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STATIC STABILITY AND DYNAMIC ANALYSIS OF BARGE FOATERS FOR AN OFFSHORE WIND TURBINE

A.C.Mayilvahanan[1] and R.Panneer Selvam[2]

Abstract: *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. Reliable 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 used 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 and compared to find the best floater. In this study a barge 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; dynamic analysis; barge floater, integro-differential equation, spectrum, response amplitude operator.*

INTRODUCTION

Offshore wind energy has been the focus of many of the engineers and researchers these days. Less turbulence, low wind shear, vast area availability and high wind speed within a shorter distance are some of the advantages while seeking energy from the offshore. 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. The support systems used for the wind turbine system near the coast can be fixed or floating. The floating structures can also be used 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 and compared to find the best floater. As the barge type floater is comparatively simple to construct compared to other floaters like semi submersibles and TLPs the performance of this simple floater under wave and wind loading for supporting a 5-MW offshore wind turbine is undertaken.

Several types of floaters to support the offshore wind turbine have been investigated by different

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researchers. 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 objective of the work is to study the performance of the barge floaters with different aspect ratios (B/L ratio) 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 barge floater with wind turbine is shown in Fig. 1.

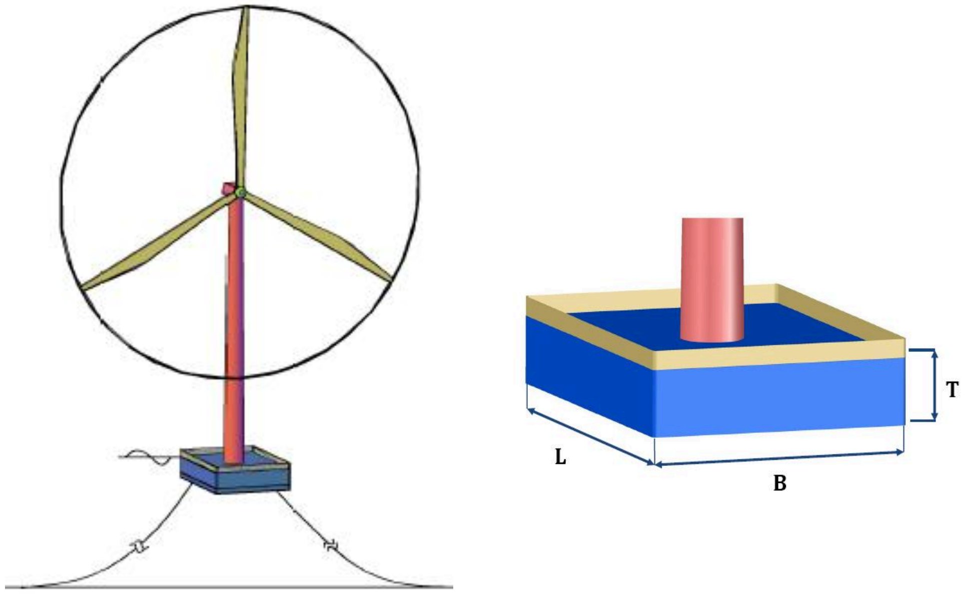


Fig. 1 Schematic view of the barge floater

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.

STATIC STABILITY ANALYSIS OF FLOATERS

The hydrostatic calculation is initially carried out to determine the optimal size and shape of the barge that will provide sufficient stability in unmoored operating conditions. The parameters that have been considered for the static stability analysis are structural and ballast weight, 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 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.

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

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 ($k_{55,\text{Design}}$) for a rectangular barge in pitch motion is given by Eq.2 (Freris, 1990, Manwell, 2002).

$$k_{55,Design} = F_B Z_B + \rho g \frac{LB^3}{12} - M_S g Z_S \qquad (2)$$

where F_B is the buoyant force; Z_B is the centre of buoyancy**;** M_S is the total mass and center of the gravity of the system; Z_S is the center of the gravity of system; L is the length of the barge B is the breadth or width of the barge.

The stability calculations are performed for B/L ratio varying from 0.4 to 1.0 with fixed metacentric height (GM) value of 1.0m and with fixed displacement. The barge was 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 barge type floater for different B/L ratios are given in Table 1. To maintain the desired GM value of 1.0 m for all the cases , the barge mass varied from 633t to 741 t and the ballast from 3900 t to 4015 t for the different barge floaters considered in this study. The barge floater with B/L = 0.40 requires more structural as well as ballast weight to achieve the stability criteria (GM) when compared to the floater with B/L =1.0 because of the reduction in the transverse waterplane moment of inertia. This in effect reduces the BM value and is counteracted by increasing the ballast weight.

