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Hydrodynamic Analysis of Deep Drafted Column Structured (DDCS) Floater for an Offshore Wind Turbine

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Abstract

Power generation from offshore wind turbines is widely seen as a main source of sustainable energy supply in coming decades. As wind speed increases rapidly with distance from the coast, potential sites for extracting the offshore wind energy for the use of coastal community exist in many places. 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 60 m. In deep waters, a floating substructure is found to be more economical than a bottom fixed structures. The present study focuses on hydrodynamic behavior of Deep Drafted Column Structured (DDCS) type floater with different aspect ratios for its suitability to support an offshore wind turbine. The responses are obtained in the frequency domain for two cases in three different sea states: the complete system under wave loading only and the complete system under wave and wind loading.

Keywords: *wind turbines, DDCS, hydrodynamic, wind energy, water depth*

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INTRODUCTION

Wind energy grows abundantly in most places and methods to economically harness it to the benefit of mankind are an active area of research worldwide. Perennial and reliable source of wind energy pushed the engineers to install wind turbines near the coasts in shallow waters as well as offshore in deeper waters. Depending on the site where the wind turbine has to be located various support structure concepts exist. Tripods, jackets, and truss-type towers, monopiles and gravity base serve as substructures. Floating structures are currently being considered as support structures for offshore wind turbines in areas where deeper water demands are likely to result in more expensive bottom mounted systems. The conventional floating structure options from oil and gas field like TLP's, SPAR, semi-submersibles, barges are modified and deployed for wind turbine support structures. So globally, active research is being done to find new feasible floating options to support offshore wind turbines.

The floating structures can also be used in shallow water depth regions for its inherent advantages like construction and installation, mobility, maintenance etc. A schematic view of Deep Drafted Column Structured (DDCS) floater with four columns supporting a circular deck on top of which the offshore wind turbine is mounted is shown in Fig. 1. The hydrodynamic performance of the DDCS floater for supporting a 5-MW wind turbine under wind and wave loading is undertaken.

BACKROUND

Numerous studies have been under taken to investigate different types of shallow water sub-structures for offshore wind turbines. The different floater concepts and the applicability of the offshore wind turbine sub-structures are discussed in detail by Musial and Butterfield [1] and Bulder *et al* [2]. Bulder *et al*. [2] presented the technical and economical feasibility of floating wind energy systems in the depth range of 50m. Henderson *et al*. [3] discussed the advantages of the offshore wind turbine and Multiple Unit Floating Offshore Wind Farm (MUFOW). Different design concepts of the floating offshore wind turbine - Cylindrical floater, cylindrical floater with tension leg, inverted spar, Tri-floater, quadruple floater, Jack-up were compared. Musial *et al*. [4] addressed the different types of floating platforms for offshore wind turbine, which are classified based on the [multiple or single] floaters and mooring systems like catenary or taut-leg. Butterfield *et al.* [5] discussed the desirable features of a floating wind turbine platform. Different floating options for shallow water (5 m to 30 m), transition waters (30m to 60m) and deep waters (60 m to 160 m) are well described by Musial *et al* [4]. The fully coupled tension leg spar buoy has been examined for a 1.5 MW offshore wind turbine by Whitee [6]. Further, Lee [7] examined two floater concepts namely a three legged tension-leg platform and a four legged taut-moored system for 1.5 MW wind turbine.

