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Structural Design of Spar Platform To Support a 6 MW Wind Turbine

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Abstract: A detailed study on offshore floating wind turbines, the working principle of SPAR floater and the conceptual design of SPAR floating platform used for floating wind turbines are presented. This study discusses the preliminary design methodology of SPAR floating structure for the DOWEC 6 MW off shore wind turbine. Structural design and stability is done analytically as per the API RP 2A. Buckling stress analysis is examined with ANSYS Software. Heave and pitch motions have been chosen as the critical design parameter. And the hydrodynamic numerical simulations have been performed using panel method.

Key words: Panel method, design, methodology, stability, analysis, buckling stress

INTRODUCTION

Now a days the demand for renewable energy has increased significantly by Kooijman *et al.* (2003). Onshore wind farms are currently reaching their capability limits and the trend is to move offshore. Earlier periods, offshore wind farms adopt fixed structures as support. These are not suitable to exploit sites with deep water depth. In the decades (Frye *et al.*, 2011; Roddier *et al.*, 2010; Soker *et al.*, 2000), the oil and gas industry answered to this challenge by adopting floating structures and today they are common in use.

Compared to fixed structures, floating support structures must provide enough buoyancy to sustain the wind turbine weight plus its own weight. Enough rotational stability also has to provide to prevent the system from capsizing and good wave response motion to prevent the structures from experiencing large dynamic loads or compromise the performance of the wind turbine. This thesis describes only the conceptual and preliminary stages of the floating support structure design process.

MATERIALS AND METHODS

Spar-type floating wind turbine: The spar-type wind turbine consists the floating foundation which is referred as the floater, the tower and the Rotor-Nacelle Assembly (RNA). The floater may be towed in the horizontal position to calm waters near the deployment site. It is then upended, stabilized and the tower and the RNA mounted by a derrick crane barge-type before finally being towed by escort tugs in the vertical position to the deployment site for connection to the mooring system. The floating foundation consist a steel and/or concrete cylinder filled with a ballast of water and gravels to keep the centre of gravity well below the centre of buoyancy which ensures the wind turbine floats in the sea and stays upright since it creates a large righting moment arm and high inertial resistance to pitch and roll motions (Tao and Cai, 2004). The floater is ballasted by permanent solid iron ore ballast, concrete or gravel from a chute. Alternatively, the ballast tanks may be injected with grout. It should be remarked that the spar-type is difficult to capsize. The draft of the floating foundation is usually larger than or at least equal to the hub height above the mean sea level for stability and to minimize heave motion (Karimirad *et al.*, 2011). Therefore, it is necessary to have deep water for deployment of this spar-type floating wind turbine as adequate keel to seabed vertical clearance is required for the mooring system to be effective. The trajectory control is discussed in a soft computing approach on ship trajectory control for marine applications (Sethuramalingam and Nagaraj, 2015a) and design model on ship trajectory control using particle swarm optimisation in Green Engineering and Technologies (IC-GET) (Sethuramalingam and Nagaraj, 2015).

Input data: Because of its low motions, the spar can use a taut mooring system at a reduced scope and cost compared with a full catenary system. Each mooring line is anchored to the seafloor with driven or suction pile. The hull end of the line passes through a fairlead located on the hull below the water surface then, extends up the outside of the hull to chain jacks at the top. The restoring forces are mainly generated by the elasticity of the mooring line (Fig. 1-3).

