FLOATING OFFSHORE WIND TURBINES: TENSION LEG PLATFORM AND TAUGHT LEG BUOY CONCEPTS SUPPOTING 3-5 MW WIND TURBINES

by

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Abstract

The development is presented of two low weight, motion resistant stiff floating wind turbine concepts for deployment in water depths ranging from 30 to several hundred meters in seastates with wave heights up to 30 meters supporting 3-5 MW onshore wind turbines. The floating wind turbines may be fully assembled at a coastal facility in their upright position prior to being towed to the offshore site by a stabilizing floater. The Tension Leg Platform (TLP) is moored to gravity anchors with tensioned vertical tethers while the Taught Leg Buoy (TLB) is moored to the gravity anchors with taught mooring lines inclined relative to the seafloor. The linear and nonlinear wave loads on the floater are obtained using methods developed for the design of oil and gas offshore platforms. The wind loads are obtained from wind turbine models that do not require the full coupling of the wind turbine aero elastic dynamics with the tower, floater and mooring system dynamics. Simulations are presented of the floater responses in seastates with significant wave heights up to 14 meters and in water depths ranging from 30 to 150 meters demonstrating low nacelle accelerations and mooring line dynamic tensions.

1. Introduction

Wind is a rapidly growing renewable energy source, increasing at an annual rate of 25-30% with the vast majority of wind power generated from onshore wind farms. Their growth is however limited by the visual impact caused by large wind turbines, the lack of inexpensive land near major population centers and restrictions associated with the transportation of large wind turbine components inland. Wind energy generated from floating offshore wind farms near major population centers or in close proximity to strong electric grids is the next frontier. Vast sea areas with stronger and steadier winds are available for wind farm development and 5 MW wind turbine towers located 20 kilometers from the coastline are barely visible. Current offshore wind turbines are supported by monopoles or other structures mounted on the seafloor at coastal sites a small distance from shore and in water depths of 10-15m. The primary impediment to their growth is their visual impact and their prohibitive cost as the water depth increases.

This article presents the development of a new generation of floating wind turbine concepts supporting 3-5 MW onshore wind turbines, drawing upon research carried out over the past three decades at MIT for the design of offshore oil and gas platforms and since the early 2000’s for floating wind turbine systems [1]. Both concepts can support conventional onshore wind turbines which do not require significant modification for their use in the offshore environment. Simulations are presented of the responses of a Taught Leg Buoy (TLB) with inclined taught mooring lines and a Tension Leg Platform (TLP) system with vertical tethers in water depths ranging form 30 to 150 meters and in seastates with significant wave heights 6, 10 and 14 meters supporting a 3 MW Vestas V90 and a Re Power 5 MW wind turbine. Performance metrics important for floating wind turbine systems include the nacelle acceleration and the mooring line dynamic tension. Low nacelle accelerations are necessary for the reliable operation of the wind turbine and low mooring line dynamic tensions lead to light gravity anchors and longer fatigue lives for the mooring lines, the buoy and tower structures. The sensitivity of both performance metrics on the TLB and TLP design attributes, wind turbine weight, water depth and wave environment are discussed.

2. Description of TLB and TLP Concepts

Figure 1-2 present the Tension Leg Platform (TLP) and Taught Leg Buoy (TLB) floating wind turbine concepts. The TLP floater is inspired by the synonymous concept developed by the oil industry. The TLP wind turbine floater consists of a slender cylindrical buoy connected to the seafloor with vertical tethers attached to the buoy in the vicinity of the waterline. The buoy displacement is larger than the weight of the wind turbine and the steel weight of the buoy structure. The reserve buoyancy acts to tension the tethers which are connected to gravity anchors on the seafloor. The floater carries no permanent ballast and its steel weight is low. The reserve buoyancy of the buoy is selected so that the tethers do not go slack in a 3 hour seastate with a probability of 98%. The TLP floating wind turbine system may be fully assembled in its upright position at a coastal facility using a single crane and a stabilizing floater. The stabilizing floater is also used to tow the fully assembled TLP system to the offshore site where it is connected to pre-installed gravity anchors (Figure 3). The tethers are then pre-tensioned by removing water ballast from the buoy.