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.

Table 1 Hydrostatic and mass properties of different

B/L ratio	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Length , L (m)	53.90	45.50	39.60	35.13	31.62	28.88	27.30
Breadth , B (m)	21.60	22.73	23.75	24.59	25.30	25.99	27.30
Draft, T (m)	4.49	5.040	5.55	6.04	6.53	6.96	7.00
Barge mass (t)	741.21	707.66	683.51	663.57	648.03	635.57	633.50
Ballast (t)	3900	3930	3965	3983	4000	4018	4015
Total mass, M_s (t)	5338.67	5335.12	5345.97	5344.03	5345.49	5351.03	5345.96
Vertical center of gravity, VCG (m)	5.41	5.01	4.62	4.27	3.90	3.51	3.557
Vertical Center of buoyancy K_b(m)	2.25	2.52	2.78	3.02	3.26	3.48	3.50
Heave natural frequency (rad/s)	0.86	0.84	0.83	0.82	0.81	0.80	0.82
Pitch natural frequency (rad/s)	0.67	0.54	0.43	0.34	0.26	0.19	0.11

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.

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

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

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.

$$F_x = F_L \cos\phi + F_D \sin\phi \tag{5}$$

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

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):

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

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).

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

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 BARGE FLOATERS 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. The comparison of the RAO of the different B/L ratios for the wave heading angle of 0° is shown in Fig. 2. In the comparison RAO for B/L= 0.4 and 0.8 are not included as the values obtained are very high. It is observed that heave RAO is maximum for barge with B/L = 1.0 and lowest for the barge with B/L = 0.5. The pitch RAO peaks at the respective natural frequency of the different barges. The pitch RAO is maximum for barge with B/L=0.5 and minimum for the barge with B/L=1.0. The pitch responses are most significant power production efficiency parameter and hence the barge with lower pitch RAOs are favorable. The barges with B/L=1.0 have lower pitch RAOs compared to other barges.

TIME DOMAIN RESPONSE USING INTEGRO-DIFFERENTIAL EQUATION OF MOTION

The equation of motion of the unmoored stationary floating body will have all the six degrees of freedom under harmonic excitation and can be written as

$$\sum_{j=1}^{6}\left[\left(m_{ij} + a_{ij}(\omega)\right)\ddot{x}_j(t) + b_{ij}(\omega)\dot{x}(t) + c_{ij}(\omega)x_j(t)\right] = f(\omega)e^{-i\omega t} \quad (i = 1 to 6) \tag{8}$$

where $\ddot{x}(t)$, $\dot{x}(t)$ and $x_j(t)$ are acceleration, velocity and displacement, m_{ij} is the mass matrix of the body, a_{ij} is the frequency dependent added mass matrix, b_{ij} is the frequency dependent radiation damping matrix, c_{ij} is the Hydrostatic stiffness matrix of the floating body, $f(\omega)$ is the amplitude of wave force, ω is the circular frequency of the wave, and t is the time. It is very important in the random seaway representation, to express the added mass and damping coefficients, which are functions of frequencies, by their time domain counterparts. This can be represented by Fourier transform of a convolution integral involving retardation function.