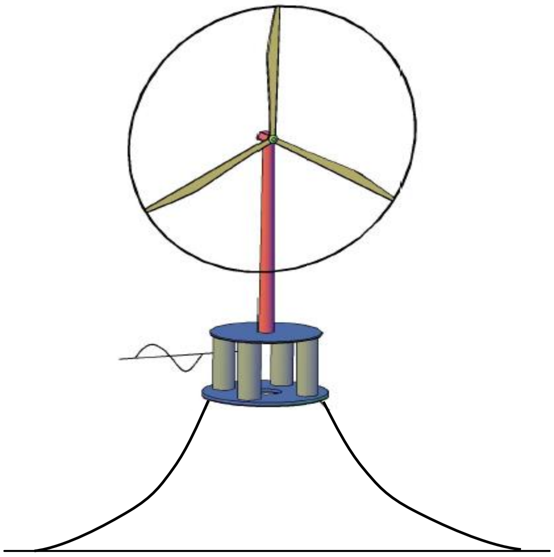


Fig. 1: *Schematic View of DDCS Floater with Wind Turbine.*

The semisubmersible type floater with tension moorings for 5 MW NREL wind turbine in a water depth of 61 m is analysed by Fulton *et al*. [8]. Wayman [9] studied the dynamic behaviour of three different types floaters namely, shallow drafted barge (cylinder), TLP (surface) and TLP (submerged) under wind and wave loading. Tracy [10] carried out a parametric study for the design of floating wind turbines for four types of floaters namely TLP with deep drafted cylinder, TLP with shallow drafted cylinder, deep drafted and shallow drafted concrete ballasted cylinder with slack mooring for supporting the NREL base line 5 MW wind.

The design basis, analysis and hydrodynamic behaviour of a three legged floating structure (wind float) with taut mooring system for a water depth of 150 m for 5 MW offshore wind turbine are studied by Roddier *et al.* [11] and Cermelli *et al.* [12]. As installing a higher rated capacity offshore wind turbine is advantageous and potential offshore wind farming sites exist in the Indian subcontinent, the present paper details the numerical study undertaken to investigate the hydrodynamic performance of DDCS type floaters with different aspect ratios supporting a 5 MW NREL offshore wind turbine in 100 m water depth for different sea-states in Indian coastal waters under wind and wave loading.

Deep Drafted Column Structred Floaters (DDCS):

Deep drafted column structured floater is unconventional floater configuration as shown in Figure 2. DDCS floater achieves stability through the combination of buoyancy and ballasting. It consists of four columns supporting a circular deck on top of which the wind turbine is mounted and a circular pontoon at the base. Circular opening (like moonpool) is provided at the center of the circular pontoon base to increase the damping of the system and reduce the wave force, as well. It has the characteristics of both the spar and semisubmersible. The air gap provided is according to the recommendations of API RP 2A [13] which is 1.5 m plus half of the maximum wave height. The free board is fixed as 6.5 m. The static stability and dynamic analysis was carried out for six DDCS floaters with fixed metacentric height (GM) of 1.0 m, of varying D/d ratio (i.e. ratio of the diameter of pontoon (D) to the diameter of column (d)) and h/H ratio (i.e. ratio of the height of column (h) to height of pontoon (H)).

Wind Turbine Model

The wind turbine model 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. 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 [14]

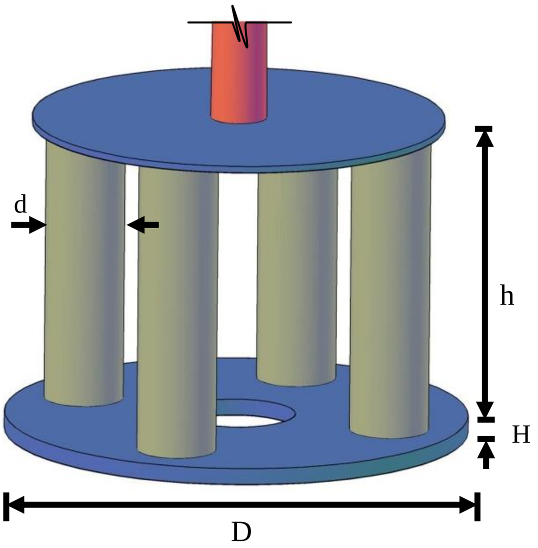


Fig. 2: *DDCS Floater.*

Static Stability of Floaters

The hydrostatic calculations have been performed to determine the optimal size and shape of the DDCS 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 and fixed metacentric height (GM) of 1.0 m. 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 [9, 10].

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 [15].

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

Where V_0 is the wind speed; A is rotor area; ρ is density of air; a is axial inflow factor and taken as 1/3. The value of 'a' is considered for the condition at which the turbine generates maximum power [16]. The design restoring moment (k_{55}, Design) for the DDCS floater in pitch motion is given by Eq.2 [15, 16].

$$k_{55,Design} = F_B Z_B + \rho g I_T - M_S g Z_S \qquad (2)$$

Where F_B is the buoyant force; Z_B is the centre of buoyancy; I_T is the transverse moment of inertia of the water plane; M_S is the total system mass; Z_S is the center of the gravity of system. The DDCS floater is designed to have higher design restoring moment see Eq. 2, than the pitch moment or heel moment which is obtained by multiplying F_{Thrust} by the lever arm (height of the hub from the base of the tower).