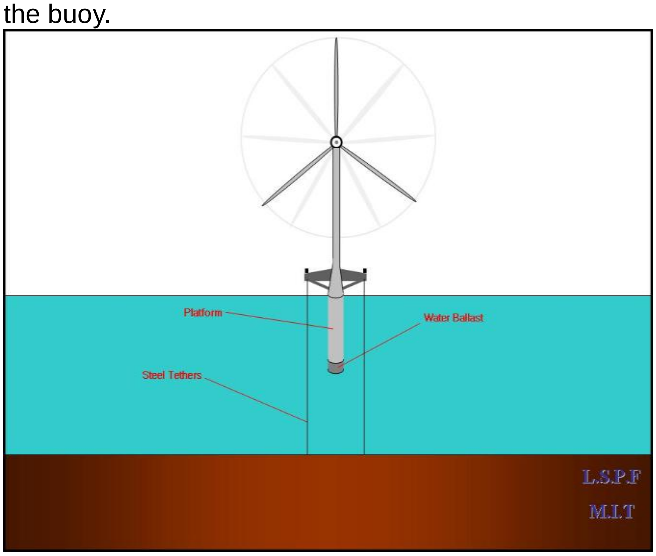


Figure 1: Tension Leg Platform

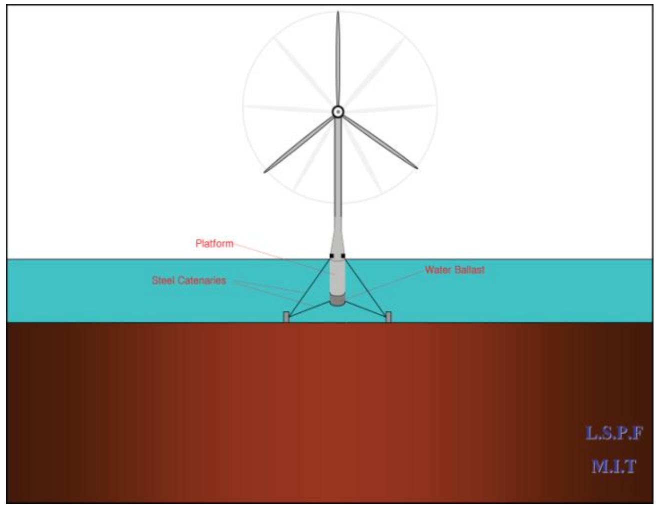


Figure 2: Taught Leg Buoy

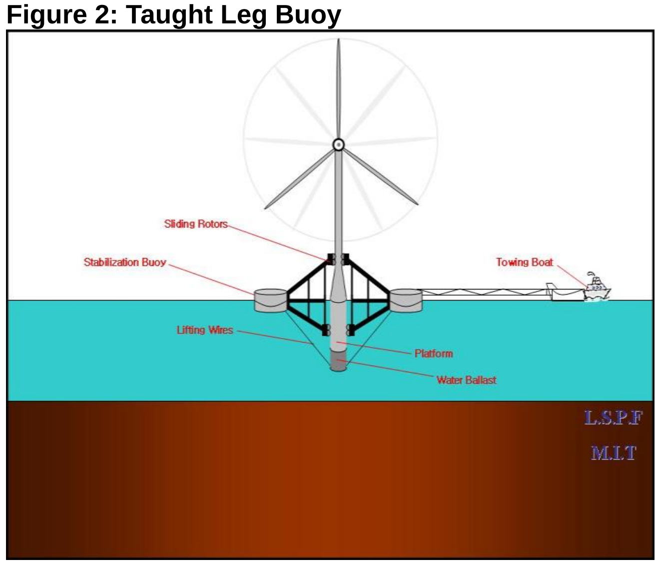


Figure 3: Stabilizing Floater for Assembly and Transportation

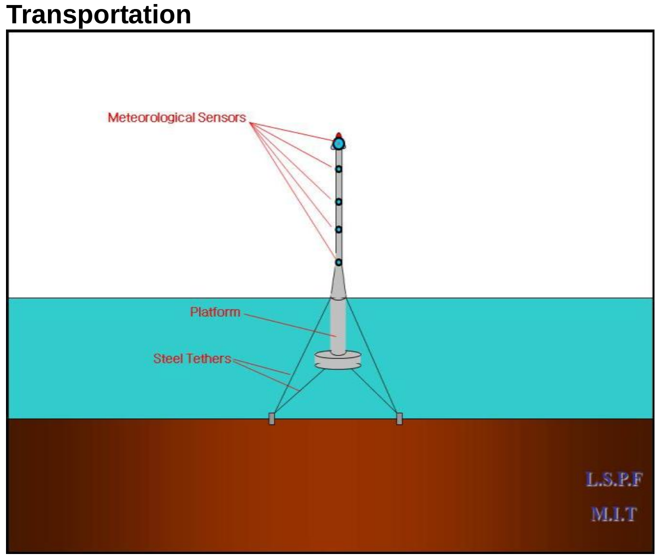


Figure 4: TLB Floating Meteorological Tower

The Taught Leg Buoy (TLB) concept also consists of a slender cylindrical buoy free of permanent ballast with reserve buoyancy necessary to pre-tension two layers of mooring lines inclined relative to the seafloor where they are connected to gravity anchors. The assembly, transportation and installation of the TLB may be carried out using a process similar to that for the TLP. The inclination of the TLB mooring lines relative to the seafloor restrict its rigid body motions due to wind and wave excitation. Therefore the TLB is a stiff floater concept that can respond only due to the flexural deflections of the mooring lines and the tower. Consequently, the nacelle displacement and acceleration are very low even in severe storms.

Figure 3 illustrates the stabilizing floater consisting of cylindrical buoys and a steel frame connected to the floater with collars that provide stability in pitch while allowing the floater to slide vertically. The draft of the floater during assembly and transportation may be reduced by varying the water ballast or by pulling the wire ropes attached to the bottom of the floater with winches installed in the stabilizing buoys. A single stabilizing floater may be used for the transportation of multiple TLP or TLB units. The same floater may be used to provide stability during the ballasting of floating wind turbine units installed offshore, their detachment from the anchors and their towing to a coastal facility for major maintenance. The TLB floater may also be used for the support of a meteorological tower installed offshore, illustrated in Figure 4.

3. Equations of Motion

