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PAGES: 10-19


ORIGINAL PDF URL: <https://dergipark.org.tr/tr/download/article-file/1346809>



Dynamic analysis of a tri-floater with vertical axis wind turbine supported at its centroid

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Submitted: 15.10.2020

Accepted: 17.02.2021

Published: 31.03.2021



Abstract: The paper deals with the dynamic analysis of a tri-floater with a 1 MW offshore Vertical Axis Wind Turbine (VAWT) placed at its centroid. Six line catenary mooring system was used for controlling the horizontal movement of the floater. The floater was modeled as a rigid body with six degrees of freedom. Mass, damping and hydrostatic stiffness were calculated by using hydrostatic stability condition. The aerodynamic load on Vertical Axis Wind Turbine was calculated via the stream tube theory. Wave profile was calculated using Airy's wave theory followed by the use of Morison's equation to determine the inertial and drag forces on the floater. A computer program was developed by using the MatLab package for force calculation including wind and wave excitations as a dynamic analysis. The Newmark - beta method was performed for these analyses. The equation of motion for the floater was solved in time domain. Restoring force by mooring lines at each instant of time was calculated based on the cable profile. Responses of the tri-floater with VAWT in different sea conditions were analyzed. It was proven that surge, heave and pitch are the predominant motions for a straight (00) wave. These motions were also analyzed for the waves with different inclinations and their responses were also considered and compared.

Keywords: *Dynamic analysis, Offshore wind turbine, Tri-floater, Wind energy, Vertical axis wind turbine*

Cite this paper as: Thoppil, A., Akbar, A.A., & Rambabu, D Dynamic analysis of a tri-floater with vertical axis wind turbine supported at its centroid. *Journal of Energy Systems* 2021, 5(1), 10-19, DOI: 10.30521/jes.811097

1. INTRODUCTION

Offshore wind energy has a promising future for the ample wind resources and the steadily evolving wind turbine technology. Compared to the land-based wind energy plants, the concept of offshore wind energy is more attractive in many aspects, including more consistent and stronger winds, less noise and pollution concerns, etc. Wind turbines are mainly classified as Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). VAWTs have many well-known advantages over HAWTs, which could be potentially magnified in offshore applications [1]. For example, VAWTs have lower centers of gravity, much less sensitivity to extreme wind conditions, and superior up-scaling potentials than their HAWT counter parts. Here, responses of the tri-floater with VAWT in different sea conditions were analyzed and it was found that surge, heave and pitch are the predominant motions for a straight (0°) wave. These motions can be analyzed for the waves with different inclinations and the responses are studied and compared as well.

Hooft [2] studied the hydrodynamic aspects of semi-submersible platforms, by subdividing the structure into slender and simpler elements. The forces on each member were calculated by using Morison's approach and the forces were summed up assuming that the hydrodynamic properties of each element of the submerged construction were not influenced by the neighboring elements. Tong [3] explored the conceptual design of a float consisting of a steel tripod space frame with the wind turbine mounted on it. The tower was bolted onto the deck of a concrete cylindrical buoy hull with a wide bottom disk consisting of 8 line catenary mooring system to control the motion. A 1.4 MW offshore wind turbine was provided for locations, where the water depth varied between 100 m to 300 m. In other study, Bulder and co-workers [4] presented the technical and economic feasibility of floating wind energy systems for water depths greater than 50 m. In their work, a cost analysis was carried out on different floating platforms and it was concluded that Tri-floater was the best option. Ruoyu and co-workers [5] studied the dynamic behavior of a semi-submersible floating foundation of a 600 kW capacity wind turbine in 60 m deep water by considering the coupled load effects of wind turbine-tower-floating foundation, mooring lines and the ocean environment. Borg and co-workers [6] presented different models of VAWTs with suitable floating platforms and studied different approaches to model the mooring systems by focusing on the behavior of the structure at the preliminary stages of design, adequately. Owen and Griffithy [7] studied the vibration and kinetic stability of large-scale floating VAWTs considering rigid-flexible couplings, and developed a software package. Rajeswari and Nallayarasu [8] conducted experimental and CFD studies on the hydrodynamic responses of a scaled VAWT with three column semi-submersible floater. In a different study, Ramtin and co-workers [9] analyzed the fatigue life sensitivity of monopole - supported offshore wind turbines under operational and non-operational conditions using time domain finite element simulations. They asserted that the fatigue life increased significantly due to the reductions in the bending stress caused by the increased damping. Islam and co-workers [10] presented a thorough review on the aerodynamic models of the straight-bladed VAWTs. Blonk [11] conducted research on the technical and economic feasibility of two floating VAWT concepts by using simplified BEM and hydrostatic models. Similar fully-coupled numerical models have also been used to test different floating VAWT model concepts [12,13,14,15,16,17,18,19].

