Seismic Response of Spar Floating Offshore Wind Turbine

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Abstract. The future of the offshore wind market is looking forward to floating foundations as they are more promising in deep waters. Seismicity is a concern along the offshores of the Western United States and East Asia, which has fueled scientific interest in seismic design. This study focuses on the performance-based seismic design of spar floating wind turbines. Spar is a ballast stabilized structure anchored to seabed using catenary mooring lines. A three-dimensional model of the platform- mooring -anchor system is developed in ABAQUS CAE, where the soil is modeled using non-linear Winkler's spring. The hydrostatic stiffness is represented using springs. Hybrid beam elements (high axial stiffness compared to bending stiffness) are used to model the mooring line. The effect of high-intensity earthquake shaking, peak ground acceleration, predominant frequency, and the impact of combined seismic-wave loading are evaluated in detail. Wave loads are observed to govern the design of spar wind turbines. In all the cases considered, seismic responses are found to be minimal. This preliminary study noted that spar floating wind turbines are less susceptible to earthquake dynamics due to the catenary shape, low mass of cable, and the long natural vibration period. This study will help to evaluate the feasibility of spar floating wind turbines in seismically vulnerable areas.

Keywords: *Spar- floating offshore wind turbine; seismic ground motion; suction caisson; Wave load*

1 Introduction

In the present scenario, shifting to renewable energy sources is urgently needed. Although wind energy is one of the most promising forms of renewable energy, it requires good attention to make it more economical and viable. The availability of robust and less turbulent wind, less noise, and being far away from public visibility makes offshore wind turbines more attractive. However, the infrastructure of offshore wind farms is expensive and complex, especially in deeper water, and requires high-standard construction equipment. Water depth directly affects the cost of foundations, making it uneconomic to build fixed structures in deep water. In this situation, floating wind turbines would represent a significant advancement.

There are three fundamental concepts for floating wind turbines based on the way they attain static stability: Spar, semi-submersible, and Tension leg platform. Spar is a ballast stabilized structure that achieves rotational stability by keeping its center of gravity well below the center of buoyancy and translational stability from the catenary or taught mooring line. Semi-submersible is characterized by a large water plane area, while a pre-tensioned mooring line makes TLP stable. The world's first operational floating wind turbine, Hywind (Statoil), was installed in Norway in 2009. In 2019, 11.4 MW of floating offshore wind was established and about which 8.4 MW are in Portugal and 3MW from Japan. Thus, the total offshore wind reached 65.7 MW across the world by 2019 and of which 32 MW in the UK, 19 MW in Japan, 10.4 MW in Portugal, 2.3MW in Norway, and 2 MW in France and planned to increase the total capacity to 2GW by 2030.

Previous studies on bottom fixed offshore wind turbine show that wind turbines are prone to earthquake shaking (Patra et al., 2022; Patra and Haldar, 2022, 2021; Bhattacharya et al., 2021; Amani et al., 2022; Risi et al., 2018 and James and Haldar, 2022). However, the seismic studies on floating wind turbines are limited. Seismic waves are transferred to the floater as compressional Primary (P) waves via cables and will pull the cables and transfer the movement to the floater. It can also be argued that the cables cannot transmit seismic waves due to the low mass of cables and the high damping offered by the surrounding water. Many seismic studies have been conducted on floating structures such as oil and gas platforms and tunnels, but on the seismic vulnerability of floating wind turbines is limited. Kawanishi et al. (1993) studied the response of TLP under vertical earthquake shaking along with wind, wave, and current loads. The vertical component superimposes the tension in tethers, but it is within the permissible limit. The acceleration caused due to the ground shaking hardly gets transmitted into the hull. The earthquake Response of the TLP Under Offset condition indicates that TLPs have poor resistance against wind waves and current loads, and the behavior will deteriorate when vertical excitation combined with the lateral loads. Liou et al. (1988) analyzed the vertical motion, tether force, and foundation uplift of a TLP when the subsoil is excited by seismic waves. The maximum seismic response was due to the vertical earthquake ground motion in the narrow band around the fundamental frequency of TLP, which indicates the need to select a proper accelerogram for the design of TLPs. Chandrasekaran et al. (2006) conducted the seismic analysis of Offshore Triangular Tension Leg Platforms and reported that TLPs would show non-linear behavior when seismic loading was combined with wave load. Retnamma and Shaji (2016) conducted a seismic study on mini TLP and concluded that the earthquake response on TLP reduces as the water depth increases. The maximum reduction in response is observed for heave motion compared to pitch and surge. The dynamic response of deep-water tension leg platforms under different PGA, wave heading angles, and ground motion directions are studied by Yu et al. (2021). Downward excitation increases tension, but it was within limits.

