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STATIC AND DYNAMIC ANALYSIS OF SEMI-SUBMERSIBLE TYPE FLOATERS FOR OFFSHORE WIND TURBINE

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ABSTRACT

The wind potential in offshore site faster and steadier than on land and makes lesser wear on the turbine components besides generating more electricity per turbine. Wind energy is a reliable source of sustainable power generation and has been an active area of research globally to economically harness the energy for human use. Such a consistent source of wind energy pushed the engineers to install wind turbines near the coasts. As more farms came on the shore, the coastal community perceived as an eyesore and nuisance which raised the demand of installing the wind turbine further offshore. In shallow water, fixed structures like tripods, jackets, and truss-type towers, monopiles and gravity base are functionally and economically feasible for depths up to 100 m. In deep waters, a floating substructure can be more economical for offshore wind turbine. The floating structures can also be deployed in shallow water depth regions for its inherit advantages like construction and installation, mobility, maintenance etc.Different floating options like TLP's, SPAR, Semi-submersibles, barges besides new floating structural configurations are being actively analyzed. In this study a semi-submersible type floater of different aspect ratios is investigated for its performance under wave and wind loading.

Keywords: *offshore wind energy; floating offshore wind turbines; static stability; hydrodynamic analysis; semi-submersible floater, spectrum, response amplitude operator.*

1. INTRODUCTION

As the offshore wind posses less turbulence, low wind shear, vast area availability and high wind speed within a shorter distance from shore, offshore wind energy has been the focus of many of the engineers and researchers these days. The support structure for the offshore wind turbine can be fixed or floating. The floating structures can also be deployed in shallow water depth regions for its inherent advantages like construction and installation, mobility and maintenance. As the interest worldwide is in the development of offshore wind farms, different floating option like TLP's, SPAR, Semi-submersibles, barges besides new floating structural configurations are being actively analyzed. The performance of the semi-submersible floater under wave and wind loading for supporting a 5-MW offshore wind turbine is undertaken.

2. BACKROUND

Several types of floating supporting structures for offshore wind turbine have been investigated by different researchers around the world. Bulder et al. (2002) presented the technical and economical feasibility of floating wind energy system in the depth range of 50m. Based on the cost analysis he concluded that the Tri- floater concept was technically and economically feasible option. Musial et al. (2004) addressed the different types of floating platforms for offshore wind turbine. They made the cost comparison analysis for Tri-floater and TLP. Based on the comparison study, it was concluded that cost of TLP is lesser than the Tri-floater concept. Lee (2005) examined two floater concepts namely, a three legged tension-leg platform and a four legged taut-moored system, for floating wind turbine systems of 1.5MW capacity for their performance in wind and wave. Tempel (2006) focused on the design basis of supporting structure for 2.0MW offshore wind turbine. A monopile supporting structure was the focus of his study, the methodology of aerodynamic load calculation on wind turbine and total system response analysis in the frequency domain method were presented. Wayman (2006) studied the three different types of floating supporting structures; shallow drafted barge (cylinder), TLP (surface) and TLP (submerged). It was concluded that the barge has lowest cost of construction among the others, but TLP submerged supporting structure exhibited least response in all conditions.Tracy (2007) carried out a parametric study on concrete ballasted cylinder with different combinations of draft and mooring systems. The aim of the work is to study the performance of the semi-submersible floaters with different aspect ratios to support a 5 MW NREL offshore wind turbine in 100m water depth for different sea-states in Indian coastal waters under wind and wave loading. The schematic view of the semi-submersible floater with wind turbine is shown in Figure 1.