2. MODEL DESCRIPTION AND METHODOLOGY

2.1. Methodology

To predict the response of a floating wind turbine system in wind and wave environment, a computational model for dynamic analysis is proposed to be developed which considers both wave loading on the submerged floater and the aerodynamic loading on VAWT. Forces and moments due to

gravity, wind and waves are exerted on both the wind turbine assembly and floater. Wind forces and moments are primarily exerted on the rotor of the wind turbine and supporting tower, while wave forces act only on the floater. The forces and moments are produced on the wind turbine blades and supporting tower are transferred to the floater. Those resulting oscillatory forces and moments cause some dynamic displacements on the floating wind turbine system. The floating wind turbine system needs to be designed so that it should withstand the most severe sea state expected to be encountered during its lifetime. The floating structure must support its own weight and that of the wind turbine. A tri-floater semi-submersible has three columns connected by pontoons. As the column and pontoon diameters are small, Morison's formulation is performed for the wave force calculation. Mooring system response is assumed to be quasi-static. Dynamics of mooring lines is not considered as it will not have much impact on the results as the turbine is installed in shallow water. The analysis is performed in the time domain and the equilibrium equation is solved by using Newmark-beta method.

The different parameters of the tri-floater are given in Table 1 and the plan view of the tri-floater as it supports the Vertical Axis Wind Turbine is shown in Fig. 1.

Table 1. Basic floater dimensions.

Item description	Dimension
Column diameter	7.7 m
Column height	24 m
Column draft	12 m
Distance between column centers	68 m
Pontoon diameter	3.3 m
Heave plate diameter	15.4 m
Total volume displacement	3078 m ³

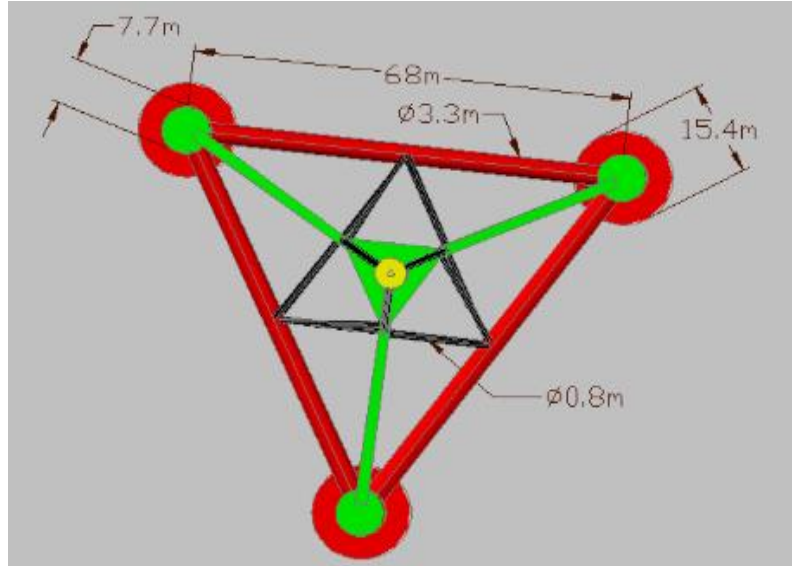


Figure 1. The studied tri-floater with the plan view.