The static stability analysis is carried out for six DDCS floaters with circular 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 varied from 5.0 to 7.0 and h/H ratio is varied from 10 to 40. Hence, totally twelve configurations arrived and out of which six only considered for the further analysis. The variation of structural weight of the DDCS floater is 1874 t to 2208 t and the ballast is varied from 3050 t to 4720 t to achieve the stability. The comparisons of hydrostatic and mass properties of DDCS floaters are given in Table 1.

Table 1: *Mass and Hydrostatic Properties of DDCS Floaters.*

Description of items	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Pontoon diameter to column diameter (D/d) ratio	5	6	6	6	7	7
Pontoon height to Column height (h/H) ratio	10	10	30	40	10	30
Pontoon diameter, D (m)	49.75	56.14	48.14	50.66	65.11	59.31
Pontoon height , H(m)	1.41	1.38	0.76	0.51	1.27	0.63
Column diameter, d (m)	9.95	9.36	8.03	8.45	9.30	8.47
Column height, h (m)	14.09	13.82	22.74	20.49	12.73	18.78
Diameter of moonpool (m)	12.44	14.04	12.04	12.67	16.28	14.83
Diameter of deck (m)	32.56	34.76	34.05	33.28	35.35	34.26
Length between columns(C/C) (m)	22.61	25.40	26.02	24.83	26.04	25.79
Free board (m)	6.50	6.50	6.50	6.50	6.50	6.50
Operating draft(m)	15.50	15.20	23.50	21.00	14.00	19.40
DDCS floater mass (t)	1874	2135	2049	1957	2208	2074
Ballast (t)	4552	4355	3300	3050	4720	3240
Total mass(t)	7123	7188	6047	5705	7625	6012
Heave natural period (s)	20.76	25.72	24.80	24.50	31.24	30.05
Pitch natural period (s)	63.96	73.60	73.93	78.32	89.23	90.41

Aerodynamic Load on Wind Turbine

The aerodynamic load on the wind turbine is calculated using the blade element momentum theory (BEM), based on blade momentum theory and blade element theory and is also called as strip theory. In this calculation the aerodynamic interactions between the strips are ignored [15]. The wind speed and the rotor speed used in this study are 11.4 m/s and 12.1rpm respectively. 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 normal 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. The total axial force on the wind rotor blades which consist of 17 sections:

$$F_{x,Total} = N_{blades} \sum_{i=1}^{17} F_x \qquad (6)$$

Where N_{blades} is number of blades.

WAVE AND WIND ENVIRONMENT

The wave environment is described by P-M spectrum. The spectral density for fully developed seas represented by P-M spectrum is given by [17]:

$$S(\omega) = \frac{5H_s^{\,2}\omega_0^{\,4}}{16}\omega^{-5}\exp[-1.25(\frac{\omega}{\omega_0})^{-4}] \qquad (7)$$

Where $S(\omega)$ is the wave spectral ordinate; H_S is significant wave height, ω_0 is the peak frequency and g is the acceleration due to gravity. Three types of sea states are considered for the analysis namely moderate, rough and very rough based on the magnitudes of H_s as 1.67 m (sea state-4), 3.22 m (sea state-5) and 5.30 m (sea state-6) and the corresponding peak frequency associated with these sea states are 0.914 rad/s (6.87 s), 0.688 rad/s (9.13 s) and 0.60 rad/s (10.47 s) respectively. These sea states correspond to the west coast of India [18].

For wind environment, the mean wind speed variation is represented by Power-law. The turbulence can also be represented in a spectral form and the random wind field is modeled in this paper by the Harris wind spectrum. There are many mathematical wind spectrum models are available to describe the turbulence. The spatial variation of turbulence is not considered in this study. The effect of lower frequency components of longitudinal velocity fluctuations is important in the offshore [15]. The mathematical form of the Harris wind spectrum is given by [15, 19].