Static structural analysis: The strength of the structure has been investigated with FEA simulations using ANSYS. A three dimensional model of the structure has been created. The diameter of the cylinder and the

Fig. 1: Spar-type floating wind turbine

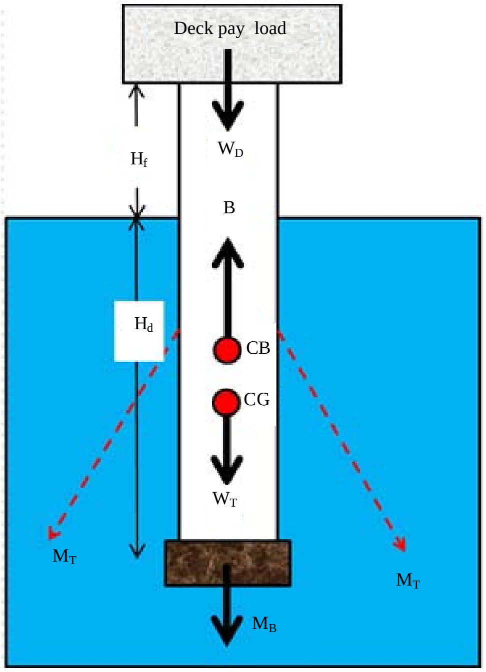

Fig. 2: Free dody diagram of spar

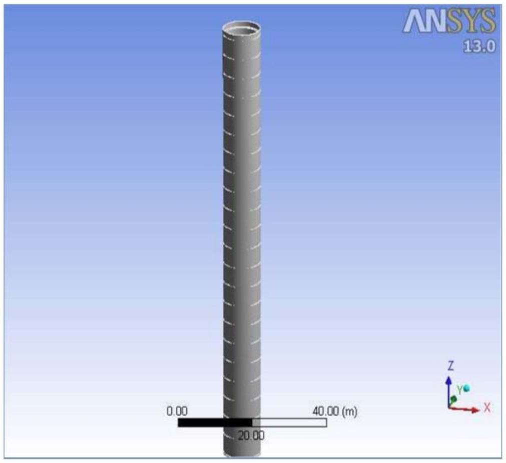

Fig. 3: 3D Model of spar with ring stiffener

Table 1: General specifications DOWEC 6 MW wind turbine for the use in large wind farms in the North Sea (The details of the 6 MW wind turbine has taken from DOWEC-F1W2-HJK-01-046/9 (September 2003) (Ref. No.1)

Variables	Values
Nominal power	6.0 MW
Rotor diameter	129 m
Design tip speed	80.0 m/sec
Nominal rotor speed	1.844 rpm (at maximum torque)
Air density	1.225 kg/m^3
Cut in speed	3.0 m/sec
Rated wind speed	12.1 m/sec
Cut out speed	25.0 m/sec
Rotor hub cone angle	-2.5° (upwind)
Rotor tilt angle	5°
Pre bend of the blades	2.0 m at tip, upwind, additional to the 1.0° hub coning
Tower	80 m long, tubular shaped
Hub height above the sea level	95.5 m
Tower mass	225 MT
Nacelle	189 MT
Rotor+Hub	83 MT
Miscellaneous	7 MT
Total mass (approximation)	504 MT
Tower wall thickness	0.027 m
Tower base outer diameter	6.0 m
Mass moments of Inertia about centroid coordinate axes, I	2.178×10^{10} kg.m^2
I_{YY}	2.1765×10^{10} kg.m^2
I_{ZZ}	1.22×10^{8} kg.m^2
Radii of gyration about centroid coordinate axes, R_x	82.06 m
Ry	82.063 m
Rz	6.126 m

Table 2: Environmental condition

Site	North sea
Maximum wind speed	12 m/sec
Maximum current speed	2 m/sec
Maximum wave height	11 m (for 50 years)
Water depth	200 m
Design wave period (T)	12 sec

Table 3: Support structure (Spar) dimensions

Variables	Values (m)
Spar radius	5.0
Draught	100.0
Free board	12.0

Table 4: Difference weight and their values

Variables	Values
Displacement weight	78853250 N
GM	21.21 m
Centre of gravity (from bottom of cylinder) (KG)	28.89 m
Centre of buoyancy (from bottom of cylinder) (KB)	50 m

stiffener spacing are 10 and 5 m, respectively (Table 1-4). The model and stiffeners have meshed with shell elements. Finally, the structure experiences a maximal stress of 157 MPa (Fig. 4 and 5). This leads to the reserve factor 2. The stiffener size and the plate thickness have been tuned to match the structural requirements. Not overcoming the reserve factor of 2.