The small amplitude of the responses of the TLP and TLB concepts even in severe seastates justify the use of linear theory and frequency domain analysis for the modeling of their responses in stochastic wind and wave environments. The linear wave forces and moments acting of the buoy floater were evaluated using WAMIT™. The mooring line statics and dynamics were modeled using the program LINES [2] extended for the TLP and TLB concepts in order to account for elastic deformations, hybrid mooring lines consisting of segments made out of chain, wire and synthetic materials and intermediate ballast loads. The wind turbine rigid body dynamics were modeled using the program FAST [3]. The fluctuating wind forces on the wind turbine rotor were found not to affect significantly the rigid body responses of the TLP and the TLB and the wind turbine was found not to contribute a significant positive or negative aerodynamic damping to the surge of the TLP. The static wind thrust was used to determine the mean offset of the TLP and TLB, the LINES code was used to determine the mooring system restoring coefficient matrix around the mean offset position, and the linear wave loads and rigid body responses were determined for both floating wind turbine systems in the frequency domain as described below.

The six-degree-of-freedom rigid body equations of motion in the frequency domain in complex matrix notation take the form

$$[M_{added}(\omega)+M_{turbine}+M_{buoy}]\ddot{\xi}+[B_{turbine}+B_{buoy}(\omega)]\dot{\xi}$$
$$+[C_{turbine}+C_{buoy}+C_{mooring}]\xi=[X(\omega)]e^{i\omega \cdot t}$$
$$[M_{total}(\omega)]\ddot{\xi}+[B_{total}(\omega)]\dot{\xi}+[C_{total}]\xi=[X(\omega)]e^{i\omega \cdot t}$$
$$\xi(t)=Z(\omega)e^{i\omega \cdot t};\xi_i, i=1,\ldots,6$$

The mooring line restoring coefficient matrix accounts for the line pretension and their elastic elongation and ensures static stability when the stabilizing floater shown in Figure 3 is removed. The wind turbine floater inertia, added mass, damping, exciting force and restoring coefficients are evaluated as in floating body dynamics and the wind turbine rotor is treated as a rigid rotating body.