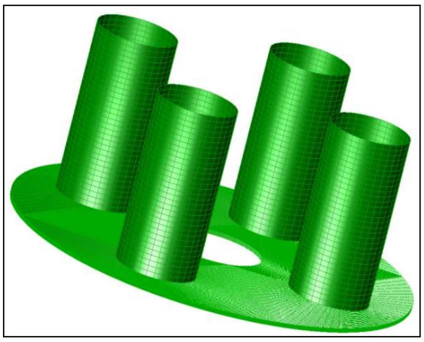
$$\frac{nS(f)}{u_*^2} = 4\frac{\Lambda}{(2+\Lambda^2)^{\frac{5}{6}}}\ ; \qquad \Lambda = \frac{1800f}{\bar{U}_{10}} \qquad (8)$$

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

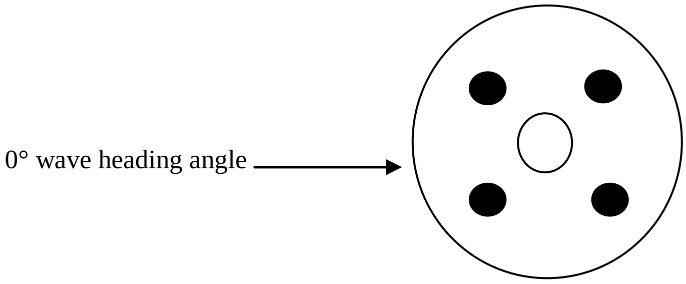
HYDRODYNAMIC ANALYSIS OF FLOATERS

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 main program consist of two top-level sub-programs POTENT and FORCE, which evaluates the velocity potential and desired hydrodynamic parameters, respectively. The POTENT sub program finds the velocity potential on the body surface for specified modes, wave period and wave heading angles. Where as the FORCE sub-program find the velocities and pressure on the body surface, and then the hydrodynamic quantities such as added mass and damping coefficients, Motion of body in terms of RAO, Exciting force from Haskind relation and diffraction potential etc. are evaluated and these forms the output. Typical application of WAMIT program consists of preparing appropriate input files, running the WAMIT and finally processing the WAMIT output. Typical input files includes the geometric data file consisting of the geometry of the body represented, the dimensional length characterising the body dimension or the length used to non-dimensionalize the output quantities from WAMIT, acceleration due to gravity, symmetric plane, number of patches etc. WAMIT does not include viscous damping effect and need to introduce an external damping in the program to get reasonable results. Usually viscous damping values are obtained from free decay test. In this study, estimates of viscous damping values to be used in the WAMIT analysis are obtained based on literature [20]. For the DDCS a reasonable damping ratio of 7% in heave and 4% pitch are used as external damping in the WAMIT analysis. The panelized view of the DDCS floater is shown in Figure 3. (a) and the wave heading angle considered for analysis is depicted in Figure 3 (b).

The hydrodynamic analysis of the floaters with wind turbine as static mass is carried out using WAMIT for 0° wave direction. The design water depth is 100m and wave periods ranging from 2 s to 24 s. The variation of surge/sway RAO of the DDCS with different D/d and h/H ratios for 0° wave heading angle follow a similar trend except the floater with D/d =6 and h/H =40 has higher response than the other floaters. The heave RAO is maximum for the model with D/d =6 and h/H =40 and lowest for the model with D/d=6 and h/H =30 for wave



(a)



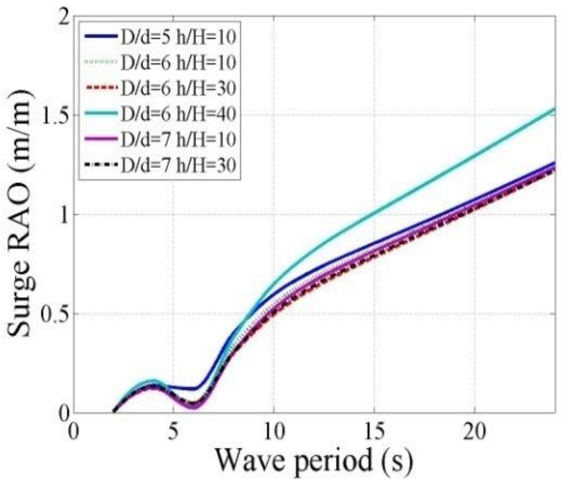
(b)

