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Research Article

Dynamic analysis of offshore triceratops supporting wind turbine: Preliminary studies

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Abstract

Offshore triceratops, the recent innovation in deep water compliant platforms, is primarily designed to withstand lateral forces through its geometric shape. The uniqueness of the platform is the presence of the ball joints between the legs and deck, which partially restrain the transfer of rotations from the legs to the deck and vice-versa. However, displacements such as surge, sway, and heave motions are transferred, ensuring a rigid connection between the legs and the deck. Efficient operations of offshore wind turbines are more dependent on the support systems on which they are mounted. Increased stability and reduction in stress concentration in rigid connections are desirable. Nonlinear dynamic response analysis is carried out in FAST by coupling the frequency response of the platform obtained in ANSYS AQWA with that of the HydroDyn module of FAST. The current study investigates a fully coupled three-dimensional hydro-aerodynamic model of triceratops mounted with a horizontal axis wind turbine. Unsteady Blade Element Momentum theory (BEM) is used to estimate the aerodynamic loads, which encompasses the effect of wind shear using a power law and spatially coherent turbulence. In contrast, Morison equations are used to estimate the hydrodynamic loads on the platform. After the preliminary proportioning of the platform, Response Amplitude Operator (RAO) plots are drawn to illustrate the partial motion transfer between the deck and the buoyant legs. Based on the preliminary studies, it is seen that the environmental loads do not impose instability, reinforcing the dynamic stability of the platform. Frequency responses for operating and parked conditions illustrate the coupling between the degrees of freedom and the influence of the rotor motion of the wind turbine on the platform deck. Tether tension variation is assessed in all three legs for the operational sea states to check the safety standards for a compliant system to avoid tether pull-out. The presented study is prima facie to encourage the suitability of triceratops as floaters to support the wind turbine under moderate sea states.

1. Introduction

Non-renewable energy, such as oil, nuclear power, coal, and natural gas, are the preliminary sources of energy for most parts of the geographical canopy (Fulton et al., 2006; Srinivasan, 2020). Offshore wind energy is one of the viable alternatives due to its inexhaustible and non-polluting nature (Henderson & Morgan, 2003; Srinivasan et al., 2022). Wind energy stands out as the most evolved and viable technology in comparison to its counterparts (Musial & Butterfield, 2004; 2006). While environmental problems and human discomfort are unavoidable when it comes to

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onshore wind farms, offshore wind farms are devoid of such problems. While there are several advantages of offshore wind farms, high CAPEX and complexities arising from supporting structure, foundation, commissioning, and decommissioning are quite significant (Butterfield et al., 2005; Nielsen et al., 2006; Srinivasan, 2014; Srinivasan & Nagavinothini, 2020).

Offshore triceratops offers partial isolation to the deck due to the ball joints, thus enabling safe operability by avoiding roll and pitch motion under wave loads (Srinivasan, 2017; Srinivasan et al., 2013; Srinivasan & Jain, 2016; Srinivasan & Subrata, 2012; Srinivasan et al., 2010). The triangular deck is supported by deep-draft buoyant legs, which are taut-moored to the seabed using pre-tensioned tethers. Compliance offered in the horizontal plane is like that of a Tension Leg Platform (TLP). The taut-moored tethers and deep-draft buoyant legs offer stiffness in the vertical plane. Offshore triceratops is a hybrid combination of a TLP and Spar. Ball joints that are placed in between the deck and buoyant legs isolate the deck partially by restraining the transfer of rotation from buoyant legs to the deck and vice-versa. Under lateral loads, rotational responses of the deck are significantly lesser than that of the buoyant legs (Srinivasan et al., 2011; Srinivasan & Madhuri, 2013; Srinivasan & Seeram, 2012a; 2012b; Srinivasan & Madhuri, 2015; 2012). Further, their resistance to lateral loads is improved by stiffening the buoyant legs (Chandrasekaran et al., 2022; Srinivasan et al., 2015; Srinivasan & Senger, 2017; Srinivasan, 2015).

Support systems of offshore wind turbines are chosen from a wide range, namely TLPs, tri-floaters, shallow-draft barge, and fixed platforms (Chandrasekaran et al., 2023a; 2023b; Hendersen & Patel, 2003; Srinivasan, 2016; Skare et al., 2007; Wayman et al., 2006; Zambrano et al., 2006; 2007). Linear frequency domain analysis is used for systems in which wind turbine characteristics are included by supplementing the mass matrix. In contrast, hydrodynamic damping and linear restoring forces are supplemented with rotor aerodynamics and gyroscopes. Ignorance of the elasticity of wind turbines is evident from the studies. Henderson and Patel (2003) addressed this shortcoming using a state-domain approach. Studies have also showed that the influence of platform motion on the rotor loads and captured power is not dominant, but a strong dependency on the aerodynamics of the rotor exists (Larsen & Hanson, 2007). Time-domain aero-servo-elastic wind turbine simulators are used to include the consequences of platform motion on the performance of a 5-MW wind turbine. Thanks to the recent development of design code FAST with both AeroDyn and HydroDyn modules, a complete aero-hydro elastic analysis of wind turbines is possible. FAST code accounts for damping and added mass from linear radiation, including free surface memory effects.