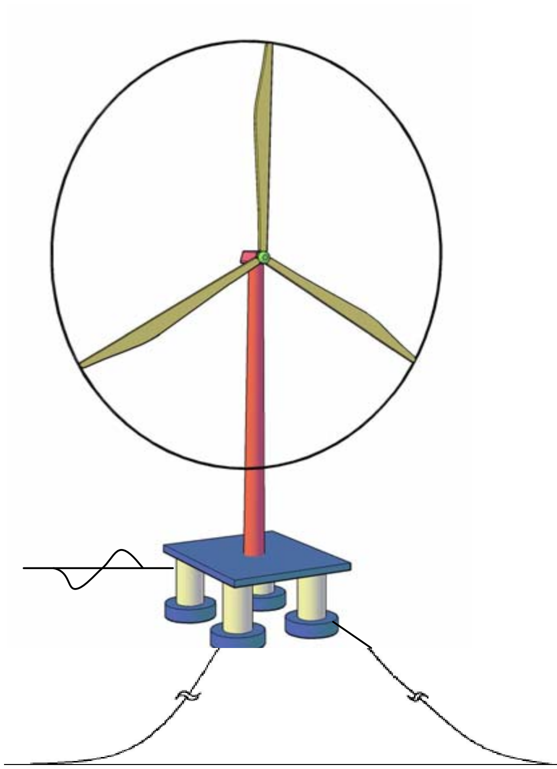


Figure 1. Schematic view of the semi-submersible type floater

3. DETAILS OF THE NREL 5 MW WIND TURBINE MODEL

The wind turbine used in this study is the National Renewable Energy Laboratory (NREL), USA, 5-MW offshore baseline wind turbine model. This model does not correspond to an operating turbine, but it is a realistic representation of a three-bladed upwind 5-MW wind turbine; its properties are drawn and extrapolated from operating machines and conceptual studies. NREL suggested a 5 MW wind turbine or higher for offshore (Jonkman, 2009). It is variable speed, upwind rotor orientation model with a rotor of 126 m diameter at a hub height of 90 m and mass of the turbine is 697.46 t.

4. STATIC STABILITY OF FLOATERS

The hydrostatic calculation is initially carried out to determine the optimal size and shape of the semi-submersible floater that will provide sufficient stability in unmoored operating conditions. The parameters that have been considered for the static stability analysis are adequate restoring in pitch motion to limit pitch angle to 10 degrees beyond which the wind turbine loses substantial efficiency, fixed metacentric height (GM) of 1.0m. The system should be stable within the standard threshold value of heel angle and also must maintain an acceptable steady-state heel angle (less than 10 degree) in maximum static wind loading conditions (Wayman and Sclavounos, 2007 and Tracy, 2007).

The static stability analysis was carried out for six different semi-submersible floaters, with a square deck and fixed GM of 1.0 m, of varying D/d ratio (i.e. ratio of the diameter of pontoon to the diameter of column) and h/H ratio (i.e. ratio of the height of column to height of pontoon). The D/d ratio is 1.0 for h/H ratio equal to 1.0 and D/d ratio is 1.5 for H/h ratio ranging from 2.0 to 5.0. The semi-submersible is designed with restoring moment greater than that of the design restoring moment given by Eq. (2). The detailed comparisons of hydrostatic and mass properties of the semi-submersible type floater are given in Table 1. The semi-submersible floater mass has been varied from 2285.32 t to 2405.52 t and the ballast from 3360 t to 4800 t for the different models considered in this study.

The static wind thrust is calculated based on the 1-D blade momentum theory, the disk is considered friction less and there is no rotational velocity component in the wake. The force in the stream wise direction resulting from the pressure drop over the rotor is the thrust, F_{Thrust} and is given by Eq.1.

$$F_{Thrust} = 2\rho C_T a(1-a)V_o^2 A \quad (1)$$

where V_o is the wind speed, A is rotor area; ρ is density of air; C_T is the coefficient of thrust; a is Axial inflow factor and is taken as 0.333 (Freris, 1990). The value of 'a' is considered for the condition at which the turbine generates more (max) power. The design restoring moment ($k_{55,\ Design}$) for the semi-submersible floater in pitch motion is given by Eq.2 (Freris, 1990, Manwell, 2002).

$$k_{44,Design} = F_B Z_B + \rho g I_T - M_S g Z_S \quad (2)$$

where F_B is the buoyant force; Z_B is the centre of buoyancy; $\boldsymbol{I_T}$ is transverse moment of inertia of the floater; M_S is the total mass and center of the gravity of the system; Z_S is the center of the gravity of system.