Suroor et al. (2019) stated that horizontal seismic motion does not influence the TLP due to the high flexibility of tendons in the lateral direction. Therefore, they are safe from platform and tendon forces. However, it may cause significant damage due to the slacking of tendons if horizontal shaking combines with strong currents and high sea waves (extreme environmental events). Suzuki et al. (2010) conducted a seismic study of TLP by observing the responses at the nacelle level and column corner. The tendon tensions due to vertical seismic excitation are appeared to be within the design range, and no slack is observed due to seismic loading. Bhattacharya et al. (2021) studied the effect of the vertical and horizontal components of seismic motion on the performance of the TLP wind turbine. They concluded that TLP-type floating wind turbines are more susceptible to vertical than horizontal ground motion. Vertical shaking causes overturning failure in TLP. Also studied was the effect of fault rupture in TLP under two conditions: (i) loss of the pretension force in the tension leg and (ii) increased tension due to the pull of the foundation under the tension leg. Loss of pretension force in TLP is most critical compared to additional tension in the tension leg since it creates an additional rotational effect at the tower top.

All the above studies are limited to tension leg platforms, and very few studies have been done on a spar floating wind turbine. Considering the high seismicity record of potential offshore wind farms and the fact that wind turbines are expensive and a slight flaw could result in a substantial loss, it is imperative to do a seismic analysis on floating wind turbines. This study focused on the seismic analysis of a spar floating wind turbine. This paper is organized into three sections. First is the evaluation of seismic performance with respect to an earthquake of high PGA. The effect of wave loading along with seismic excitation is examined further. Finally, the vulnerability of the wind turbine to earthquakes of different predominant frequencies and PGAs are evaluated. This study will aid in determining the feasibility of floating structures in seismically active regions by assessing the seismic sensitivity of spar floating wind turbines.

2 Numerical Model and Validation

A three-dimensional model of the platform- mooring -anchor system is modeled in ABAQUS (CAE, 2018) is shown in Fig. 1. The soil is represented using API-based p-y, q-z, and t-z curves (API 2011). The undrained shear strength, s_u is assumed to be 50 kPa with a uniform variation along the depth. The submerged unit weight is 7.5 kN/m^3. The mooring lines are secured to the seafloor using a suction caisson. The hydrostatic stiffness is provided using springs. Quadratic hybrid beam elements (high axial stiffness compared to bending stiffness) are used to model the mooring line. At the initial stage, buoyancy loading is applied at the center of buoyancy (at 60m from MSL), together with gravity loading. The detailed dimensions and properties of the platform-mooring-anchor system are given in Matha (2010). The model is validated by comparing the obtained natural frequency with the reported one in the literature, Matha (2009) (see Table 1)

Table 1 3D FE analysis and the reported natural frequencies of the spar floating OWT (Matha, 2010)

Mode	**Observed (Hz)**	**As reported in Matha (2009) (Hz)**
Platform surge	0.0079	0.0080
Platform sway	0.0079	0.0080
Platform heave	0.0329	0.0324
Platform roll	0.0353	0.0342
Platform pitch	0.0353	0.0343
Platform yaw	0.160	0.1210