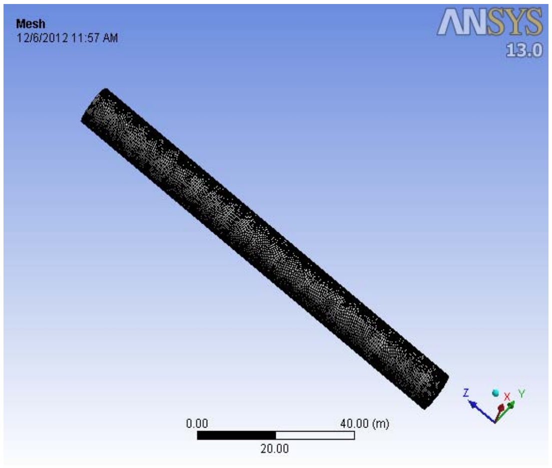

Fig. 4: Mesh

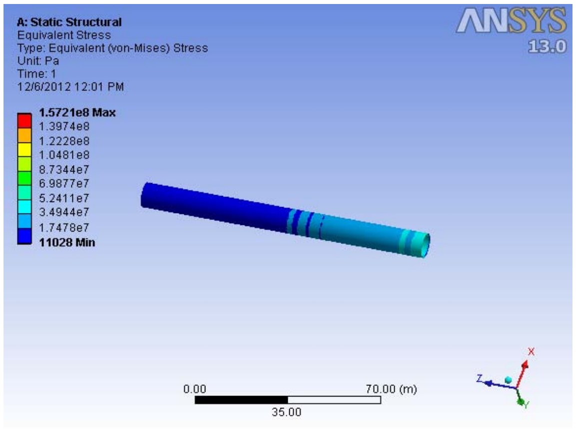

Fig. 5: Stress visualization of the stiffened cylinder FEA Model

Hydrostatic stability: The spar is a floating platform that mainly uses the relative position of the CG with respect to the CB to achieve static stability. The configuration of spar requires the use of ballast to lower the CG position in order to increase the restoring arm and provide enough stability (Fig. 6): distance from bottom to COG:

$$KG = \frac{W_t.(H_d+H_f)+0.5W_s.(H_d+H_f)}{W_T+W_s+W_B}$$

Where:

W = Weight of turbine
W = Weight of spar
KG = 28.8557 m

Distance from bottom to COB:

$$KB = 0.5H_d = 50\text{ m}$$

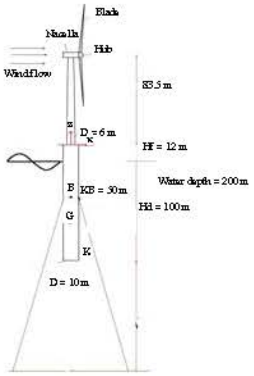

Fig. 6: Schematic layout of spar wind turbine

Water plan moment of inertia:

$$1 = \frac{\pi}{64}.D^4 \quad 1 = 490.625\text{ m}$$

$$\text{Displaced volume} = 7850\text{m}^3$$

$$BM = 1/ = 0.0625\text{ m}$$

$$GM = KB+BM-KG = 50+0.0625-28.8557 = 21.2068\text{ m}$$

RESULTS AND DISCUSSION

Hydrodynamic analysis: Numerical simulations have been performed to compute the Response Amplitude Operators (RAOs) and the wave response motions. The WAMIT software computes RAOs of motions using diffraction radiation theory. The geometry of the spar is modelled using Multisurf Software. The model does not represent the tower and the turbine in order to reduce computing time. Instead of that, the weight and inertia of the system have been computed from Patran software and input manually to WAMIT (Table 5 and 6; Fig. 7).