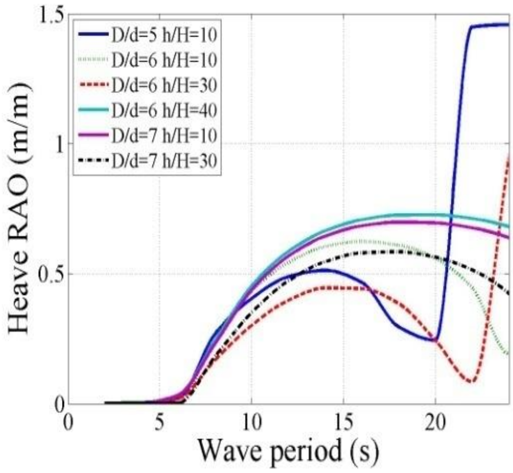
Fig. 3: *(a) Multisurf Model of DDCS Floater and (b) Wave Heading Angle.*

Periods below 20 s. The floater with D/d =6 and h/H =30 has lowest pitch response than the other floaters in this category. Amongst the six different models the one with D/d =6 and h/H=30 is chosen as the best model based on its lowest heave and pitch responses. The comparison of the RAO for 0º wave heading angle is shown in Figure 4.The heave and the pitch natural period of the chosen floater are 25 s and 74 s and both are higher than the wave period range.

Load Conditions for the Response Analysis

Many of the offshore oil and gas industries use the linear frequency domain analysis and hence the floating wind turbine system can also be analysed using linear frequency domain analysis [9]. The interaction of the wind turbine (with control systems) with the floater is incorporated in the equation of motion (in frequency domain) by considering the appropriate damping and restoring properties of the 5 MW NREL wind turbine. The mass properties of the 5 MW NREL wind turbine are referred from the available





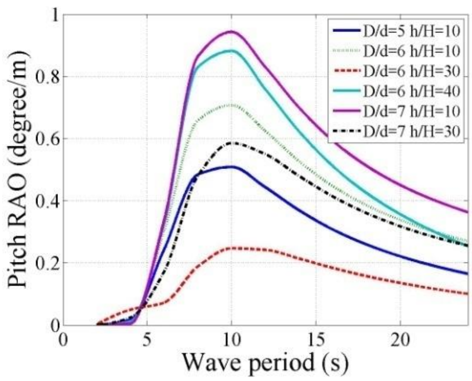


Fig. 4: *RAO Comparisons of DDCS Floaters with Different Aspect Ratios for 0° Wave Heading Angle.*

Literature. Tracy [10] used FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code to generate the mass matrix, damping matrix and restoring matrix by considering flexible deformation modes of the 5MWwind turbine for maximum thrust operating point correspond to a wind speed of 11.4 m/s. The floater is connected to the sea bed through the slack (catenary) mooring system and it is assumed that the slack mooring is provided only for station keeping. Hence the mooring system interaction is not included in this study. The environment correlation between the waves and the wind is not considered in this study. The wave and wind events are considered as independent events for the analysis. The complete load analysis of the whole system including waves, wind and the wind turbine interaction is shown below:

Case (I): The Complete System with Wave Loading Only:
Responses of the floaters under wave loading only for three different sea states {See Figure 5 Flowchart link (A)}

Case (II): The Complete System with Wave and Wind Loading
Responses of the floaters including the interaction effects of wind turbine under wave and wind loading for three different sea states **{See** Figure 5 Flowchart link (A) + (B) +(C)**}**