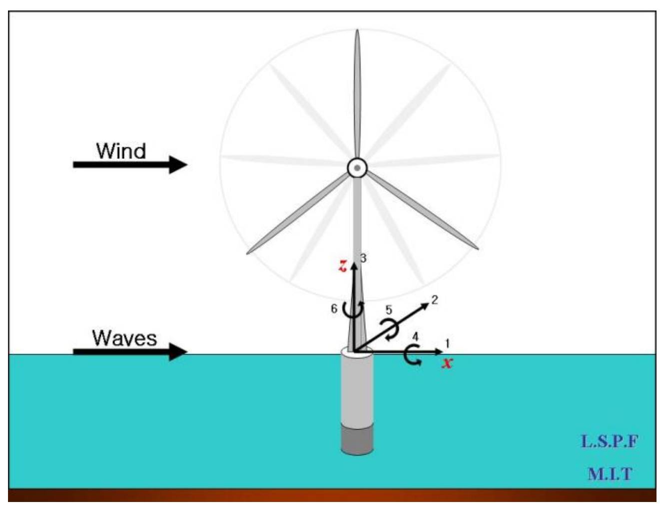


Figure 5: Coordinate System and Rigid Body Modes of Motion

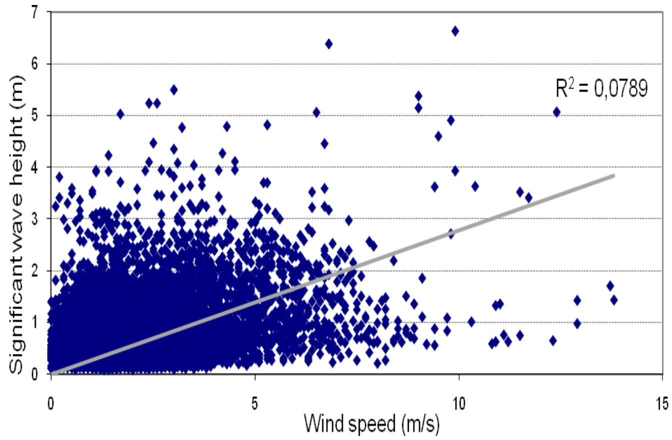


Figure 6: Correlation of Significant Wave Height and Wind Speed at Offshore Site in Palermo, Italy

The solution of the complex matrix equations of motion provides the response amplitude operators (RAOs) used to compute the root mean square (RMS) deviation of the i-th mode using the following expressions.

$$\sigma_i^2 = \int_0^\infty \left| Z_i(\omega) \right|^2 S(\omega) d\omega$$

The spectral density of the sea states used in the present study is given by the following parametric expression.

$$S(\omega) = H_s{}^2 T_1 \frac{0.11}{2\pi} \left(\frac{\omega}{2\pi} \right)^{-5} e^{-0.44\left(\frac{\omega}{2\pi}\right)^{-4}}$$

H_s is the significant wave height and T_1 is the modal period of the ambient seastate.

4. Structural Design and Fatigue Analysis

The steel structure of the buoy was optimized with respect to the buoy steel thickness and the number of ring stiffeners using the *DNV-RP-C202* offshore standard. The loading on the structure includes the maximum wind thrust on the rotor, hydrostatic pressure around the buoy, extreme force from the wave and extreme tension from the mooring lines around buoy. For the fatigue analysis the tower and buoy are modeled as a long slender cylindrical structure with variable properties under axial and transverse loading. A Timoshenko beam model was developed in the frequency domain that accounts for bending and shear deformation, linear and angular momentum effects. The model accepts the wind thrust spectral density as an excitation mechanism at the top of the tower and the linear and nonlinear wave force spectral density as the excitation mechanism at the buoy. This model evaluates the tower, buoy and mooring system flexural natural frequencies, the system stress transfer functions and the fatigue life of the mooring lines, buoy and tower.