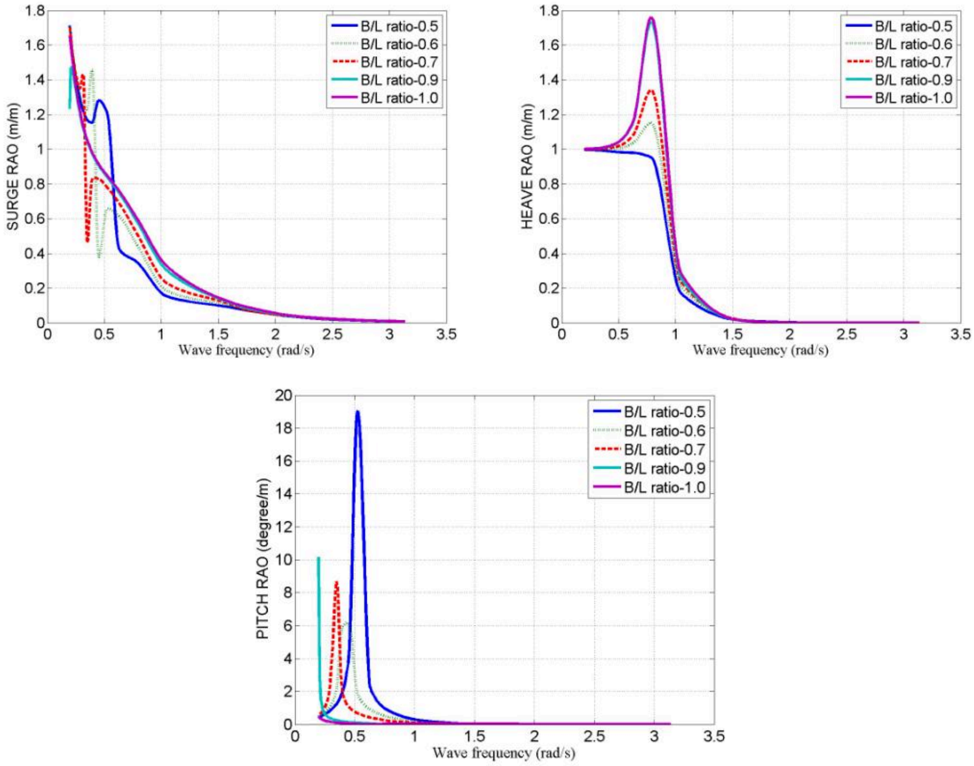


Fig.2. RAO of barge floater with different B/L ratio for 0^0 wave heading angle

$$\sum_{j=1}^{6}\left[\left(m_{ij}+a_{ij}(\infty)\right)\ddot{x}(t)+\int_{0}^{t}R_{ij}(t-\tau)\,\dot{x}(\tau)d\tau+k_{ij}x_{j}(t)\right]=f_{i}(t) \qquad (9)$$

where $a_{ij}(\infty)=a_{ij}(\omega)+\frac{1}{\omega}\int_{0}^{\infty}R_{ij}(t)\sin\omega t dt$; $c_{ij}(\omega)=\int_{0}^{\infty}R_{ij}(t)\cos\omega t dt$

$$R_{ij}(t)=\tfrac{2}{\pi}\int_{0}^{\infty}c_{ij}(\omega)\cos\omega t d\omega$$

In the above, $a_{ij}(\infty)$ is the infinite frequency added mass and $R_{ij}(t)$ is the retardation function at time *t*.

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.

Case (I) Response Analysis of Floater with Wave Only

This condition may exist in case of pre-installation stage of the wind turbine. The integro-differential equation, see Eq. (9) is used to obtain the response for the coupled 3 degrees of freedom of system i.e. surge-heave-pitch. The responses of barge floater for different sea states are shown in Fig. 3 and response statistics are listed in Table 2 for 0° and 45° wave heading angles for three different sea states namely sea states 4, 5 and 6. The maximum surge amplitude is 1.96 m, the maximum heave amplitude is 2.73m and the maximum pitch amplitude is 0.45 degree and occurred for sea state-6 of 0° wave heading.