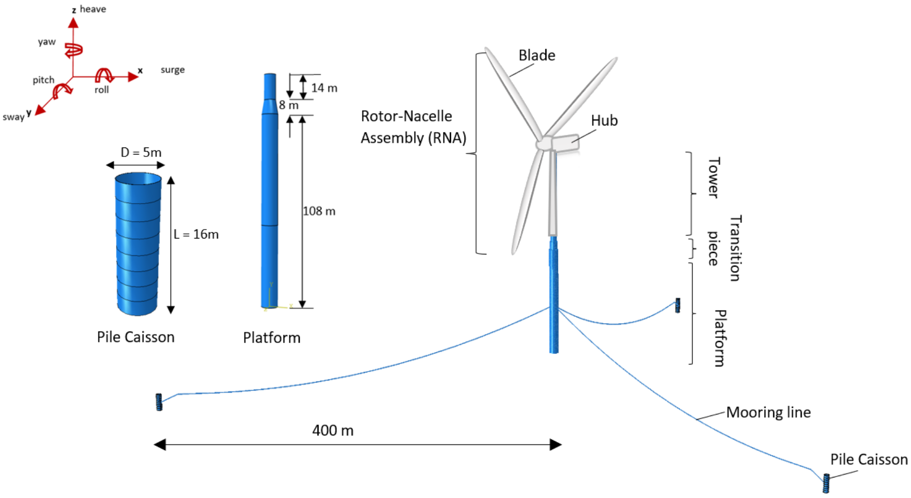

Fig. 1. Numerical Model of Spar floating wind turbine developed in Abaqus CAE

The seismic vulnerability of a spar floating wind turbine is evaluated by applying earthquake motion in two horizontal components. Three earthquakes are chosen based on the predominant frequency and are scaled down to 0.1g, 0.3g, and 0.5g. The properties of earthquakes used in this study are reported in table 1. The typical acceleration time history of the Kocaeli earthquake before scaling is shown in Fig. 2

Table 2. Properties of earthquakes used in this study

Earthquake	Predominant Frequency of H_1 (Hz)	Predominant Frequency of H_2 (Hz)	V_{s30} (m/sec)	Rupture distance (km)	Mag.
Northridge, 1994	1.22	0.88	370.52	99.59	
Kobe, 1995	0.59	2	312	0.27	6.9
Kocaeli, 1999	0.195	6.1	523	13.49	7.51

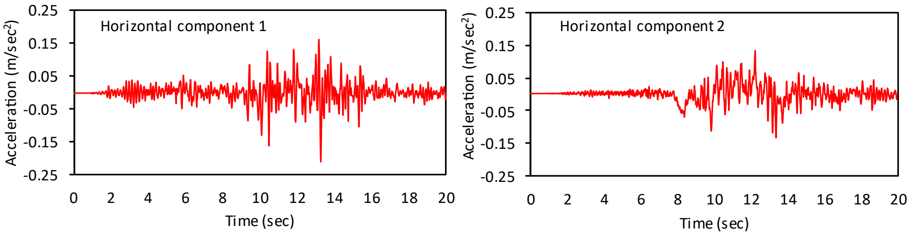

Fig. 2. Acceleration time history of unscaled Kocaeli (1999) earthquake.

3 Performance-Based Design

The performance is evaluated by examining the acceleration, lateral displacements, and rotational response at the nacelle. For the smooth performance of the wind turbines, DNV codes suggest limiting the combined pitch and roll rotation to 7 - 10 degrees, and the displacement in surge and sway direction is restricted to 0.2 times water depth (Bhattacharya et al., 2021).

4 Results and Discussion

All other environmental and operational loads are initially neglected to evaluate the earthquake susceptibility in detail. Further, the performance is assessed under combined seismic, wave, and operating loads. Finally, the effect of Peak Base acceleration (PBA) and predominant frequency of earthquake on the spar wind turbine is evaluated and discussed in the following section.