The VAWT is placed symmetrically on the centroid of the triangle formed by the tri-floater. The distance between the centers of the columns is 68 m. The properties of the VAWT are given in Table 2 and 3D view is shown in Fig. 2. The proportioning of the VAWT (radius, height, etc.) ensures a rated power scale $P = 1$ MW. A 3-bladed VAWT is also considered with its simplest NACA0012 shape with the corresponding aerofoil.

Table 2. Turbine and tower dimensions.

Item description	Specification
Machine rated power	1 MW
Rotor diameter	38 m
Blade cross section	NACA0012
Blade chord	0.5334 m
Length of blade	17.01 m
Height of hub	83 m above sea water level
Rated rotor speed	27 rotations per minute
Tower base diameter	7.5 m (hollow)
Tower top diameter	4.5 m
Length of tower	70 m
Centre of gravity of tower	31.8 m above tower base
Tower weight	3528 kN
Total machine weight	3352 kN

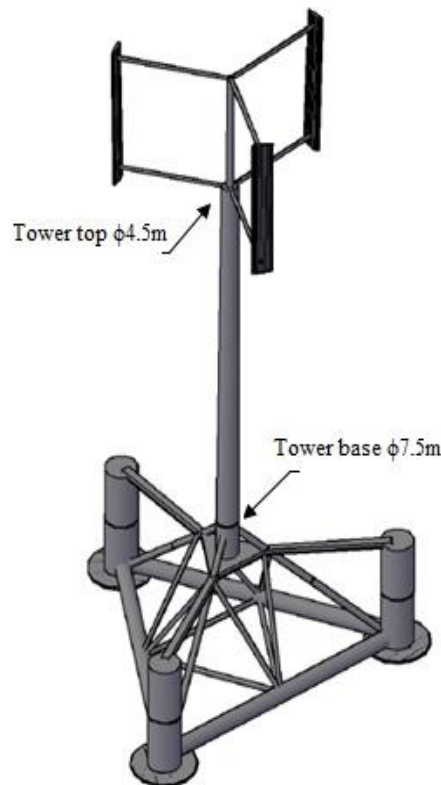


Figure 2. Tri-floater with VAWT

3. AERODYNAMIC ANALYSIS

3.1. Wind Speed

External wind conditions in the offshore regime is defined in guidelines by Det Norske Veritas (DNV), International Electro technical Commission (IEC) and Germanischer Lloyd (GL). The wind speed at 10 m is often used as the reference height in all the standards. The wind profile, $V(z)$ denotes the average

wind speed as a function of height z above the ground. According to the GL standards, the normal wind speed profile is given by the power law. The wind velocity at hub height is determined by Eq. 1.

$$V(z) = V(z_r) \left(\frac{z}{z_r} \right)^\alpha \text{ for } t > T \quad (1)$$

Here, z_r and α are the power law exponent, which takes a value of 0.11 for all wind speeds in offshore conditions (as per GL standards). Wind velocity at the hub height varies by time. Design wind velocity is calculated from gust velocity as follows:

$$V(z, t) = V(z) - 0.37 V_{gust} \sin\left(\frac{3\pi t}{T}\right) \left(1 - \cos\left(\frac{2\pi t}{T}\right)\right) \text{ for } 0 < t < T \quad (2)$$

where, T and V_{gust} are the gust characteristic time period and the largest extreme gust magnitude, respectively. Strictly, it is defined as,

$$V_{gust} = 1.53 (V_{e1} - V_{hub}) \quad (3)$$

where, V_{e1} is the one-year extreme wind speed calculated from height above GL (Eq. 4) and V_{hub} is the wind speed at the hub height.

$$V_{e1} = 1.12 V(z_r) \left(\frac{z}{z_r} \right)^\alpha \quad (4)$$

3.2. Wind Force on Tower

Wind force acting on the tower produces considerable effect on the floater motion. Wind velocity increases with height, whereas the tower projected area decreases with height. The tower is divided into a number of sections and force acting on each section is determined and added to calculate the total force on the structure. To calculate the projected area of any section, the diameter of tower at any height z is required and is determined by Eq. 5.