Table 1 Hydrostatic and mass properties of semi-submersible floaters

Details of semi-submersible floaters	Model 1	Model 2	Model 3
Breadth to length ratio (B/L)	1	1	1
Pontoon diameter to column diameter (D/d) ratio	1	1.5	1.5
Column height to pontoon height (h/H)	1	1	2
Pontoon diameter, D (m)	9.8	15.3	15.2
Pontoon height, H (m)	10.3	7.3	5.2
Column diameter,d (m)	9.8	10.2	10.1
Column height, h (m)	10.3	7.3	10.5
Free board (m)	6.5	6.5	6.5
Operating draft (m)	20.7	14.5	15.7
Displacement (t)	6343	7905	7359

Details of semi-submersible floaters	Model 4	Model 5	Model 6
Breadth to length ratio (B/L)	1	1	1
Pontoon diameter to column diameter (D/d) ratio	1.5	1.5	1.5
Column height to pontoon height (h/H)	3	4	5
Pontoon diameter,D(m)	14.9	14.8	14.6
Pontoon height, H (m)	4.3	3.5	3.5
Column diameter,d (m)	9.9	9.9	9.7
Column height, h (m)	12.8	14.0	15.0
Free board (m)	6.5	6.5	6.5
Operating draft (m)	17.0	17.5	18.0
Displacement (t)	7052	6890	6605

5. AERODYNAMIC LOAD ON ROTOR BLADES

The blade element momentum theory (BEM), based on momentum theory and blade element theory, is used to find the forces on the rotor blades. Momentum theory finds the forces at the blade based on the conservation of linear and angular momentum. Blade element theory determines forces at a section of the blade based on the function of blade geometry.

The combination of these two methods is used to analyse the blade elements and is called as strip theory or blade element momentum (BEM) theory. In this calculation the aerodynamic interactions between the strips are ignored (Freris, 1990, Manwell, 2002). The drag (F_D) and lift forces (F_L) for each section of the blade are given by Eq.3 and Eq.4.

$$F_D = 0.5 C_D(\alpha)\rho_{air} V_{rel}^2 b\Delta r \quad (3)$$

$$F_L = 0.5 C_L(\alpha)\rho_{air} V_{rel}^2 b\Delta r \quad (4)$$

where F_L is the aerodynamic lift force; F_D is the aerodynamic drag force; C_L is the aerodynamic lift coefficient; C_D is the aerodynamic drag coefficient b is the airfoil cord length ; α is the angle of attack ; V_{rel} is the relative velocity and Δr is the radial length of blade sections. The axial force on the rotor axis is combination of lift and drag forces as given in Eq.5.

$$F_x = F_L \cos\phi + F_D \sin\phi \quad (5)$$

where F_L is the aerodynamic lift force; F_D is the aerodynamic drag force; ϕ is the angle of inflow.

6. WAVE ENVIRONMENT IN INDIAN COASTAL WATERS

The wave parameters, frequency of the spectral peak (ω_p) and significant wave height (H_s) of the Indian Ocean environment (east and west directions) are referred from the literature published (Sannasiraj, 2007). Three types of sea states are considered for the analysis namely moderate, rough and very rough based on the magnitudes of H_s as 1.67m (sea state-4), 3.22m (sea state-5) and 5.30m (sea state-6). The corresponding peak frequency associated with these sea states are 0.914 rad/s, 0.688rad/s and 0.60rad/s respectively. In the present study, P-M spectrum has been used for the sea state representation. The spectral density for fully developed seas represented by P-M spectrum is given by (Chakrabarti, 1987):

$$S(\omega) = \alpha g^2 \omega^{-5} \exp[-1.25(\frac{\omega}{\omega_0})^{-4}] \qquad (6)$$

where $S(\omega)$ is the wave spectral ordinate; $\alpha = \frac{5 H_s^2 \omega_0^4}{16 g^2}$, H_S is significant wave height, ω_0 is the peak frequency and g is the acceleration due to gravity. For wind environment, power-law is used to represent the mean wind speed variation.There are many mathematical wind spectrum models are available to represent the turbulence. In offshore context, the effect of lower frequency components of longitudinal velocity fluctuations is important (Manwell, 2002). In our present study Harris wind spectrum is considered for the analysis. The mathematical form of the Harris wind spectrum is given by (simiu and scanlan, 1996 and Manwell, 2002).

$$\frac{nS(f)}{u_*^2} = 4 \frac{\Lambda}{(2+\Lambda^2)^{\frac{5}{6}}} ; \qquad \Lambda = \frac{1800 f}{\bar{U}_{10}} \qquad (7)$$

where $S(f)$ is the spectral ordinate at frequency f; u_*^2 is the shear velocity or frictional velocity of flow field.