2. Numerical analyses

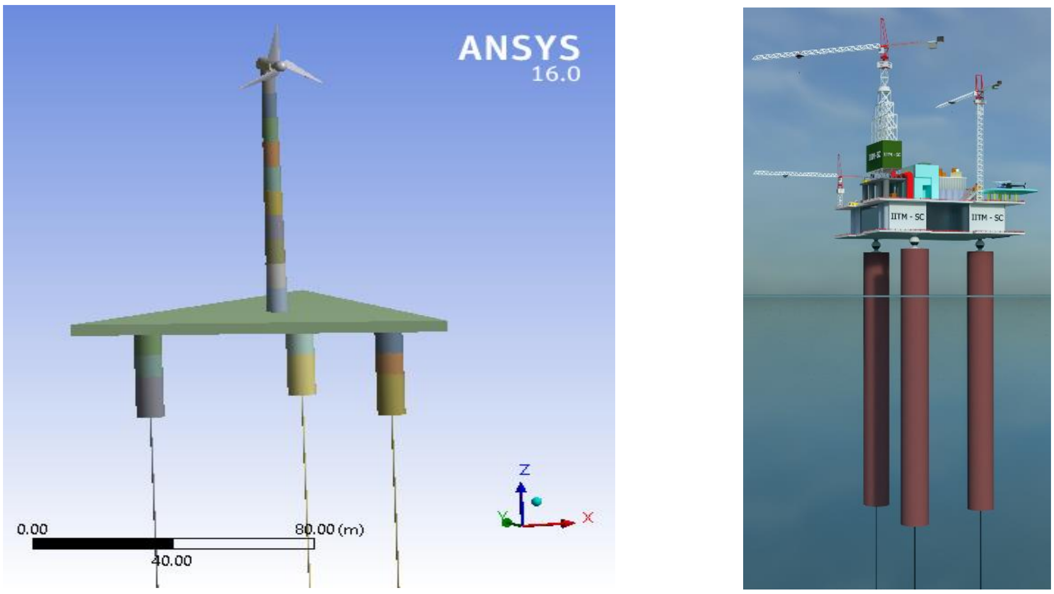
The FAST code, developed by the National Renewable Energy Laboratory (NREL), which is a coupled dynamic analysis simulator, is used in the present study. Subroutines in the FAST code such as AeroDyn and HydroDyn seek wind and hydro data, respectively, for the analysis. AeroDyn calculates wind load along blades using blade element theory, while TurbSim (Turbulence modeling scaling) generates wind data for FAST code. HydroDyn calculates wave load on a floating system (Jonkman, 2003; Jonkman & Bhul, 2007). Matha et al. (2010) developed fully coupled aero-elastic and hydrodynamic models for offshore wind turbines, illustrating the modeling techniques of such coupled analysis.

Hydrodynamic loading on triceratops arising from irregular waves is simulated using a JONSWAP spectrum with FAST code. A floating wind turbine is considered as two bodies, namely a floater and a wind turbine. Therefore, an interactive dynamic relation between the floating platform and wind turbine becomes necessary, leading to multi-body dynamics. Kane’s method for multi-body dynamics, used in the current study, handles the interaction between the floating platform and the wind turbine. Multi-body motion has 22 degrees of freedom (DOF) for a two-bladed horizontal axis floating wind turbine model and 24 DOF for a three-bladed horizontal axis floating wind turbine model.

A 5MW baseline wind turbine, supported by a triceratops, is investigated under the combined action of wave and wind. Details of the 5MW wind turbine, mast, structural properties of triceratops, and sea states are chosen appropriately. **Table 1** shows a summary of details. A preliminary design of the base floater is carried out to ensure stability checks and recentering capacity under free-floating conditions; a positive meta-centric height is maintained. Numerical analyses are carried out by coupling the frequency domain parameters obtained in ANSYS AQWA with that of the FAST. **Figure 1** shows the triceratops and the numerical model of the wind turbine on the triceratops. Triceratops is modeled in ANSYS AQWA software. Cylindrical elements are used to model buoyant legs, while plate elements are used to model the deck. The meshing of the model is done using quadrilateral plate elements with the total number of nodes and elements as 9,406 and 9,398, respectively. The mast of the wind turbine is considered a point load, acting on the mass center of the deck.

Table 1 Geometric properties of the system.