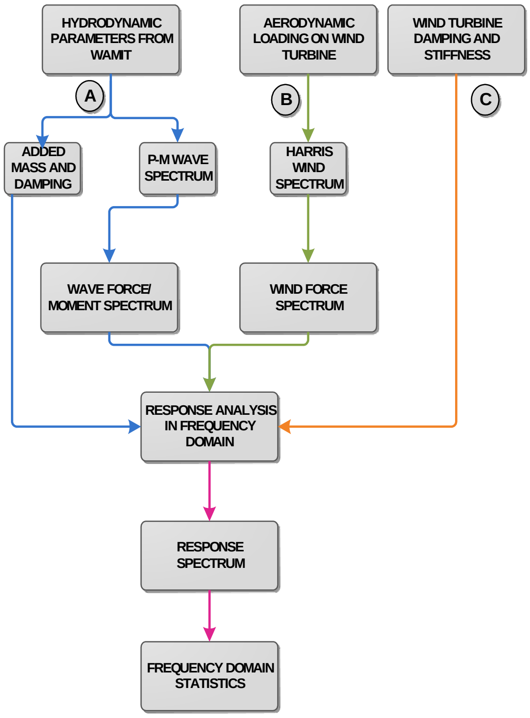


Fig. 5: *Flow Chart of Load Analysis.*

Case (I): The Complete System With Wave Loading Only:

The governing equation of motion of the response analysis includes only wave loading is given Eq. 9.

$$[-(M_{added}(\omega)+M_{floater}+M_{WT})]\omega^2\bar{X}(\omega)+B_{floater}(\omega)i\omega\bar{X}(\omega) + C_{floater}\,\bar{X}(\omega)=\bar{F}_{wave}(\omega) \quad (9)$$

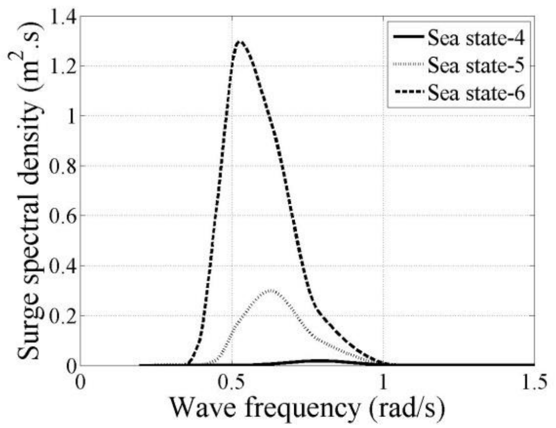
where $M_{floater}$, $M_{added}(\omega)$ and M_{WT} are the mass & added mass matrices of the floater and mass of wind turbine, $B_{floater}(\omega)$ is the damping matrices of the floater, $C_{floater}$ is the stiffness matrices of the floater, $\bar{F}_{wave}(\omega)$ is the wave excitation force vector, $\vec{X}(\omega)$ is the Fourier transform of the response vector $x(t)$. The response spectrum is shown in Fig. 6 for 0° wave heading angle for three sea states. The response increases for higher sea states as expected and the pitch response are small as the pitch natural frequency is far higher than the spectral peak of the excitation force. From the response spectrums the response statistics namely significant response, H_s $(=4\sqrt{m_0}$, where m_0 is the area under the spectral density curve) and root mean square response, H_{rms} (= $2\sqrt{2m_0}$) are obtained and these are listed in Table 2. The maximum significant surge response is 2.3 m and occurred at sea state-6 of 0° wave heading angle. The maximum significant heave response is 1.4 m and occurred at sea state-6 and the significant pitch response is less than 1° degree for all the sea states.

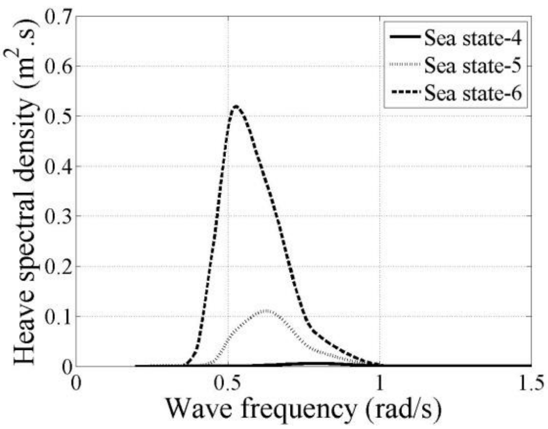
Case (II): The Complete System with Wave and Wind Loading:

The governing equation of motion of the response analysis including wave and wind loading is given Eq. 10.

$$[-(M_{added}(\omega)+M_{floater}+M_{WT})]\omega^2\bar{X}(\omega)+[B_{floater}(\omega) +B_{WT}]i\omega\bar{X}(\omega)+[C_{floater}+C_{WT}]\bar{X}(\omega)=\bar{F}_{wave}(\omega)+\bar{F}_{wind}(\omega) \quad (10)$$