The wind force and moment spectral densities are determined using a stochastic input wind speed profile. In the present study the wind thrust spectral densities are estimated using the thrust coefficient curve supplied by the wind turbine manufacturer. The nonlinear wave forces and moments were determined from a new impulse theory for the nonlinear wave loads and responses of floating bodies extended to estimate the nonlinear spectral densities of the wave loads exerted on the buoy in a stochastic wave environment [4]. The evaluation of the nonlinear spectral densities of the wave loads at the high flexural natural frequencies of the TLP and TLB systems is analogous to the estimation of the “ringing” loads on offshore Tension Leg Platforms, a topic extensively studied by the oil industry for the determination of the fatigue life of TLPs. Figure 6 plots the correlation of the hourly averaged wind speed and significant wave height at an offshore site in Palermo, Italy. It may be seen that the correlation is low suggesting that the fatigue damage from wind and wave loading may be evaluated independently and superimposed.

5. System Responses and Mooring Line Tensions

In the present study, we consider the worst possible scenario in terms of static and dynamic response combinations. The wind turbine is assumed to operate at the maximum rated power and the corresponding maximum thrust in all seastates. The tension of each line of the TLB and TLP is the sum of its pretension in calm wind and wave conditions, a static tension delta induced my the mean wind thrust at the rated power, equal to 30 and 80 tons for the 3 MW and 5 MW turbines, respectively, and a dynamic tension induced by the ambient seastate. The pretention of each line in calm wind and wave conditions is selected so that the probability that the total tension of any line becomes negative under the mean wind and wave loadings in a 3 hour seastate is less than 2%. The initial pretension of each line then drives the selection of the displacement of the floater supporting the 3 MW and 5 MW turbines. Moreover, the vertical component of the pretension determines the weight of the gravity anchors in water.

Figure 7 presents the RMS tensions of the top and bottom mooring lines of the TLB supporting the 3 MW wind turbine in two seastates with significant wave heights 6 and 10m and in two water depths. Figure 8 presents the corresponding results for the TLB supporting the 5 MW wind turbine. Figure 9 presents the RMS accelerations as fractions of the acceleration of gravity g.

Figure 10 presents the RMS tensions of the weather TLP tether supporting the 3 MW wind turbine in two seastates with significant wave heights 10 and 14m and in two water depths. The same Figure presents the nacelle surge RMS acceleration for the 3 MW TLP. Figure 11 presents the corresponding results for the TLP supporting the 5 MW wind turbine.

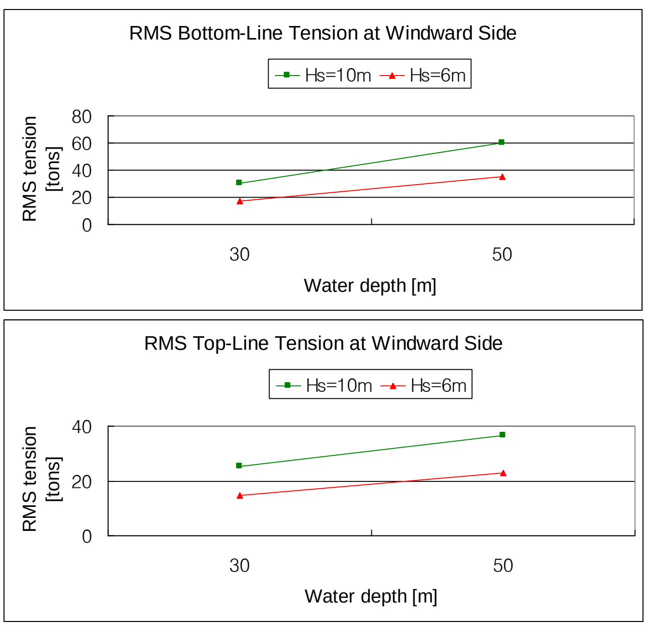


Figure 7: RMS Tension of Bottom (Upper) and Top (Lower) Windward Lines of 3 MW TLB