Description	**Value**
Water depth	600 m
Distance between each buoyant leg	70 m c/c
Outer diameter of each buoyant leg	17 m
Moment of inertia (MoI) of each leg (I_{xx}, I_{yy})	26.02×10^6 m^4
Radius of gyration of each leg (r_{xx}, r_{yy})	51.46 m
MoI of the deck (I_{xx}, I_{yy})	3.56×10^6 m^4
Radius of gyration of deck (r_{xx}, r_{yy})	29.6 m
Area of deck	1,732.4 m^2
Draft	76.7 m
Axial stiffness of tethers	84 MN/m
Buoyancy	86.74 MN
Self-weight of platform	39.82 MN
Self-weight of mast	6.8 MN
Meta-centric height	12.25 m



(a) (b)

Figure 1 (a) Wind turbine mast on triceratops; (b) Schematic view of offshore triceratops (Chandrasekaran & Chauhan, 2023).

The rigid body motion of the wind turbine, including the supporting platform, is given by:

$$[M + M_a]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f(t, x, \dot{x})\} \quad (1)$$

where $[M]$ is the mass of the total system, $[M_a]$ is the added mass arising from the variable submergence on the buoyant legs, $[C]$ is the Rayleigh damping matrix arising due to aero and hydrodynamic damping, $[K]$ is restoring and recentering forces offered by tethers, and $\{f\}$ is the force vector occurring due to wave loads on buoyant legs; wind loads on the mast are not considered. A JONSWAP (Joint North Sea Wave Project) spectrum is used for wave forces with a significant wave height of 3m and a peak spectral period of 10s. A peak enhancement factor of 3.3 is chosen for the spectrum, with a frequency resolution of 0.001 Hz. Corresponding sea state records mean wind speed of about 11.4 m/s; the Kaimal spectrum is used for wind forces. Wind turbine supported on triceratops is analyzed for two conditions: operating and parked conditions. Operating condition includes spatially coherent turbulence of 10 % on the sheared wind profile with an exponent of 0.15; shear and turbulence factors are neglected in the parked condition. Since members of triceratops are slender, their structural behavior is described by beam theory (Srinivasan, 2017; Srinivasan et al., 2013). Nonlinear dynamic response analysis is carried out in FAST by coupling frequency domain parameters of the platform obtained in ANSYS AQWA in the HydroDyn module of FAST.

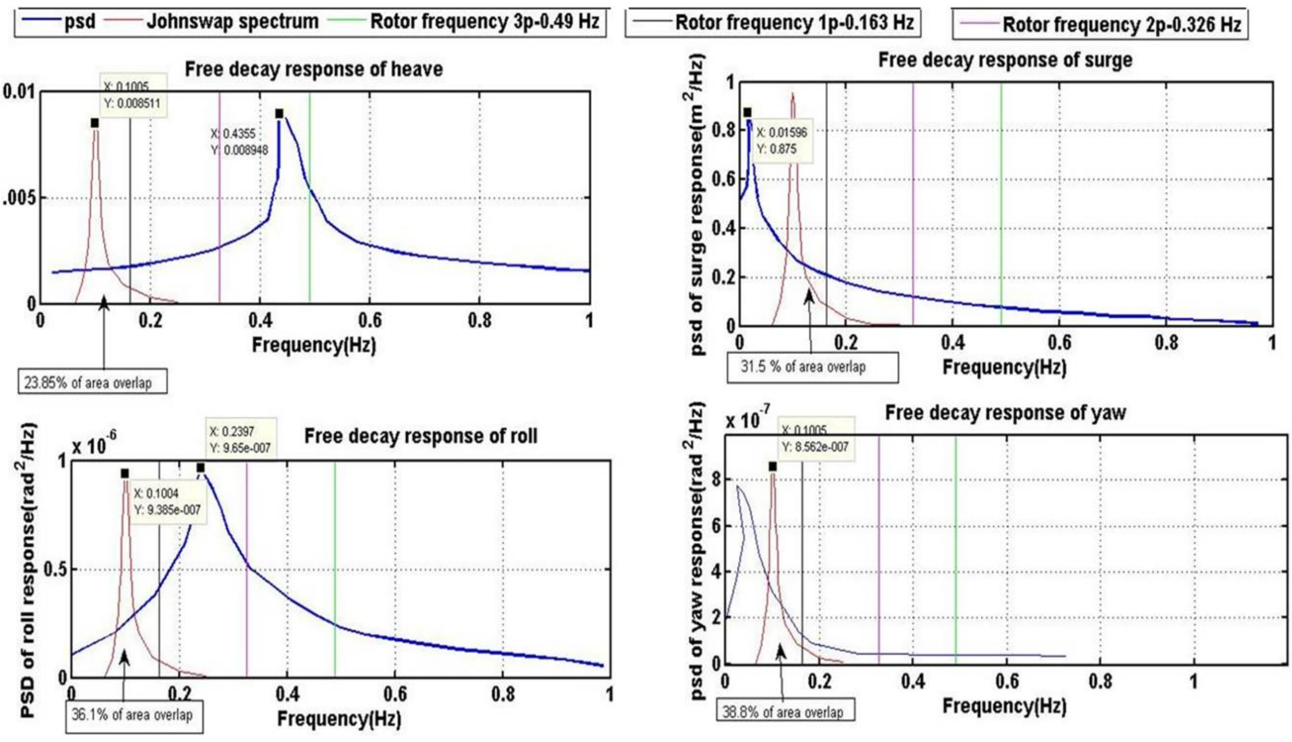


Figure 2 Power spectral density plots of free decay responses.