Where $\bar{F}_{wind}(\omega)$ is the wind excitation force vector. The time series of wind forces, $F_{x,\ Total}$ (see Eq. 6) and moments can be generated using the wind spectrum and the aerodynamic properties of the wind turbine using the Blade Element Momentum Theory as discussed previously. From these time series via Fourier Transform, the force spectrum and moment spectrum are obtained. The response spectrum is shown in Fig. 7 for 0° wave heading angle for three different sea states. The response increases for higher sea states as expected. By comparing Figure 6 and Figure 7 the role of the wind excitation is seen in the surge as well as the pitch responses. From the response spectrums the response statistics namely significant response, Hs and root mean square response, H_{rms} are obtained and these are listed in Table 3. The maximum significant surge response is 5.86 m at sea state-6 and the maximum significant heave response is 1.38 m and occurred at sea state-6. The maximum significant pitch response is 0.88° (less than 1°) occurred for all the sea states since the response is wind dominated.





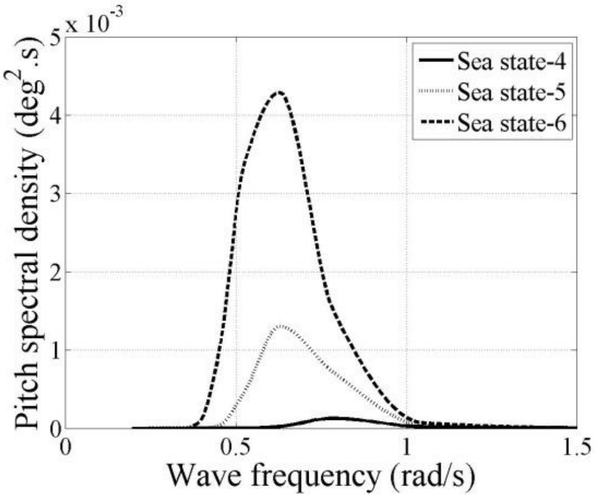


Fig. 6: *Response Spectrums of DDCS Floater in Different Sea States- Case I for 0° Wave Heading Angle.*

