction. To account for the additional heave motion damping caused by the viscous fluid drag, add a drag disc to the bottom of the hull. Hydrodynamic drag coefficient of 1.14 is assigned to the geometry. Add connection points to the hull for mooring lines and connection for power cable at the bottom. Create connection points at the sea floor, they are the mooring line anchors [6].

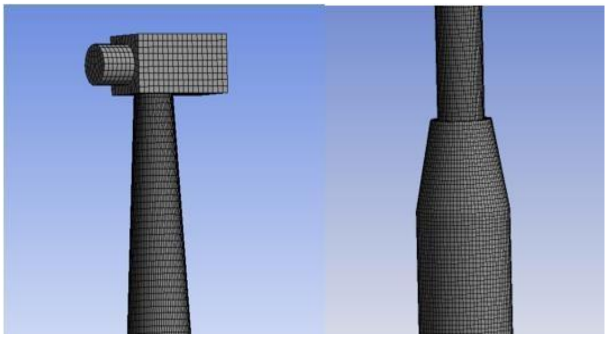


Fig -5: Quality of Mesh

A fine mesh is needed to detail some of the faces in the freeboard, tower and top component, as shown in Fig. 6. The quality of meshing depends upon the defeaturing tolerance and maximum element size parameter. A surface mesh with maximum element size of 1 m is provided to the model. A tolerance of 0.25 m is applied to the mesh. In total, 26512 numbers of elements are created.

3. RESULTS

The finite element model created is analyze using a hydrodynamic time response package for a duration of half an hour (1800 s). A significant irregular wave of height 10 m and peak period of 10s is applied for the analyses. JONSWAP (Hs) wave type is selected for the analyses. The results obtained are discussed below.

3.1 Natural Modes

Table -2: Mass summary

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Frequency(Hz)	0.00606	0.00658	0.03051	0.04473	0.04488	0.00597
Period(s)	164.96	151.92962	32.77763	22.35636	22.28168	167.49757
Damping(%)	6.5	5.82345	2.16518	0.46718	0.50019	4.62558
	Amplitude	Amplitude	Amplitude	Amplitude	Amplitude	Amplitude
X(m)	0.3812 m	9.96386 m	0.00904 m	0.34971 m	1.18663 m	0.00242 m
Y(m)	9.98677 m	0.32862 m	0.01359 m	1.38788 m	0.00885 m	0.03131 m
Z(m)	0.00449 m	0.04017 m	0.01121 m	0.14675 m	0.11763 m	9.68123 m
RX °	0.2193 °	0.01074 °	0.06906 °	9.58051 °	0.02400 °	0.13591 °
RY °	0.00702 °	0.24338 °	0.02857 °	2.44281 °	8.21855 °	0.14447 °
RZ °	0.26624 °	0.74337 °	9.99970 °	0.42010 °	5.57072 °	2.49668 °

The Natural modes for 10m wave height was obtained through hydrodynamic response. Six modes were obtained. It is observed that the structure is stable for all the modes.