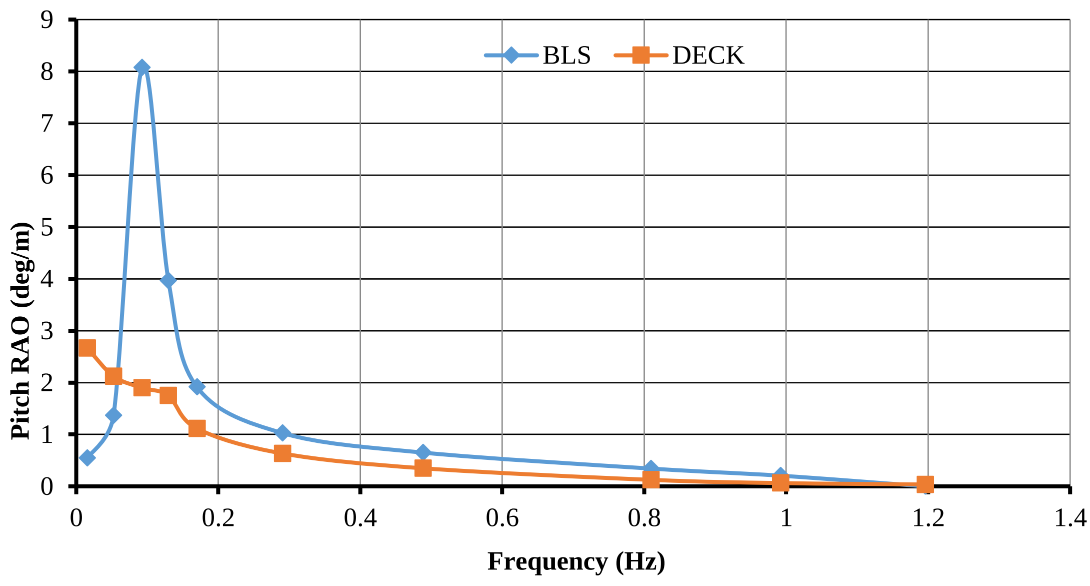
3. Results and discussion

3.1 Free vibration analysis

Power spectral density plots of free decay responses are shown in **Figure 2**. It is seen from the figures that peaks occur at 0.44 and 0.24 Hz for heave and roll degrees of freedom, respectively; surge and yaw peaks occur at 0.02 and 0.03 Hz, respectively. The latter values correspond to natural frequencies in surge and yaw, respectively. As the platform is symmetric, responses in roll and pitch and those of surge and sway are similar. PSD response shifts towards a higher frequency of the wave spectrum in stiff degrees of freedom, while reversed in the case of flexible degrees of freedom. The natural frequencies of triceratops do not lie in the resonance band of the wave spectrum in any active degrees of freedom. It is also seen that both the peaks of the wave spectrum and rotor frequency are separated from those of the responses with a safe margin. Hence, excitations that arise from waves and wind-driven rotors fail to excite triceratops, making the support system dynamically safe; distinct differences in the peak frequencies verify this statement. The area of overlap between the wave and response spectra is about 23.85, 31.5, 36.1, and 38.8 % for heave, surge, roll, and yaw, respectively. It is suggestive that wave energy influences yaw motion to the maximum, and heave to the minimum. It is interesting to note that heave response is controlled by deep draft, even though the heave natural frequency is closer to that of the rotor. Since the triceratops are stiff in the vertical plane due to taut-moored tethers, the safety of the deck is not compromised, as it is partially isolated.