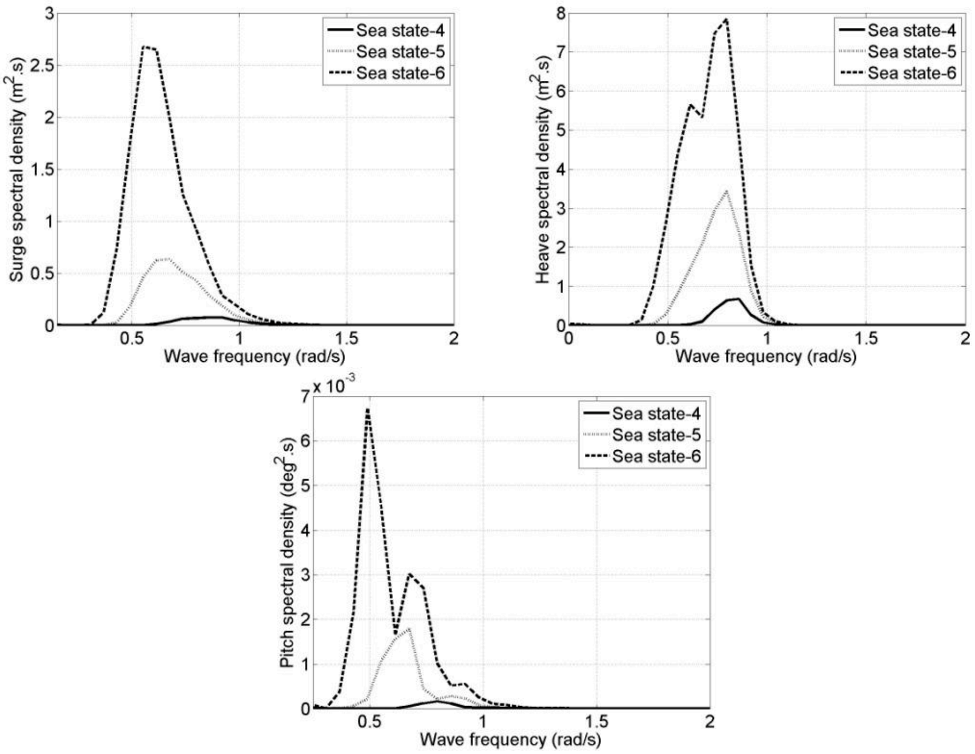


Fig.3. Response spectrums of barge floater for different sea states - Case I for 0^0 wave heading angle

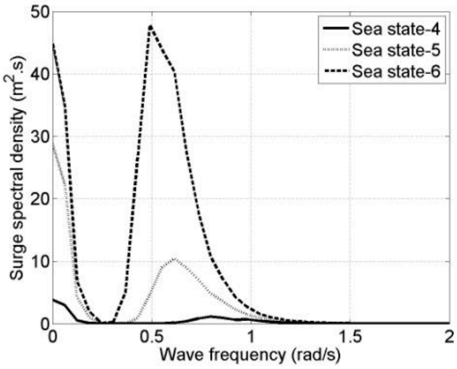
Case (II) Response Analysis of Floater with Wind and Wave

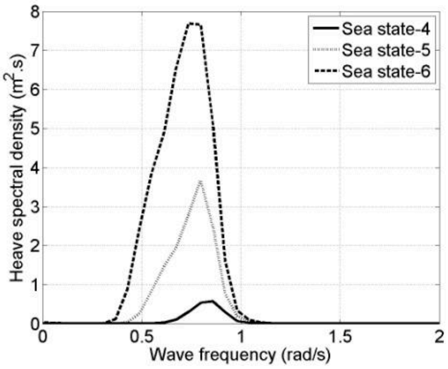
This refers the pre-installation stage of offshore wind turbine when wind is blowing. The effect of wind and wave are included in the response analysis. The wave and wind are considered as independent events and the excitation force consists of aerodynamic force and moment on wind turbine system and the diffraction forces and moments of floater. The axial aerodynamic force and moment on wind turbine system is transferred to the base which is added with surge force and pitch moment on floater due to waves. The integro-differential equation, see Eq. (9), is used to obtain the response for the coupled 3 degree of system i.e. surge-heave-pitch. The response of barge floater for different sea states is shown in Fig. 4 and response statistics are listed in Table 3 for 0° and 45° wave heading angles for three different sea states.

Table 2 Response statistics for Case I for wave heading angles of 0^0 and 45^0

Sea states	Modes	Standard deviation	max Response	H_{avg}	H_{max}	H_{rms}	H_s	$H_{1/10}$
Sea state-4 0^0 heading	Surge(m)	0.160	0.550	0.462	0.855	0.488	0.626	0.751
	Heave(m)	0.296	0.681	0.820	1.368	0.870	1.120	1.284
	Pitch(deg)	0.042	0.119	0.111	0.254	0.124	0.175	0.206
Sea state-5 0^0 heading	Surge(m)	0.351	0.936	1.064	1.971	1.114	1.445	1.728
	Heave(m)	0.708	1.417	1.957	2.964	2.055	2.621	2.867
	Pitch(deg)	0.100	0.288	0.279	0.580	0.309	0.438	0.526
Sea state-6 0^0 heading	Surge(m)	0.583	1.960	1.845	3.921	1.960	2.577	3.319
	Heave(m)	1.095	2.728	3.266	5.369	3.491	4.620	5.199
	Pitch(deg)	0.175	0.450	0.497	0.951	0.528	0.701	0.854
Sea state-4 45^0 heading	Surge(m)	0.116	0.354	0.336	0.708	0.357	0.472	0.588
	Heave(m)	0.297	0.690	0.838	1.380	0.891	1.149	1.323
	Pitch(deg)	0.030	0.086	0.084	0.179	0.092	0.130	0.159
Sea state-5 45^0 heading	Surge(m)	0.262	0.680	0.762	1.482	0.803	1.048	1.308
	Heave(m)	0.709	1.420	2.029	2.976	2.117	2.653	2.925
	Pitch(deg)	0.073	0.203	0.196	0.419	0.216	0.304	0.374
Sea state-6 45^0 heading	Surge(m)	0.430	1.468	1.291	2.936	1.372	1.799	2.252
	Heave(m)	1.097	2.719	3.177	5.388	3.399	4.517	5.167
	Pitch(deg)	0.125	0.322	0.364	0.704	0.387	0.518	0.625