3.2 Effect of Wave on Offshore Wind Turbine

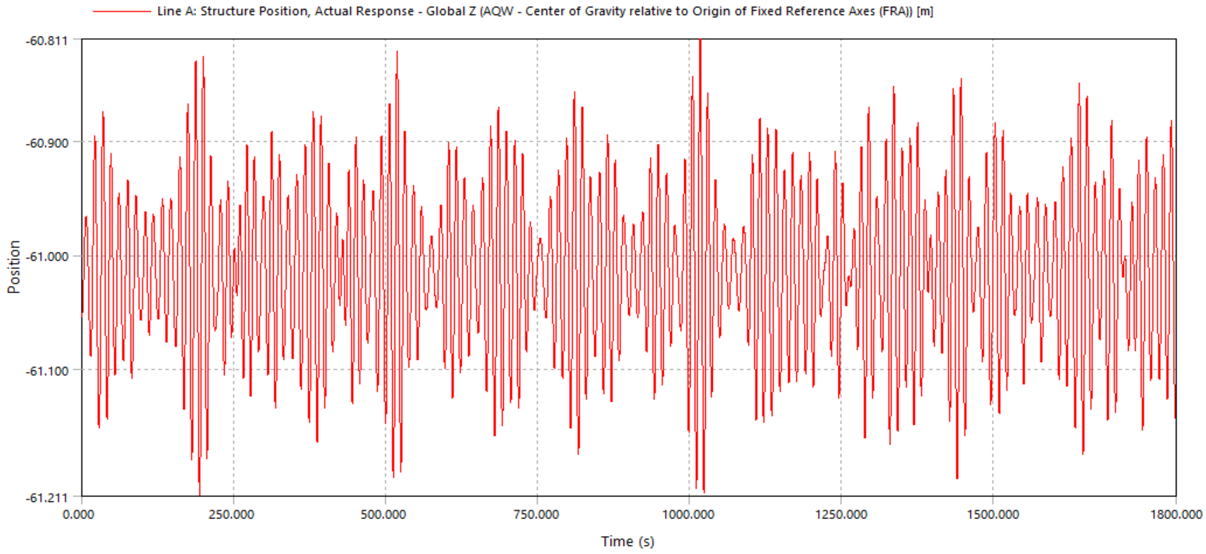


Fig -6: Position vs Time graph

The above graph represents the actual position of structure along heave (global Z) with respect to time. The position in heave is calculated with reference to center of gravity of the structure. The generated graph shows that the maximum value is -60.811m and minimum value is -61.211m.

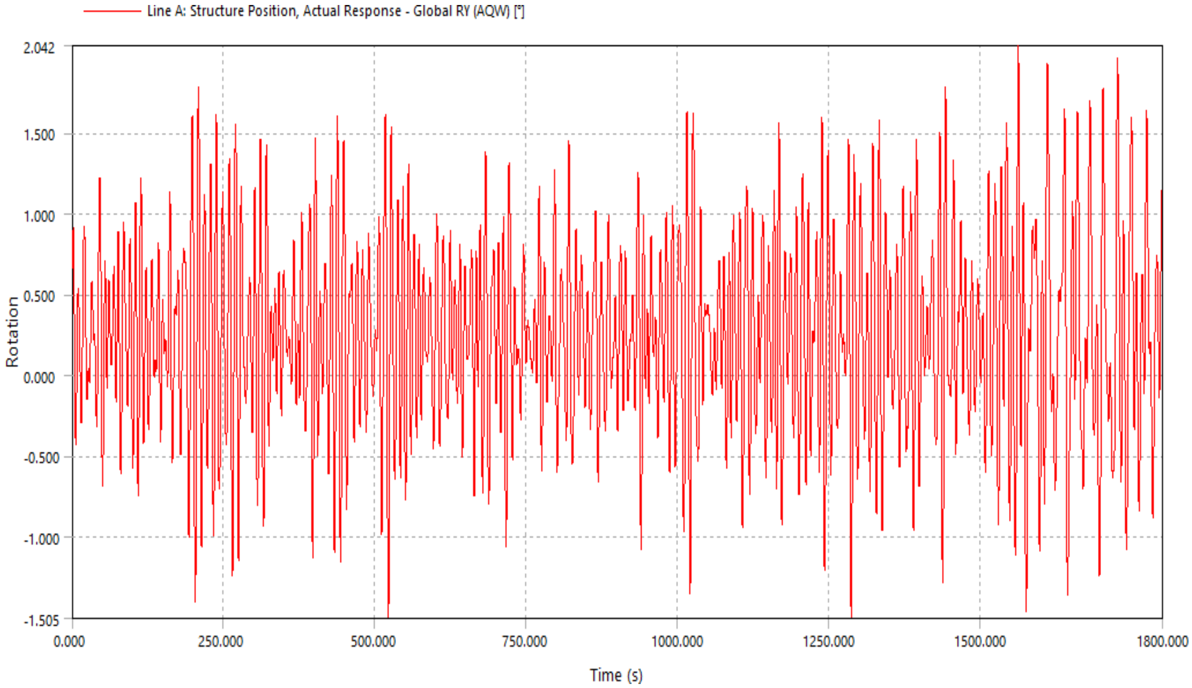


Fig -7: Rotation vs Time graph

The above graph represents the actual rotation of structure about pitch (global RY) with respect to time. The generated graph shows that the maximum value is 2.042° and minimum value is -1.505°.