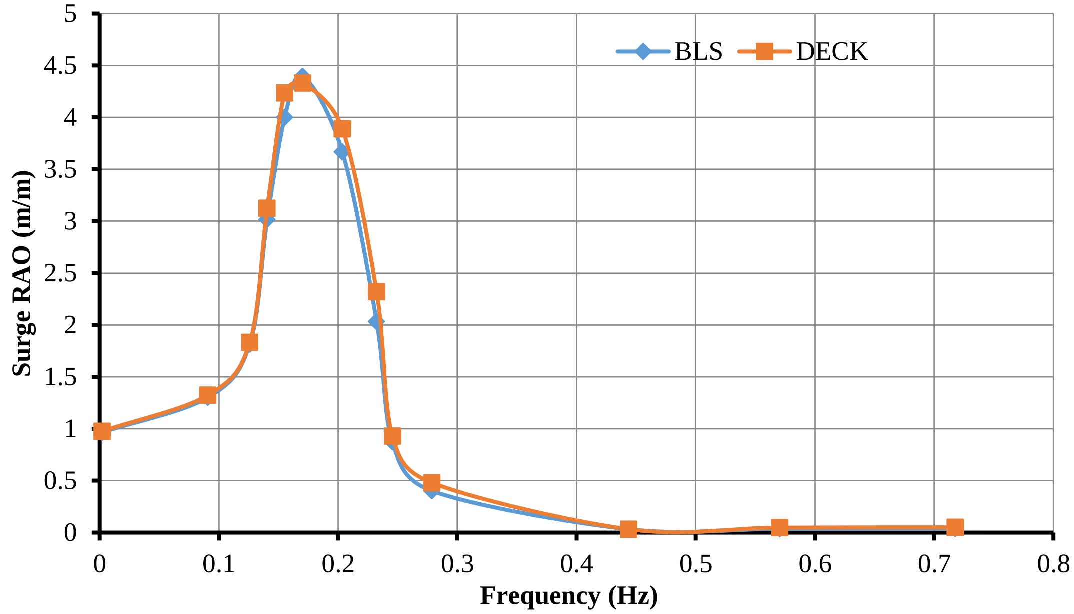
3.2 Partial isolation of deck under wave loads

The wind turbine (under parked condition), mounted on triceratops, is subjected to wave loads with a wave heading along the surge axis. Response Amplitude Operators (RAO) are plotted for heave, surge, and pitch responses, as shown in **Figure 3**. It is seen from the plots that there exists monolithic action between buoyant legs and the deck in translational degrees-of-freedom, namely surge, and heave. However, the rotational response of the deck in pitch degree of freedom is significantly reduced as ball joints restrain the transfer of rotation from the legs to the deck. The deck remains almost horizontal, even for a significant rotational response of the buoyant leg, highlighting its suitability for housing a wind turbine mast on the deck. It is interesting to note that pitch response occurs in the deck due to differential heave. Each buoyant leg is subjected to varying tether tension, causing differential heave. Partial transfer of response from the buoyant legs to the deck establishes functionality of the ball joint in isolating rotational motion but transferring translational motion. The moment-rotation capacity of the ball joint is a design constraint, which is derived based on the mass of the platform (more details can be seen in Srinivasan & Nagavinothini, 2020).

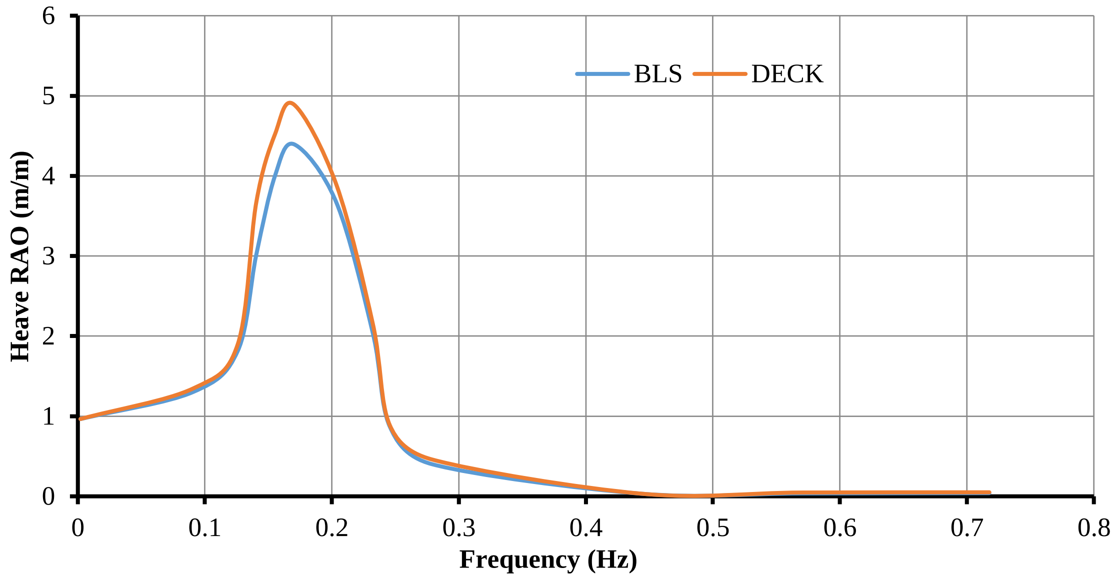


(a)

Figure 3 Response under wave loads (wind turbine parked).



(b)



(c)

Figure 3 (continued) Response under wave loads (wind turbine parked).

3.3 Response under operating conditions

The heave response of the deck, as seen in **Figure 4**, indicates almost the same magnitude under both operating and parked conditions of the wind turbine; the significant difference is that the response spectrum is broader under operating conditions. However, the heave response magnitude is not significantly altered under operating conditions, as the operating mass of the wind turbine mast is only about 17 % of the total mass of the platform. Wind load causes yaw motion under operating conditions of the turbine, which is a significant manifestation of aerodynamic load on the platform. As seen, the yaw response of the deck is significantly higher under operating conditions of the wind turbine. Although this response is not transferred to the buoyant leg due to the presence of ball joints, this results in dynamic tension variation in the tethers.