The maximum surge amplitude is 7.4m and occurred for sea state-6 of 0° wave heading, the maximum heave amplitude is 4.0m and occurred for sea state-6of 45° wave heading and the maximum pitch amplitude is 7.8° and occurred for sea state-6of 0° wave heading.





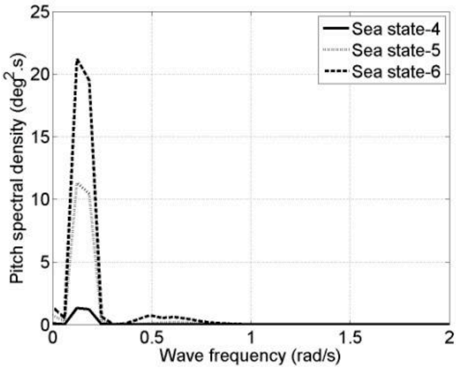


Fig.4. Response spectrums of barge floater for different sea states- case II

Table 3 Response statistics for Case II for wave heading angles of 0^0 and 45^0

Sea states	Modes	Standard deviation	max Response	H_{avg}	H_{max}	H_{rms}	H_s	$H_{1/10}$
Sea state-4 0^0 heading	Surge(m)	0.613	1.714	2.088	4.169	2.205	2.885	3.271
	Heave(m)	0.298	0.718	0.863	1.410	0.931	1.263	1.372
	Pitch(deg)	0.652	1.762	2.067	3.607	2.149	2.733	3.182
Sea state-5 0^0 heading	Surge(m)	1.440	3.602	4.778	10.282	5.149	7.033	8.299
	Heave(m)	0.718	1.745	2.147	3.586	2.240	2.829	3.342
	Pitch(deg)	1.794	5.196	5.337	9.949	5.571	7.137	8.804
Sea state-6 0^0 heading	Surge(m)	2.513	7.387	8.464	14.982	8.876	11.462	13.623
	Heave(m)	1.098	4.014	3.786	7.860	4.196	5.996	7.395
	Pitch(deg)	2.908	7.821	9.279	15.258	9.655	12.274	13.987
Sea state-4 45^0 heading	Surge(m)	0.579	1.603	2.063	3.967	2.162	2.818	3.273
	Heave(m)	0.299	0.719	0.906	1.419	0.965	1.291	1.405
	Pitch(deg)	0.634	1.706	1.858	2.889	1.914	2.401	2.702
Sea state-5 45^0 heading	Surge(m)	1.350	3.356	4.431	9.755	4.770	6.480	7.581
	Heave(m)	0.720	1.752	2.091	3.622	2.209	2.836	3.378
	Pitch(deg)	1.745	5.045	5.134	9.592	5.373	6.899	8.217
Sea state-5 45^0 heading	Surge(m)	2.350	6.898	7.664	14.038	7.999	10.176	11.650
	Heave(m)	1.099	4.022	3.351	8.089	3.774	5.485	7.050
	Pitch(deg)	2.823	7.587	8.922	14.788	9.309	11.893	14.054

Comparison of responses of Case I and Case II

In all three sea states the maximum responses occurred in Case-II since in addition to the wave forces, wind loads acting on the system. The axial force and axial moment on wind turbine system is transferred to the base which is added with surge force and pitch moment on floater due to wave. The maximum responses of floaters occurred in 0^0 than the 45° wave heading angle.

The surge and pitch response of the floater in Case-II are higher than the Case-I. The heave responses of the floater in Case-II for sea state- 4, 5 and 6 are 5%, 23% and 47% higher than the Case-I.

CONCLUSIONS

Static stability, dynamic and response analyses are carried out to study the behavior of barge floater in three different seas states. All these floaters were designed with transverse metacentric height (GM) equal to1.0m. Hydrodynamic analysis was carried out using WAMIT, for different barge type floaters with aspect ratio ranging from 0.4 to 1.0. Time domain responses are obtained using Integro-differential equation of motion and statistics of responses are compared for two different cases. The barge with aspect ratio B/L=1.0 is found to be suitable for all the three sea states.

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