$$D_z = D_b \left(1 - \frac{z}{H}\right) + D_t \left(\frac{z}{H}\right) \quad (5)$$

where, D_z is the diameter at any height z from the tower base, D_b is the tower base diameter, D_t is tower top diameter and H is the height of the tower. From the design wind velocity (V), the static wind force (F_w) acting perpendicular to an exposed area (A) can be obtained from Eq. 6.

$$F_w = \frac{1}{2} \rho_a V^2 C_s \quad (6)$$

where, ρ_a is the density of air, C_s is the shape coefficient ($C_s = 0.5$ for cylindrical sections). Based on these values and the dimensions given in Table 2, total force acting on the tower is calculated as 24.795 kN.

3.3. Loading on Wind Turbine

Power generated by wind turbine depends on the interaction between the rotor blades and the wind. The analysis of force on the turbine is carried out by assuming a control volume, where the boundaries are the surface and two cross sections of the stream tube. The analysis is based on linear momentum theory. From the conservation of linear momentum for a 1D incompressible time-invariant flow, the thrust (T) is equal and opposite to the change in momentum of air stream [20]. Here, T should not be confused with period mentioned in the previous subsection. The thrust can be stated as,

$$T = \frac{1}{2} \rho_a V_1^2 A (4a(1-a)) \quad (7)$$

where, A is the projected area of turbine blade and a is the axial induction factor. Axial induction factor is given by,

$$a = \frac{V_1 - V_2}{V_1} \quad (8)$$

where, V_1 and V_2 are the velocities of the fluid before entering the stream tube and before passing through actuator disk respectively. The thrust force on the wind turbine is characterized by a non-dimensional thrust coefficient as in,

$$C_t = \frac{T}{\frac{1}{2} \rho_a A V^2} \quad (9)$$

Straight bladed Darrieus type VAWT is among the simple wind turbines. However, its aerodynamic analysis is quite complex. Flow velocities in the up-stream and downstream sides of the Darrieus type VAWTs are not constant. The general mathematical expression for the geometric parameters of a VAWT for a specific location of the blade is described in Eqs. 10,11 and 12. The aerofoil shape has inherent lift and drag characteristics varying with an attack angle (δ) of the wind.

$$\tan \delta = \frac{V_a \sin \theta}{V_a \cos \theta + \Omega R} \quad (10)$$

$$C_N = C_L \cos \delta + C_D \sin \delta \quad (11)$$

$$C_T = C_L \sin \delta - C_D \cos \delta \quad (12)$$

where, V_a is incident wind velocity on the rotor acting as an actuator disc, θ is the momentary angular location of the aerofoil from the centre of rotor, Ω is the angular velocity of the VAWT, R is the radius of the rotor, C_L is the lift coefficient and C_D is the drag coefficient. The instantaneous thrust force (T_i) on a single aerofoil is given by Habtamu and co-workers [20] in Eq. 13.

$$T_i = \frac{1}{2} \rho_a V_R^2 (hc) (C_T \cos \theta - C_N \sin \theta) \quad (13)$$

where, h is the blade height, V_R is the relative velocity and c is the chord length of blade. The aerodynamic efficiency of a wind turbine is indicated by the power coefficient (C_p) given by Eq. 14.

$$C_p = \frac{P_{max}}{\frac{1}{2} \rho_a A V^2} \quad (14)$$

where, P_{max} is the maximum rated power of the wind turbine. The shape of aerofoil blade chosen for analysis is NACA0012. For low values of angle of incidence, the aerofoil has a high lift to drag ratio. Axial induction factor (a) for the calculation of thrust force and power produced by wind turbine is determined by an iterative procedure programmed using MatLab.