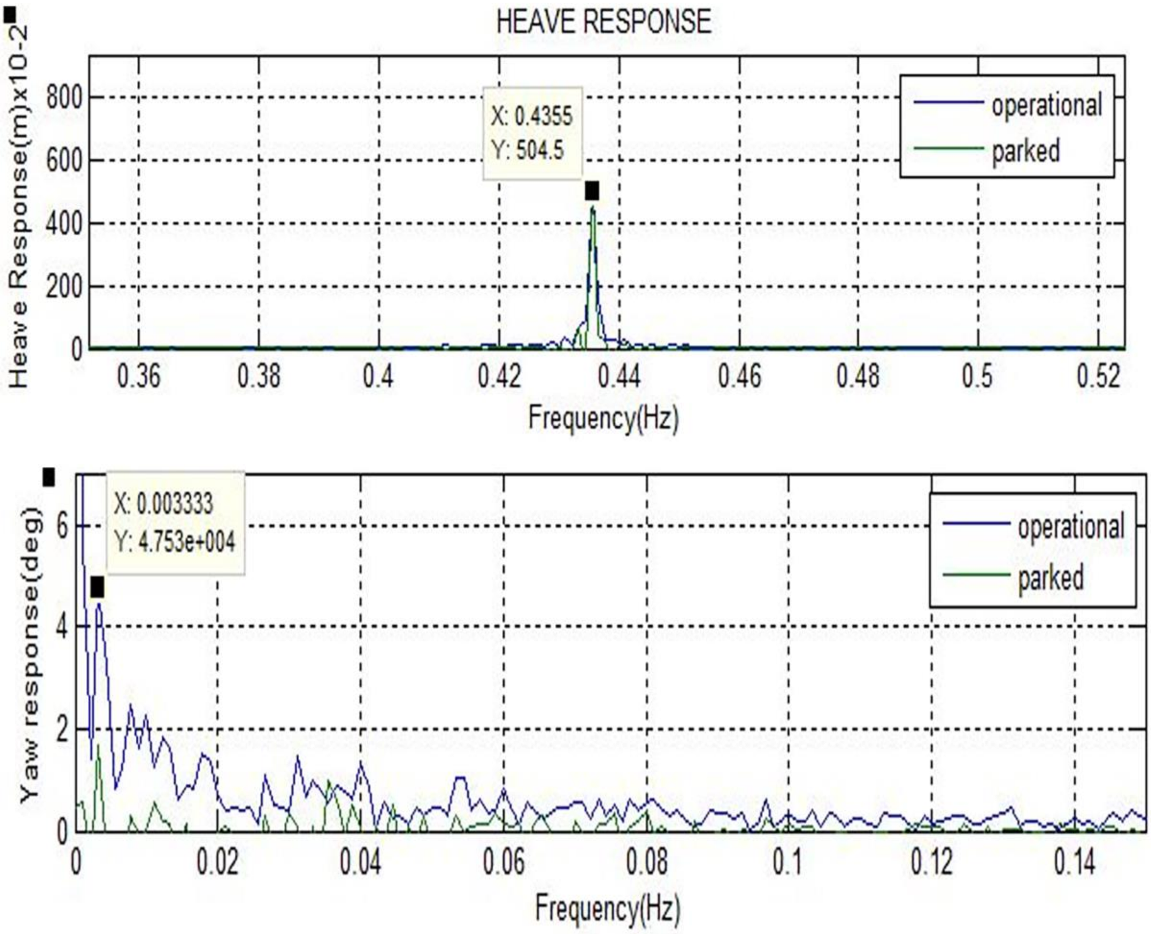


Figure 4 Heave and yaw responses.

Power spectral density plots of the system under the operating conditions in the presence of wave and wind are shown in **Figure 5**. Responses illustrate the relationship between various exciting modes and responses in the respective degrees of freedom. Peaks of heave response, seen at the dominant wave frequency and surge frequency, show a strong coupling between these degrees of freedom. This enables an effective recentering and additional damping due to set-down caused by heave motion. Roll and pitch exhibit peaks at frequencies closer to their natural ones. In addition, roll response is also excited near the dominant wave frequency under the uni-directional waves considered for the study.

Pitch response exhibits similar to roll but with a larger standard deviation due to uni-directional waves. Low-frequency excitations are driven by turbulence in both responses. Yaw response demonstrates the effect of all other degrees of freedom on yaw response, as this can be seen by the presence of smaller peaks at natural frequencies of other degrees of freedom. Rotor load excitation is seen as a peak at 0.49 Hz, suggesting the influence of rotor loads on the yaw response. A peak is observed at the 3p excitation of the rotor, indicating the effect of rotor loads on the yaw response. It is important to note that yaw response is not a result of direct wind and wave loads but is caused by the resultant effect of tension variations on tethers.