7. HYDRODYNAMIC ANALYSIS USING WAMIT

WAMIT (Wave Analysis MIT) uses three-dimensional boundary integral equation method (BIEM), to solve the linearized hydrodynamic radiation and diffraction problems for the interaction of surface waves with stationary (zero forward speed) floating structures in the frequency domain. The hydrodynamic analysis of the floaters are carried out using WAMIT for three different wave directions namely 0°, 45° and 90°. The water depth considered is 100m and the analysis is carried for wave periods ranging from 2 s to 32 s. It is necessary to introduce external damping as suggested by Chakrabarti et al. (2007) in the diffraction analysis to get reasonable estimates of RAO's in the regions of interest. A reasonable damping ratio of 4% in heave and 5% in pitch were considered in the WAMIT analysis for this floater. The panelized view of the semi-submersible floater is shown in Figure 2. The comparison of the RAO for 0º wave heading angle is shown in Figure 3.

Figure 2 Multisurf model of semi-submersible floater

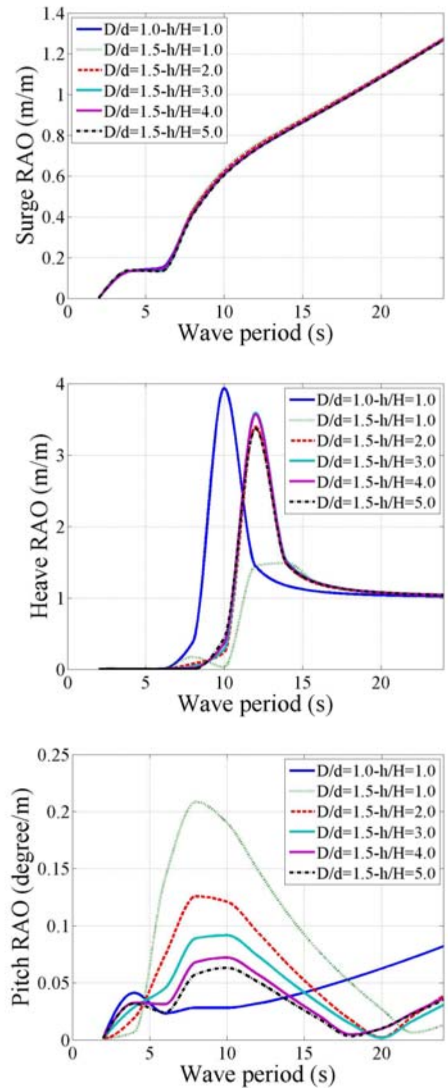


Figure 3 RAO comparison of semi-submersible with different aspect ratios for 0° wave heading angle

8. LOAD CONDITIONS FOR THE RESPONSE ANALYSIS

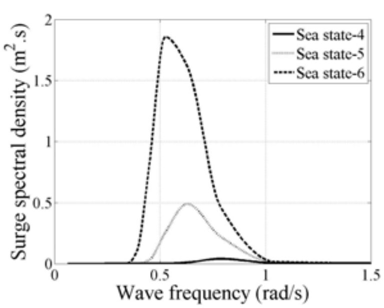
The correlation between inflow wind field and the sea state is not considered in this study. The wave and wind events are considered as independent events for the analysis.

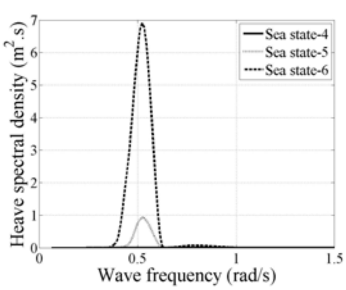
8.1 Case (I) Response Analysis of Floater with Wave Only

This condition may exist in case of pre-installation stage of the offshore wind turbine. The maximum significant height of surge response is 2.91m, the maximum significant height of heave response is 3.63m and occurred for sea state-6 of 0º wave heading. The significant height of pitch response is less than 1º for all the sea states. The response statics of the semi-submersible floater listed in Table 2 and the response spectrum obtained are shown in Figure 4 for case I for a wave heading angle of 0º.