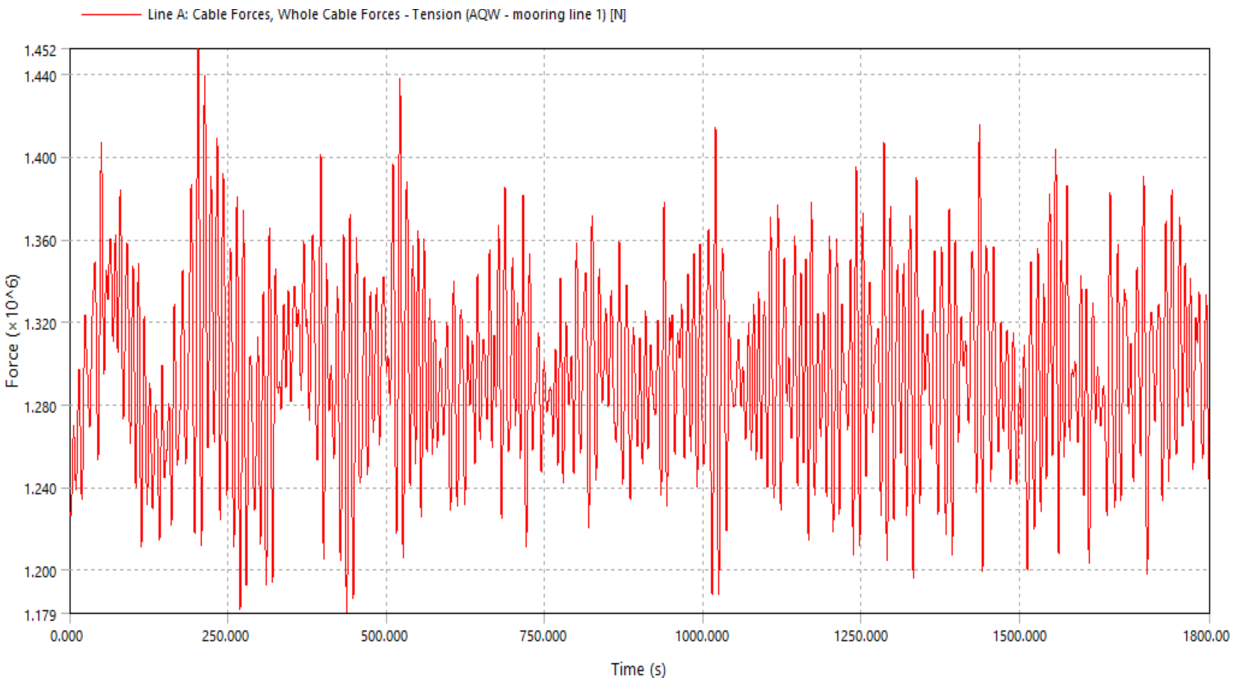


Fig -8 Force in cable vs Time graph

The above graph represents cable force in one mooring line with respect to time. The generated graph shows that the maximum value is 1452407.375 N.

4. CONCLUSIONS

In this paper a spar type floating wind turbine is studied for the dynamic response caused by hydrodynamic excitation. The effect of an irregular wave on the FOWT generated an output for the position, rotation, and force in cable, with respect to time. From the results it is concluded that:

- The structure is stable along heave (global Z). Since, the structure shifted downward by 2.71 m along heave which is less than the amplitude caused for stable mode.
- The structure is stable about pitch (global RY). Since, the structure rotated by 2.042° about pitch, which is less than the rotation cause for stable mode.
- The tensile force in one mooring line shows the maximum value of 1452407.375 N. whereas, the mooring line can take the maximum tensile force of 13600000 N.

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