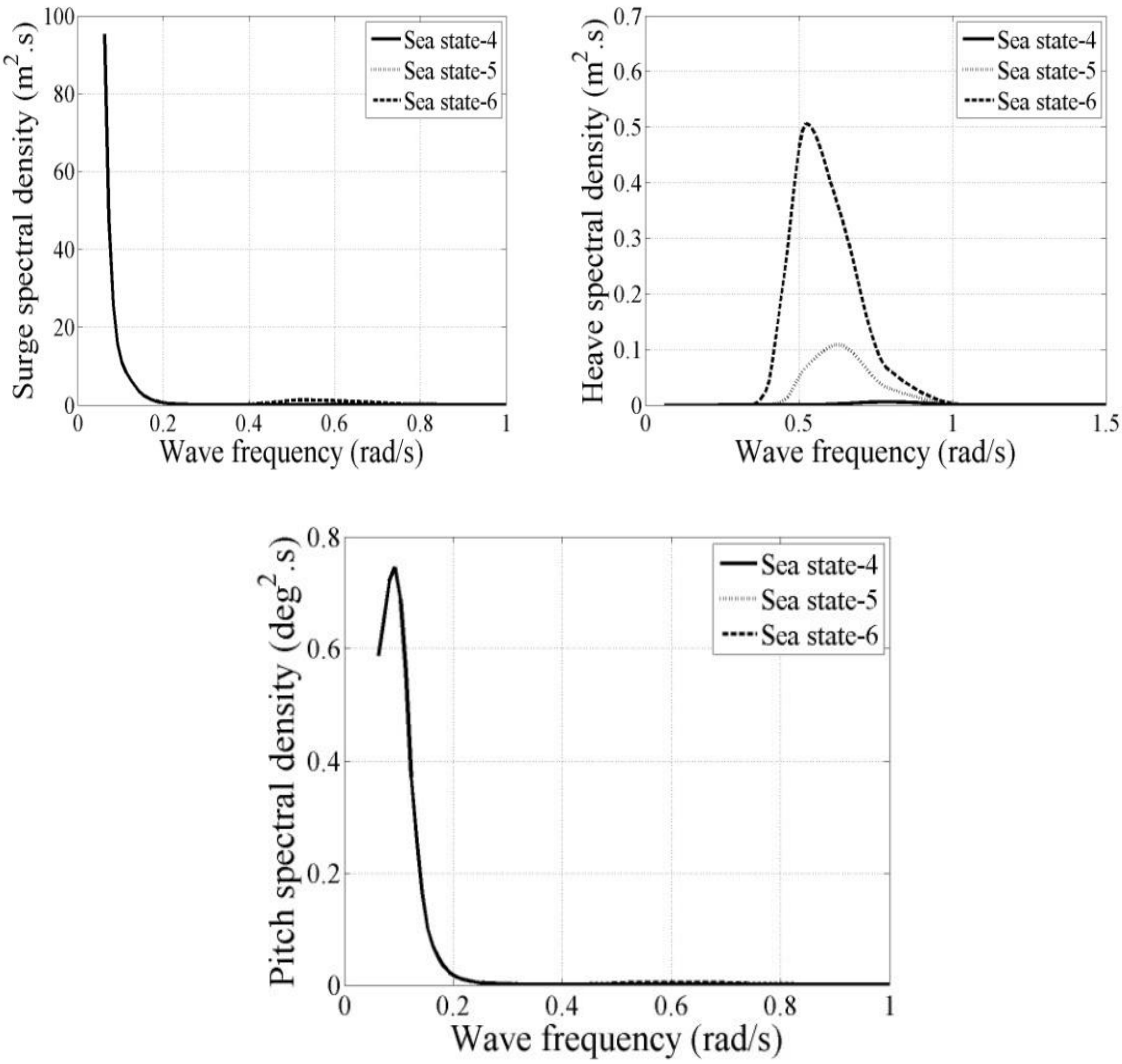


Fig. 7: *Response Spectrums of DDCS Floater in Different Sea States- Case II for 0° Wave Heading Angle.*

Table 2: *Response Statistics of DDCS Floater in Different Sea States- Case-I for 0° Wave Heading Angle.*

Sea states	Modes	Standard deviation	H_{rms}	H_s
Sea state- 4 0^0 heading	Surge(m)	0.078	0.219	0.310
	Heave(m)	0.039	0.111	0.157
	Pitch(deg)	0.006	0.018	0.025
Sea state- 5 0^0 heading	Surge(m)	0.280	0.791	1.119
	Heave(m)	0.166	0.471	0.666
	Pitch(deg)	0.019	0.054	0.077
Sea state- 6 0^0 heading	Surge(m)	0.574	1.623	2.296
	Heave(m)	0.349	0.988	1.397
	Pitch(deg)	0.035	0.100	0.141

Table 3: *Response Statistics of DDCS Floater in Different Sea States- Case-II for 0° Wave Heading Angle.*

Sea states	Modes	Standard deviation	H_{rms}	H_s
Sea state- 4 0^0 heading	Surge(m)	1.351	3.820	5.402
	Heave(m)	0.039	0.110	0.156
	Pitch(deg)	0.219	0.619	0.876
Sea state- 5 0^0 heading	Surge(m)	1.377	3.895	5.508
	Heave(m)	0.165	0.466	0.659
	Pitch(deg)	0.220	0.622	0.879
Sea state- 6 0^0 heading	Surge(m)	1.466	4.145	5.862
	Heave(m)	0.345	0.976	1.380
	Pitch(deg)	0.222	0.627	0.887

SUMMARY AND CONCLUSIONS

Static stability, dynamic and response analyses are carried out to study the hydrodynamic behaviour of DDCS 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 DDCS floaters with different aspect ratios as h/H ratio varied from 10.0 to 40.0 and the D/d ratio varied from 5.0 to 7.0. The DDCS floater with D/d =6 and h/H=30 yielded minimum RAO in heave and pitch. The response analysis is carried out in frequency domain and response statistics are compared for three different sea states for 0° wave heading angle. It is concluded that DDCS with D/d=6 and h/H=30 is suitable for all the three sea states (Sea state 4, 5 and 6) based on its lowest heave response.

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