Table 2 Response statistics for Case I

Sea states	Modes	Standard deviation	H_{rms}	H_s
Sea state-4 0^0 heading	Surge(m)	0.108	0.306	0.432
	Heave(m)	0.037	0.104	0.147
	Pitch(deg)	0.008	0.023	0.032
Sea state-5 0^0 heading	Surge(m)	0.369	1.044	1.476
	Heave(m)	0.312	0.883	1.249
	Pitch(deg)	0.019	0.054	0.076
Sea state-6 0^0 heading	Surge(m)	0.728	2.058	2.910
	Heave(m)	0.906	2.563	3.624
	Pitch(deg)	0.031	0.086	0.122





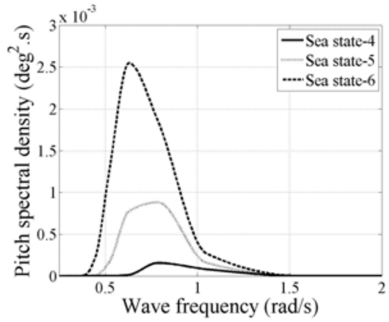


Figure 4 Response spectrums of semi-submersible floater for different sea states - Case I

8.2 Case (II) Response Analysis of Floater with Wind and Wave

The maximum significant height of surge response is 5.72 m for sea state-6 of 0° wave heading angle. The maximum significant height of heave response is 3.63m and occurred for sea state-6 of 0° and 45° wave heading angles. The maximum significant height of pitch response is 2.2° occurred for all the sea states as the system response is wind dominated one. The wind load is constant for all the sea states since the operating wind speed is considered for the determination of aerodynamic forces and moments. But the wave load will vary according to the sea state and the angle of attack. The response statics of the semi-submersible floater listed in Table 3 and the response spectrum obtained are shown in Figure 5 for case II for a wave heading angle of 0º

Table 3 Response statistics for Case II

Sea states	Modes	Standard deviation	H_{rms}	H_s
Sea state- 4 0^0 heading	Surge(m)	1.234	3.491	4.937
	Heave(m)	0.037	0.104	0.147
	Pitch(deg	0.435	1.230	1.739
Sea state- 5 0^0 heading	Surge(m)	1.284	3.631	5.135
	Heave(m)	0.312	0.883	1.249
	Pitch(deg	0.435	1.231	1.741
Sea state- 6 0^0 heading	Surge(m)	1.429	4.041	5.715
	Heave(m)	0.906	2.563	3.624
	Pitch(deg	0.436	1.233	1.743

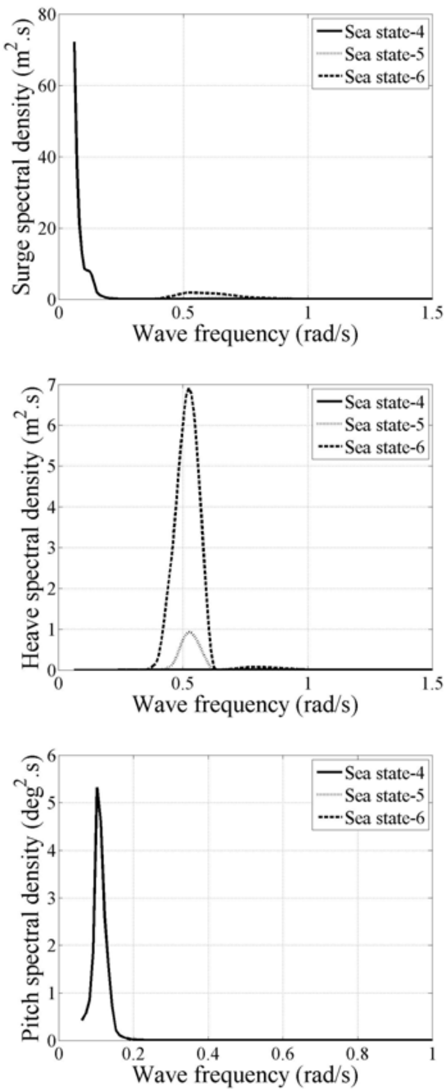


Figure 5 Response spectrums of semi-submersible floater for different sea states- case II

9. CONCLUSION

Static stability, dynamic and response analyses are carried out to find out the behavior of semi-submersible floater in three different seas states. All these floaters were designed with transverse metacentric (GM) height equal to 1.0. Hydrodynamic analysis was carried out using WAMIT, for different semi-submersible type floaters with D/d aspect ratio ranging from 1.0 to 1.5 and h/H aspect ratio ranging from 1.0 to 5.0. The semi-submersible floater with D/d=1.5 and h/H=1.0 yielded minimum RAO in heave and semi-submersible floaters with D/d=1.0 and h/H=1.0 and D/d=1.5 and h/H=5.0 yielded minimum RAO in pitch for the range of wave period excitations between 5 sec and 20 sec. The response analysis is carried out in frequency domain and response statistics are compared for three different sea states.

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