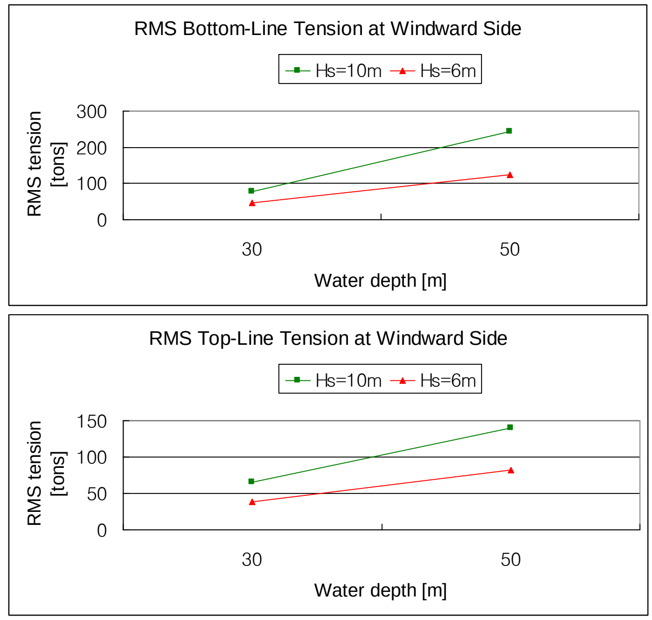


Figure 8: RMS Tension of Bottom (Upper) and Top (Lower) Windward Lines of 5 MW TLB

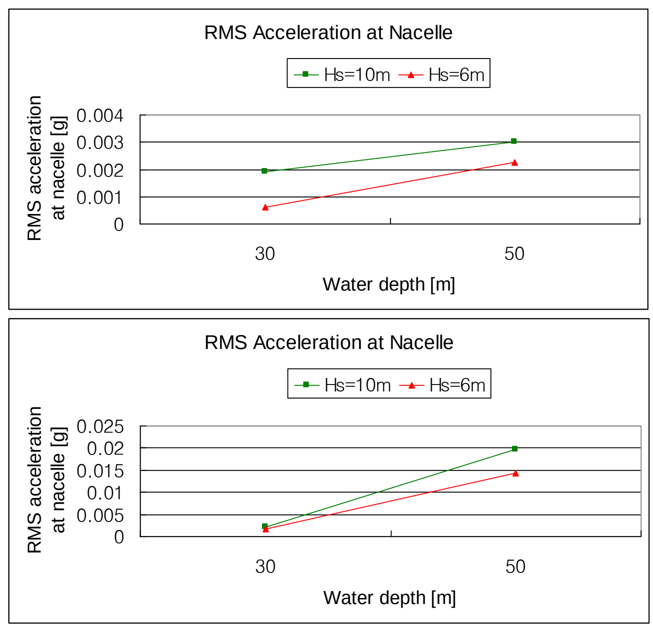


Figure 9: RMS Acceleration of Nacelle of 3MW TLB (Upper) and 5 MW TLB (Lower)