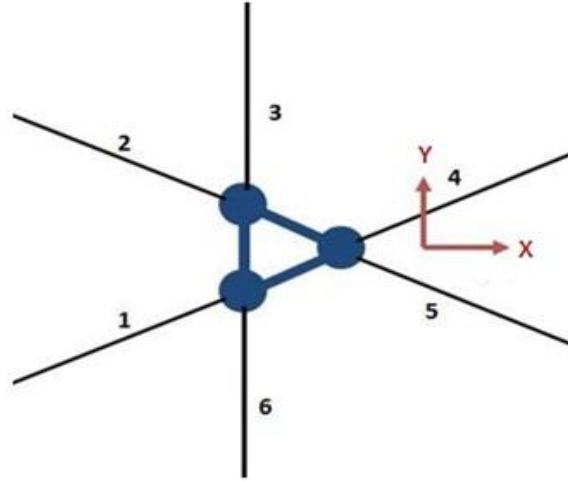


Figure 3. Mooring line configuration for the floater.

For the tri-floater, catenary mooring system is provided with 6 mooring lines. There will be 2 mooring lines connected to each leg of the floater separated by 60° each as shown in Fig. 3. Studless chain of 15 cm diameter is used as the mooring lines.

4. DYNAMIC ANALYSIS OF FLOATER

Dynamic analysis of the semi-submersible floater supporting the wind turbine involves the formulation of equation of motion for the analysis of floater behavior. The forces and moments due to wind loading on the turbine blades and tower are transferred to the floater.

4.1. Hydrodynamic Loading

In the present study, the wave description is assumed to be regular. This simplification is based on certain arguments. Irregular wave description is used for the fatigue analysis, where the lifetime load is required. The calculations were performed for operational sea and rough sea conditions. The wind velocity, wave height and time period for operational and rough sea conditions are shown in Table 3.

Table 3. Sea states used for analysis

	Wind velocity (m/s)	Wave height (m)	Time period (s)
Sea state 1 (operational)	12.2	4.2	9.2
Sea state 2 (rough)	21.1	8.78	11

5. RESULTS AND DISCUSSIONS

5.1. General

The system is modeled as a rigid body with six degrees of freedom. For the mathematical model developed, the hydrostatic stability check gives a feasible result. All the forces were transferred to the centre of gravity of the system as forces and moments. Input parameters used for validation are: Column diameter of 10.7 m, pontoon diameter of 1.8 m, pontoon length of 51.2 m, heave plate diameter of 23.7 m, column draft of 22.9 m, wave height of 13.5 m, time period of 17 s, mass of floater of 69629 kN, mass of turbine and tower of 8369 kN and tether diameter of 0.15 m.

5.2. Validation

To validate the computer program developed, experimental study on similar platform conducted by Dominique and co-workers [21] is also compared with our findings. Inputs to the program include the floater dimensions, wave parameters, wind thrust force and statics of tether lines.

Table 4. Comparison of results.

Degree of freedom		Max	Min	Root-mean-square values (RMS)
Surge (m)	Present work (Analytical)	13.32	-6.95	3.40
	As per <i>Dominique R et al.</i> [21] (Experimental study)	13.26	-6.75	3.21
	% Difference	0.45	2.96	5.91
Heave (m)	Present work (Analytical)	4.52	-5.89	1.95
	As per <i>Dominique R et al.</i> [21] (Experimental study)	4.86	-5.84	1.99
	% Difference	6.99	0.85	2.01
Pitch (degrees)	Present work (Analytical)	5.07	-3.19	1.36
	As per <i>Dominique R et al.</i> [21] (Experimental study)	4.87	-3.87	1.27
	% Difference	4.10	17.57	7.08

From Table 4, the analytical and experimental results are found to be matching closely as the percentage deviation of maximum, minimum and root-mean-square (RMS) values of surge, heave and pitch motions are less. Hence, it can be concluded that the developed MatLab program is suitable for finding the responses of the floater. It is also clear that the surge motion will be more for unidirectional regular wave acting in the surge direction of the platform coordinate system and the structure will remain in transition state for a time period much larger than that for heave and pitch motions. The amplitudes of heave and pitch responses will move to a steady state at almost the same time and the difference between the maximum amplitude of transition state and the amplitude of steady state for surge motion will be large.

Table 5. Responses for operational and rough sea conditions.