Heave natural period:

$$\text{Damping plate diameter} = 20\text{ m}$$

$$\text{Damping plate thickness} = 0.475\text{m}$$

$$\text{Damping ratio}, \xi = 0.8\% \text{ (From experimental data)}$$

$$\text{Total mass of spar } m_s = 3237081.12\text{kg}$$

$$\text{Added mass of spar } m_a = (2/3)\pi.r^3.\rho_w = 2145666.667\text{ kg}$$

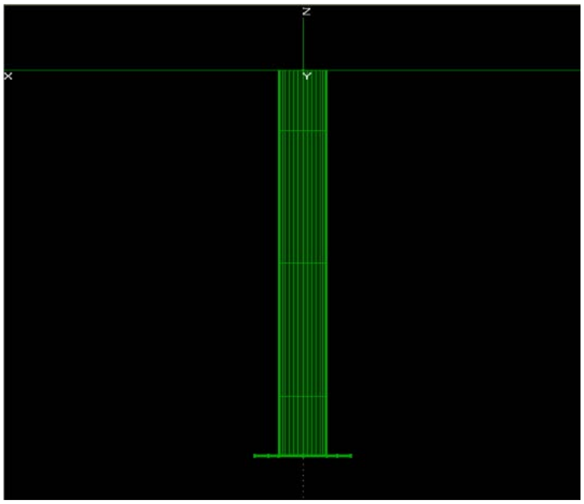

Fig. 7: Multisurf Model

Table 5: Response amplitude operator

Factors	T_0 (sec)	RAO
Pitch	11	0.00794 radian
Heave	14	0.55 m/m

Table 6: Taut mooring system

Variables	Values
Number of mooring lines	3
Angle between lines	120°
Depth of anchors from sea level	200 m
Depth to fairleads below sea level	50 m
Mooring line diameter	0.08 m
Radius to anchors from platform centreline	853 m
Radius to fairleads from platform centreline	5.2 m
Stretched mooring line length (L_0)	861 m
Line pretension (T)	15.70 MN
Youngs modulus (E)	2×10 N/m²

$$\text{Total mass, } m = m_s + m_a$$

$$\text{Heave restoring coefficient } K = \rho_w.g.A_w = 788532.5\,\text{N/m}$$

$$\text{Heave natural period } T = 2\pi\sqrt{\frac{m}{k}} = 16.4\text{ sec}$$

$$\text{Heave damping coefficient } C = 2.\xi.\sqrt{K.m} = 32963.38\text{ N-sec/m}$$

Maximum roll angle = 0.00794 radian

Wave period = 11 sec

Pitch angle <10° (for maximum wave amplitude), so, design requirement is satisfied.

Stability check based on wind force:

$$\text{Moment due to wind force, } M_{env} = F_{env}(KF - KP)$$

Where:

KF = Distance from keel to the centre of action of environmental force

KP = Distance from keel to the mooring line connecting point with the spar

$$\text{Restoring moment, } K_{pitch} = GM.\theta$$

$$\theta_{env} = M_{env}/K_{pitch}$$

θ_{env} Should be kept below 10° for wind turbine normal operational condition:

Maximum wind speed = 11m/sec

Wind force = $0.6.\rho.V^2$; Project area = 1.128 MN

KF = 193.7 m

KP = 50 m (Mooring point)

$$M_{env} = 162.188\text{ MN-m}$$

Restoring moment = 1672.16 MN-m

$$\theta_{env} = 5\times56>10$$

With mooring system: Due to the water depth of the considered site, the most suitable mooring system is the Taut mooring system. The mooring line of a taut mooring arrive typically at an angle to the seabed with the anchor point capable of resisting horizontal and vertical forces. The restoring forces are mainly generated by the elasticity of the mooring line (Table 7).