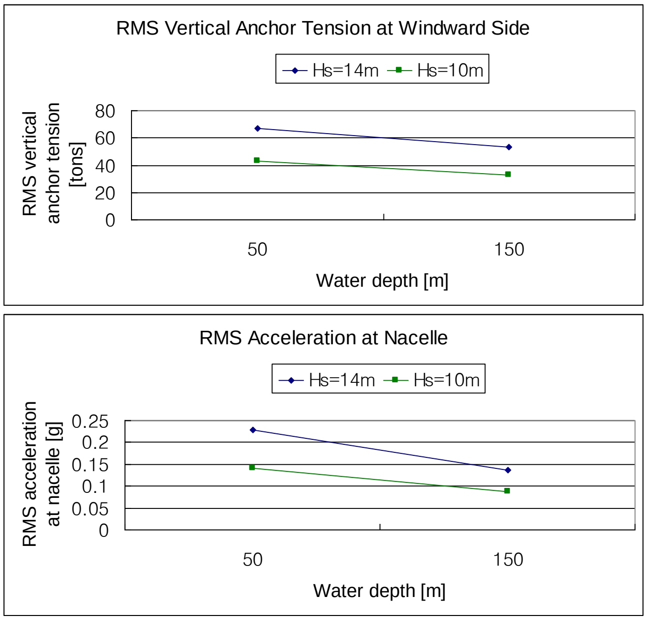


Figure 10: RMS Tension of Windward Tether (Upper) and Nacelle Surge RMS Acceleration (Lower) of 3MW TLP

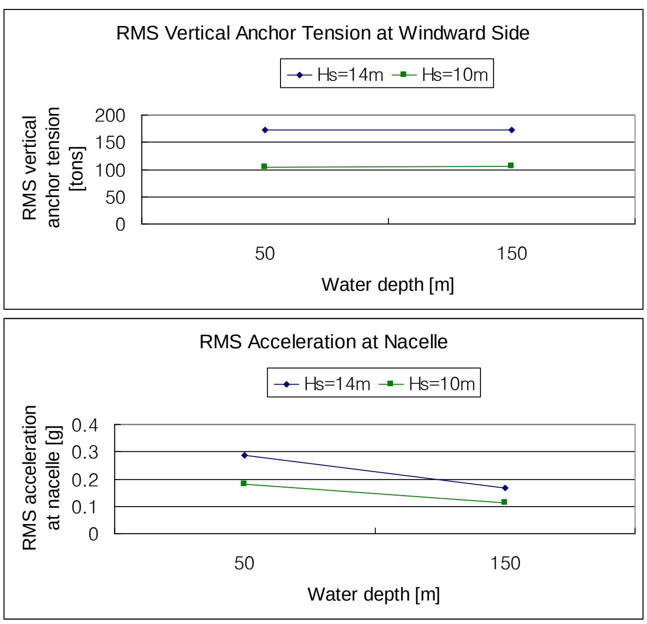
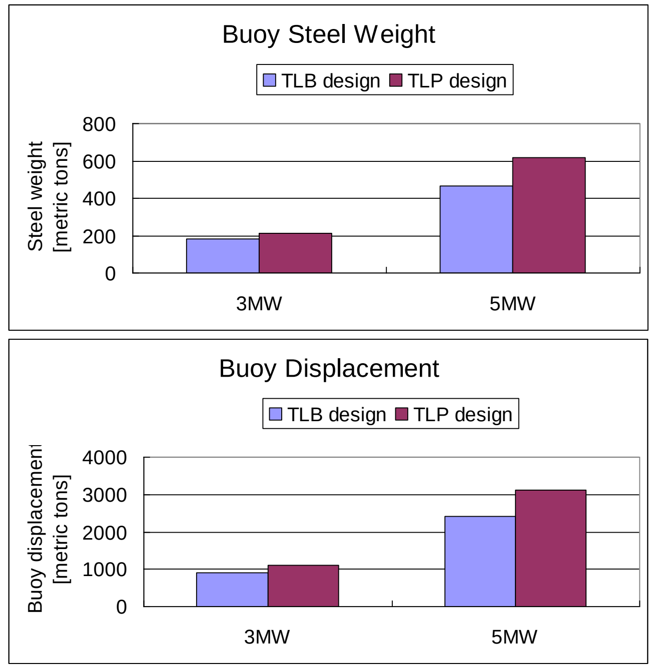


Figure 11: RMS Tension of Windward Tether (Upper) and Nacelle Surge RMS Acceleration (Lower) of 5MW TLP

Figure 12 (upper) presents the steel weight of the buoy floater supporting the 3 MW and 5 MW wind turbines designed according to the *DNV-RP-C202* offshore standard. The corresponding displacement of the buoy for the TLB and TLP supporting the 3 MW and 5 MW wind turbines is shown in Figure 12 (lower).