Degree of freedom	Operational sea				Rough sea			
	Max	Min	RMS (transient+ steady)	RMS (steady state)	Max	Min	RMS (transient+ steady)	RMS (steady state)
Surge (m)	1.1739-0.8571		0.2688	0.1964	5.3509	-5.6929	1.3146	0.915
Heave (m)	0.6391 -0.808		0.2353	0.2268	3.2543	-3.847	1.2604	1.2243
Pitch (degrees)	0.2967-0.0157		0.1613	0.1611	1.0436	-0.4777	0.3216	0.3070

Dynamic analysis is performed separately for both operational and rough sea conditions. Only the responses in surge, heave and pitch directions are predominant and responses in other directions are negligible. Table 5 gives the maximum, minimum and root-mean-square (RMS) values of surge, heave and pitch motions of floater for operational sea conditions and rough sea conditions. Due to large wave force acting on the structure in rough sea conditions, the floater responses in surge, heave and pitch have larger variation to that in operational sea conditions. For rough sea conditions, the maximum response values of surge, pitch and heave are increased by 356%, 409% and 252%, respectively when compared with operational sea conditions. The maximum of heave response in rough sea is only 3.2543 m indicating that sufficient free board would be available. For both sea conditions, surge response is less on comparison with the overall dimensions of the tri-floater indicating its high stability.

5.3. Response for Various Inclinations of Wave

Surge, heave and pitch responses of tri-floater are computed for 0° , 30° , 45° and 60° inclinations of the wave with x -axis (as shown in Fig. 3) in operational sea condition (Table 6).

Table 6. Maximum response values for 0° , 30° , 45° and 60° inclinations of wave.

Degree of freedom	0° wave	30° wave	45° wave	60° wave
Surge (m)	1.1739	1.0008	0.8343	0.6199
Heave (m)	0.6391	0.6327	0.5765	0.4842
Pitch (degrees)	0.2967	0.2663	0.2383	0.2030

From Table 6, it is clear that surge, heave and pitch degrees of freedom have maximum response values for 0° inclination of wave. The values are found to be reducing as the inclination of wave varies from 0° to 60° . The percentage reduction of maximum response value of surge from 0° to 60° is high. A decrease of 15% is found in the maximum response value of surge as the inclination of wave in operational sea conditions changes from 0° to 30° . Between 0° and 45° , the maximum response decreases by 29% and between 0° and 60° , it yields to 47%. The percentage reduction of maximum response values of heave is less compared to that of surge as the inclination of wave changes from 0° to 60° . Between 0° and 30° , a decrease of 1% is observed which decreases up-to 24% for values between 0° and 60° . Hence, the percentage reduction of maximum response values for surge is twice as that for heave between 0° and 60° inclinations of wave. Pitch response also shows considerable percentage reduction in maximum response values for a change of wave inclination from 0° to 60° . For pitch response, the percentage reduction of maximum response value lies between the variations observed for heave and surge.

6. CONCLUSION

The behavior of a tri-floater supporting a vertical axis wind turbine at its centroid for different wave conditions are studied. The height of the wave in rough sea condition is found to be more than two times as compared to operational sea condition. This is the reason for large wave forces acting on tri-floater in rough sea condition. It is determined that the effect of wave is more significant compared to wind in the platform heave motion of the tri-floater. In normal operational and rough sea condition, maximum pitch is less than 2° , which proves that the efficiency of turbines is not affected. The maximum of heave response in rough sea is only 3.2543 m, so sufficient free board would be available. For both sea conditions, the surge response is also less when compared to the overall dimensions of the tri-floater. For rough sea conditions, the pitch response attains a maximum value of 1.04° , which is less than the limiting value of 10° , ensuring turbine efficiency even under extreme conditions. With a change of sea condition from operational to rough, the maximum responses of surge, heave and pitch increase by 356%, 409% and 252% respectively. For the tri-floater, the maximum responses of surge, heave and pitch decrease as the inclination of wave changes from 0° to 60° . The percentage reductions of maximum responses are more for the surge and less for the heave. The percentage reductions of maximum responses for the surge is two times as that for the heave between 0° and 60° inclinations of wave.

Acknowledgment

The authors acknowledge the computational resources provided by National Institute of Technology Calicut for the conduct of this work.

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