3.4 Dynamic tether tension variation

Damage to compliant structures can be quantified through the damage of tethers. **Figure 6** shows the time history of tether tension variation of the three buoyant legs caused during the operation of the wind turbine; Douglas Seastate-3 is considered for the wave load. It is seen from the figure that, apart from being dynamic, the peak of tether tension at any instant of time does not necessarily mirror the remaining group of tethers. This is because there exists a phase lag between the wave approaches on each tether; when one tether gets taut moored, the other gets slackened, and vice versa. Dynamic tether tension variation, a significant manifestation of the wind turbine in operating conditions, results in differential heave. This further results in roll and pitch responses on the deck. It is important to note that rotational responses of the deck are absent under the wave action due to the presence of ball joints. **Table 2** shows the tension variation in each buoyant leg. It is seen from the table that maximum tether tension variation lies in the range of 8.6 to 14.56 %, which is less than 20 %; hence, the pull-out of tethers is unlikely, which makes the design of the supporting system safe under operating conditions.

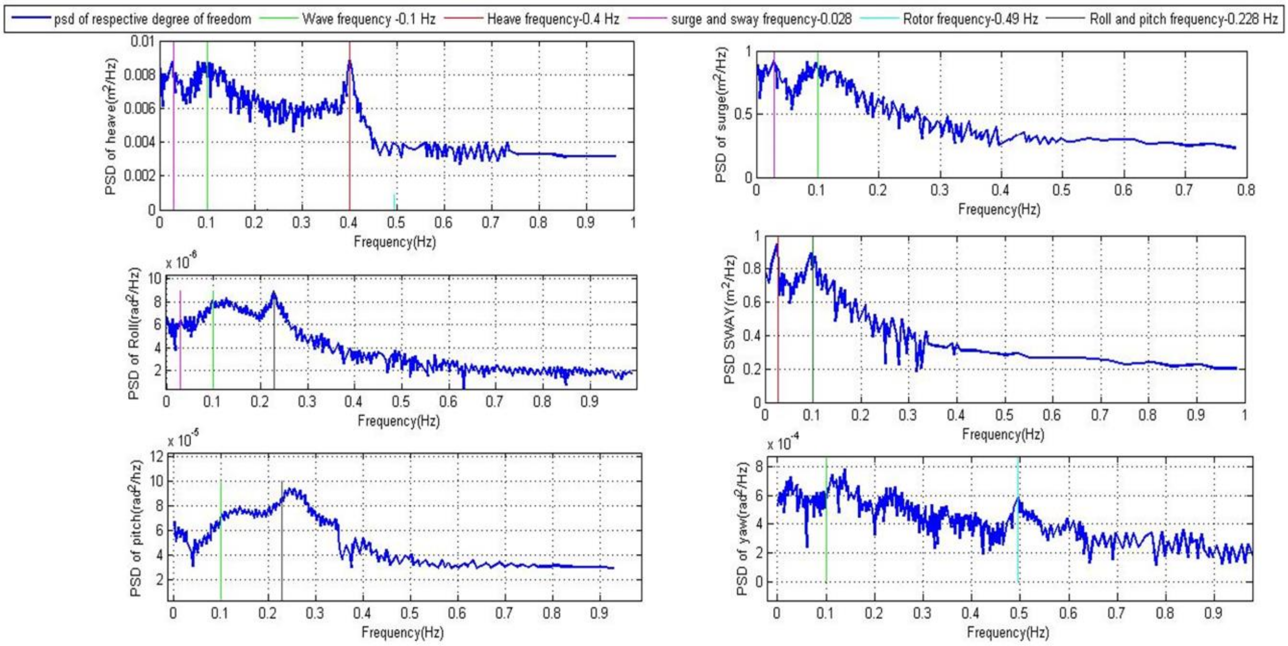


Figure 5 Response plots at various excitations.