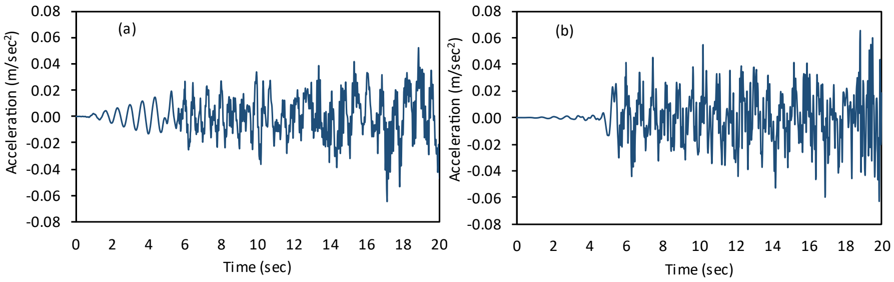

Fig. 3. Acceleration response at nacelle in (a) surge and (b) sway direction

The acceleration response in the horizontal and vertical directions is shown in Fig 3. Here, the maximum acceleration observed at nacelle is 0.06 m/sec^2, which is lower than the permissible value of 0.25g. The lateral displacement and rotational response of the tower at the topmost point are presented in Fig. 4. The maximum value is 40 mm, which is relatively small compared to the restricted value for safe performance. Similarly, the rotational responses are also observed to be minimal. Due to the catenary shape and low mass of the cable, the earthquake forces are not transmitted to the floating structure. Hence from this preliminary study, floating wind turbines with catenary moorings have marginal impact during seismic shaking.

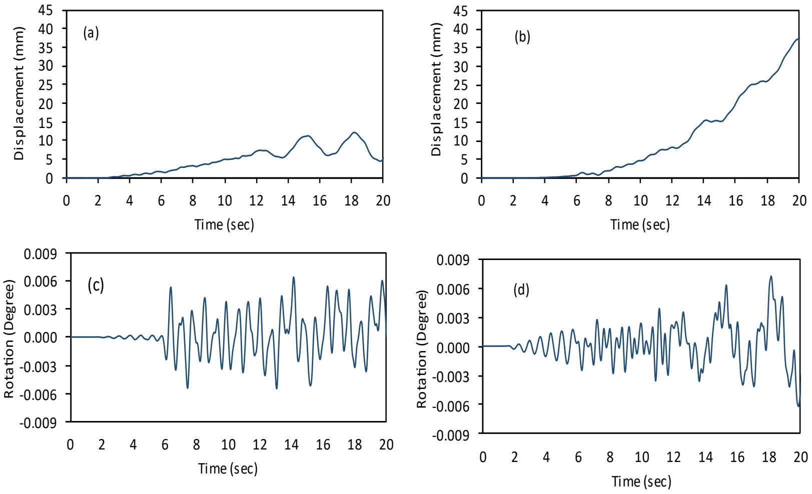

Fig. 4. Responses at tower top during Kocaeli earthquake of 1999 scaled to 0.5g (a) displacement in surge (b) displacement in sway direction (c) rotational response in roll (d) rotational response in pitch

4.1 Combined Seismic and wave loading

The effect of wave loading along with seismic excitation is evaluated further to comprehend the impact of environmental loads during an earthquake. The wind turbine is analyzed under normal operating conditions. The Kocaeli earthquake of 1999, scaled to 0.5g, is used as the input earthquake motion. Other operational loads such as 3P and 1P are included in this study, along with wave load. The wave height and wave period of 2.25m and 5 sec are selected, which is the wave climate of the Indian offshore at 150 m water depth at 20.91 latitudes and 69.25 longitudes. The wave load is applied in the x direction. Therefore, only those responses are reported in Fig 5.

The lateral displacement, the rotational response, and the acceleration at the nacelle with and without considering earthquake loads along with wave and operational loads are shown in Fig 5. The response coincides in both cases. The design of a spar floating wind turbine is therefore governed by wave loads and not earthquake loads.

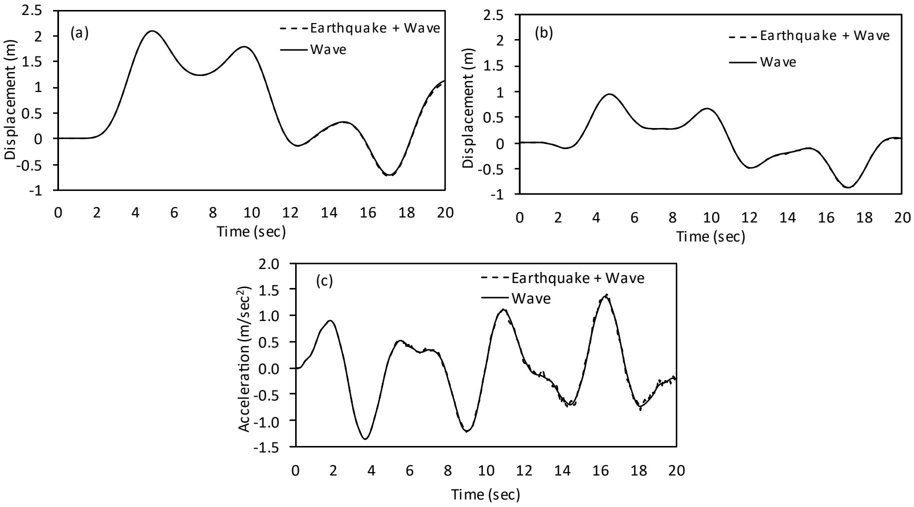

Fig. 5. The responses at nacelle during the combined seismic, wave, and operational loading. (a) Lateral displacement in surge (b) pitch rotation (c) Acceleration in the surge