The mooring system is included in the hydrodynamic simulations; therefore, the RAOs in surge, heave and pitch are used to measure (Fig. 8-12):

$$\text{Surge stiffness } K_{surge} = \frac{T}{L_0} = 18234\times6\,\text{N/m}$$

$$\text{Heave stiffness } K_{Heave} = \frac{E.A}{L_0} = 1165931.77\text{ N/m}$$

$$\text{Pitch stiffness } K_{Pitch} = K_{P_{Hydro}} + K_{P_{Leg}}$$

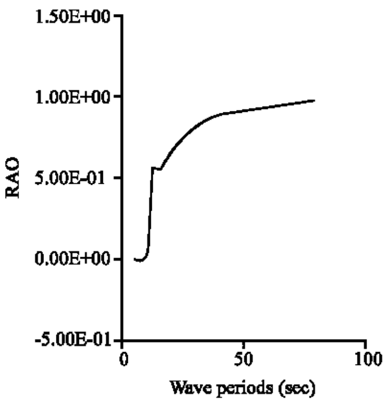

Fig. 8: Heave RAO vs. wave periods (Free floating condition) (series 1)

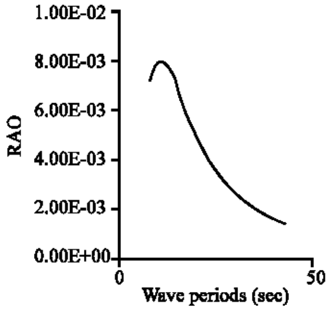

Fig. 9: Pitch RAO vs. wave periods (Free floating condition) (series 1)

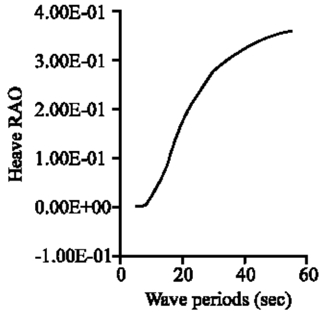

Fig. 10: Heave RAO, taut mooring system

Table 7: Response amplitude operator (Mooring condition)

Factors	T_0 (sec)	RAO
Surge	21	9.53×10^{-9}
Heave	9	1.80×10^{-2}
Pitch	9	1.94×10^{-11}

Hydrostatic pitch stiffness,

$$K_{P_{Hydro}} = \rho.g.KB - m.g.Kg + \rho.g.I$$

Where:

I = Area moment of inertia

m = Total mass

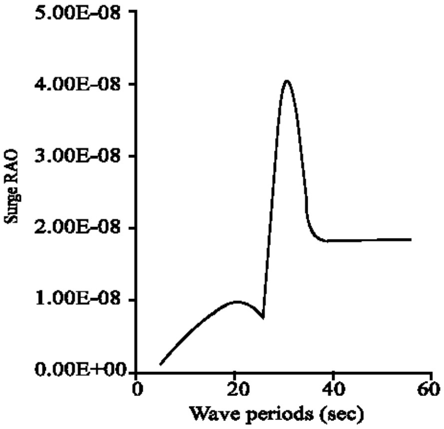

Fig. 11: Surge RAO with mooring system (series 1)

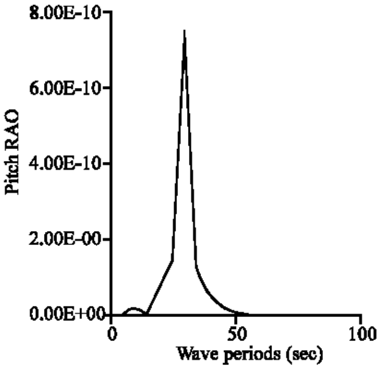

Fig. 12: Pitch RAO with mooring system (series 1)

$$\text{Tension leg stiffness, } K_{P_{Leg}} \frac{T}{L_0}(KG + L_0)KG$$

$$K_{Pitch} = 34.98\times10^{8}\,N/m$$

CONCLUSION

This thesis discusses the preliminary design of a floating support structure for the DOWEC 6 MW wind turbine MW offshore wind turbine. It focuses on the methodology adopted to design the support structure and its mooring system. The structural scantling design had been done as per API RP 2A.The strength of the structure has been investigated with FEA simulations using ANSYS. The hydrodynamic behaviour of spar is studied using WAMIT under various conditions.

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