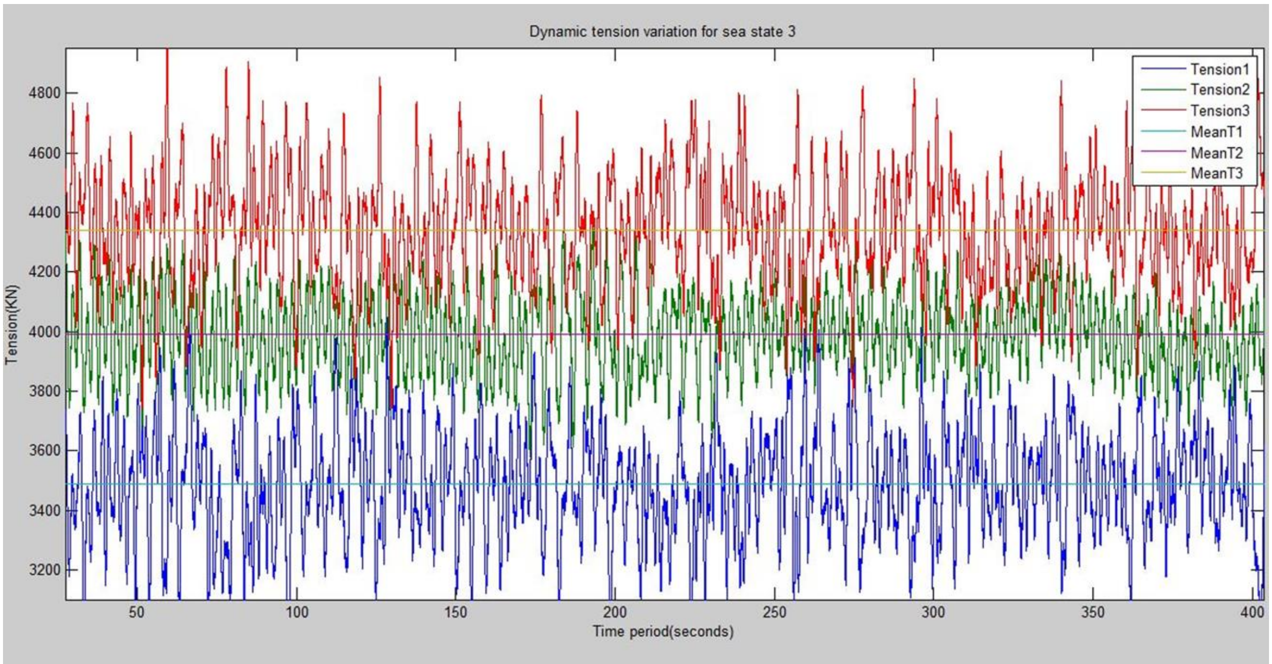


Figure 6 Dynamic tension variation in buoyant legs.

Table 2 Normalized tether tension variation.

Description	Tension (kN)			% Variation
	Max	Min	Mean	
Buoyant leg 1	3,988	2,969	3,490	14.56
Buoyant leg 2	4,337	3,662	3,990	8.60
Buoyant leg 3	4,874	4,001	4,340	12.30

3.5 Service life estimation

It is a common practice to assess the service life of compliant offshore platforms through fatigue caused by tether tension variations. Unlike fixed platforms, where strength is the main criterion for assessing damage, tether tension variation is significant, as pulling out of even one tether will make the total system positive-buoyant and unfit for operation. While the wind turbine is operating, tension variations under normal sea state do not exceed the permissible limits (as discussed above). Therefore, a very rough sea state is simulated to estimate the stress time history of tethers. A rain-flow counting algorithm is used to obtain the required stress histogram from which service life is estimated (Kai-Tung et al., 2017; Chandrasekaran et al., 2022). Damage is estimated for the simulation of 900s using the Palmgren-Miners rule. Subsequently, service life is estimated based on the total number of stress bins. **Table 3** shows the service life estimated for different sea states while the wind turbine is in operation.

Table 3 Service life estimate.

Sea state	Wind speed (knots)	Significant wave height (m)	Fatigue life (years)
3	11 to 16	0.5 to 1.25	27
6	28 to 33	4.0 to 6.0	9.47

4. Conclusions

A 5MW Baseline wind turbine, mounted on offshore triceratops, is investigated under both operational and parked conditions of the wind turbine. Under wave loads, rotational responses of the deck are significantly less than that of the buoyant legs. A fully coupled three-dimensional hydro-aerodynamic model is developed to investigate response under the aerodynamic loads, which encompasses the effect of wind shear using a power law and spatially coherent turbulence. Nonlinear dynamic response analysis is carried out in FAST by coupling the frequency response of the platform obtained in ANSYS AQWA with that of the HydroDyn module of FAST. Due to partial isolation, the deck remains almost horizontal even for a significant rotational response of the buoyant leg, highlighting its suitability for housing a wind turbine mast on the deck. Wind loads, causing yaw motion under operating conditions of the turbine, are significant manifestations of aerodynamic loads on the platform. Dynamic tether tension variations caused by the operation of the wind turbine result in differential heave. This further results in roll and pitch responses of the deck. It is seen from the analysis that maximum tether tension variation lies in the range of 8.6 to 14.56 %, which is less than 20 %; hence, the pull-out of tethers is unlikely, which makes the design of supporting system safe for operating 5MW wind turbine for the chosen sea state. While the service life of the platform is about 27 years under an operational sea state, it is about 9.5 years under a very rough sea state. By parking the turbine under such conditions, the service life of the system can be enhanced. Ultimate limit state conditions shall also govern the design, which shall be considered; however, this study is limited to the performance assessment only, and not the design perspective. The presented study is prima facie to encourage the suitability of triceratops as floaters to support the wind turbine under moderate sea states.

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