4.2 Frequency Study

The response of spar floating wind turbines to the predominant earthquake frequency is examined in detail. From the above studies, seismic loading shows a marginal impact on a spar floating wind turbine. However, the dominant frequency plays a significant influence in defining the seismic demand of a structure, as resonance with the structural frequency may amplify the seismic demand. Many past studies (Patra and Haldar, 2021; James and Haldar, 2021, 2022) have shown that monopile and jackets are prone to high-frequency vertical shaking due to the closeness of natural structure frequency with the predominant frequency of earthquakes in the vertical direction. But the effect of frequency content on floating wind turbines has not been studied in detail. Hence, to explore this effect, motions having three different predominant frequencies are considered. One is close to the structural frequency in the yaw direction (0.16 Hz), one far away from the structure frequency range, and the other between these two.

The various response at nacelle is shown in Figs 6 and 7. In x axis, predominant frequency of earthquake (f_{pr}) is normalized with respect to the natural frequency of platform in yaw direction (f_y). The maximum acceleration reported is 0.067 m/sec^2 which is much lower than the permissible limit of 0.25g. It is observed that, as the predominant frequency increases, the responses reduce. The maximum response is recorded when the ratio of predominant frequency to structural frequency is close to 1, i.e., resonance condition. In general, the horizontal component of the earthquake is characterized by low-frequency seismic waves, whereas high-frequency content is in the vertical direction. Consequently, spar floating wind turbines are significantly more susceptible to horizontal seismic motion.

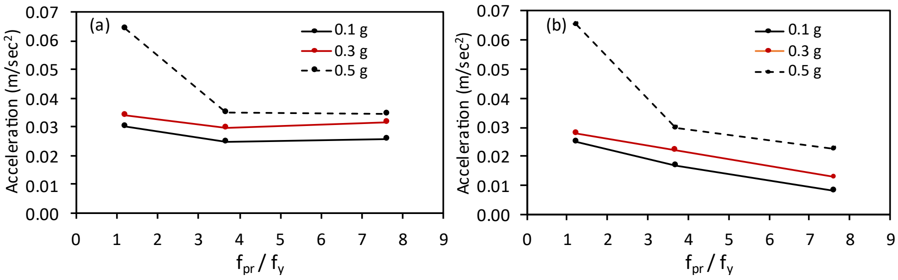

Fig. 6. Acceleration in (a) surge and (b) sway direction at nacelle

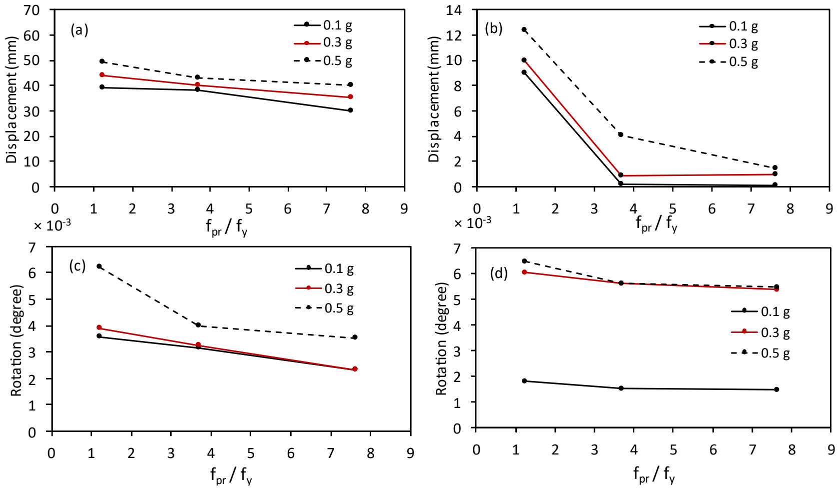

Fig. 7. The variation of lateral displacement of the tower top) in (a) surge, (b) sway direction and rotational response in (c) pitch and (d) roll direction with respect to ratio of predominant frequency of earthquake (f_{pr}) to yaw frequency (f_y)

4.3 PGA Study

Peak ground acceleration (PGA) is one of the primary determinants of the intensity of earthquakes. The significance of PGA on the seismic performance of spar wind turbines is analyzed at a deeper level. Fig 8. presents acceleration response at nacelle with respect to peak base acceleration. The variation of lateral displacement of the tower top corresponding to the predominant frequency of earthquake in the surge, sway and heave direction are shown in Fig. 9. The response increases as peak base acceleration increases. However, all the responses are within the permissible limit.

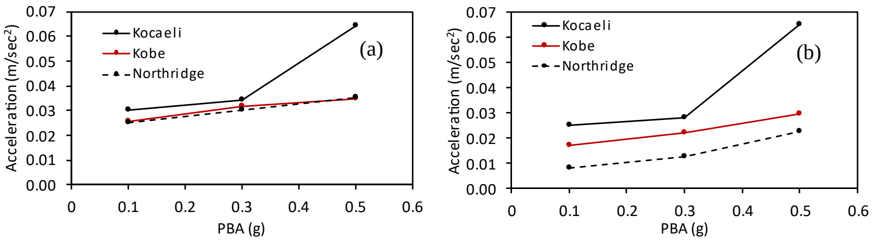

Fig. 8. Acceleration response at nacelle with respect to various PBA in (a) surge and(b) sway direction

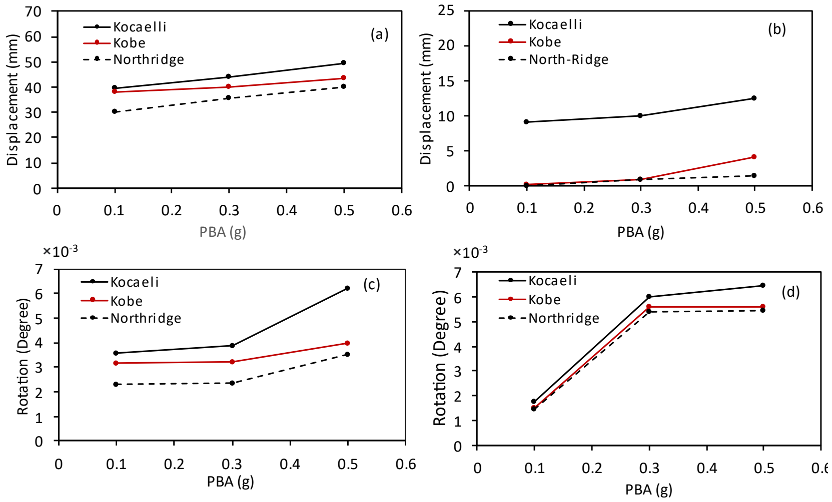

Fig. 9. Response at nacelle with respect to various Peak Base Acceleration (a) Displacement in surge, (b) displacement in sway (c) pitch rotation, and (a) rotation in roll

5 Conclusion

The seismic susceptibility of a spar floating wind turbine is evaluated to determine the feasibility of deploying floating wind turbines in seismically active areas. The effect of high-intensity earthquake shaking, peak ground acceleration, predominant frequency, and load combination effects are evaluated in detail. Observations indicate that the response to wave loads alone and seismic plus wave loads are the same. Hence, it can be inferred that wave load will govern the design. Further, the effect of peak base acceleration and predominant frequency on the seismic design of the spar is examined. The spar wind turbines are more prone to low-frequency earthquake shaking, which generally occurs in the horizontal component of near-field earthquakes. In all the cases evaluated, responses are found to be minimal. Therefore, it can be inferred spar floating wind turbines are less susceptible to earthquake dynamics due to the catenary shape, low mass of cable, and the long natural vibration period. This is a preliminary study on assessing the safety of wind turbines during ground shaking. This study's future scope is anticipated to include a more in-depth examination of the secondary risks associated with earthquakes.

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