(Sea conditions: water depth=30m (TLB) / 50m (TLP); sea state Hs=10m)
Figure 12: Steel Weight of Buoy (Upper) and Buoy Displacement (Lower) for TLB and TLP Supporting the 3 MW and 5 MW Wind Turbines

Comparison of TLB and TLP Floaters

The weight of the 3 MW Vestas V90 wind turbine is 257 tons, including the tower, nacelle and rotor. The corresponding total weight of the 5 MW Re Power wind turbine is 694 tons. These weights are the payloads carried by the buoys. The ratio of payloads of the 5 MW to the 3 MW wind turbine is 694/257=2.7. It is seen from Figure 12 that the buoy steel weight increases linearly with the payload and the same applies to the buoy displacement. The uplift capacity of the gravity anchors in water is the difference between the buoy displacement and the sum of the weights of the buoy and of the wind turbine. For the 3 MW TLB system the cumulative gravity anchor uplift capacity is 722 tons and for the 5 MW system the cumulative capacity is 1945 tons. For the 3 MW TLP system the anchor uplift capacity is 898 tons and for the 5 MW TLP system the corresponding capacity is 2493 tons. The TLB anchor capacity indicated above has been selected for a water depth of 30m and an anchor footprint of 30m from the buoy axis. The TLB anchor capacity increases with the water depth and in waters over 50m deep is substantially higher than that in 30m of water depth for the same anchor footprint of 30m. Both the TLB and TLP have four symmetric sets of mooring lines and tethers.

For the TLP the anchor capacity is independent of the inclination of the tethers which are always vertical and in the present study have a footprint of 25m from the buoy axis. The TLP anchor capacity decreases with increasing footprint due to the increase of the tether moment arm. The tether pretension and hence the anchor capacity is selected so that the surge natural frequency falls to the left of the peak of the seastate spectrum and is less than about 0.25 rad/sec corresponding to a natural period of more than 25 seconds. The natural period increases with the length of the tethers which for the TLP floaters considered in the present study are connected to the buoy in the vicinity of the waterline. Evidently, the natural period increases with increasing water depth leading to smaller nacelle accelerations. Therefore, the TLP is the preferred floater in water depths greater than about 50m. It may be seen from Figure 11 that the nacelle surge RMS accelerations are around 15% of g in a water depth of 150m even in a seastate with significant wave height of 14 m. The corresponding RMS tether tensions are less than 60 tons for the 3 MW turbine and less than 180 tons for the 5 MW turbine. The TLB dynamic tensions in water depths around 30-50m are comparable to the tensions of the TLP in water depths over 50m. The horizontal wind and wave loads are easily supported by the horizontal seabed resistance of gravity anchors with the weights and footprints indicated above. It is therefore concluded that the TLB is the preferred system in water depths less than about 50m and the TLP is superior in water depths greater than 50m.

6. Economics of TLB and TLP Floating Wind Turbines

The TLB and TLP buoys may be assembled with the onshore wind turbine in their upright position at a coastal facility using the stabilizing floater shown in Figure 3. This operation requires a single crane. The fully assembled wind turbine system supported by the stabilizing floater may be towed out to the offshore site by a conventional towboat. The gravity anchors are assumed to have been lowered to the seabed without the need of a prior geotechnical study. The connection of the mooring lines and tethers to the buoy and their pre-tensioning by de-ballasting of the buoy is a simple marine operation. The cost of the wind turbine tower, nacelle and rotor is assumed to be comparable to that of onshore systems of the same rated power adapted for operation in the offshore environment. The cost of construction of the buoy is proportional to its weight which is shown in Figure 12 and may be undertaken together with the construction of the tower by the same entity by taking advantage of economies of scale. The cost of the mooring lines and tethers is not expected to be large in water depths of up to a few hundred meters. Finally, the gravity anchors may be manufactured out of a low cost material, for example high density concrete or the mineral olivine.

The selection of the proper wind turbine tower height, swept area and rated power is essential for the economics of utility scale offshore wind farms. The steel weight of the tower, buoy and mooring lines increases linearly with the weight of the wind turbine. Therefore wind turbines with high rated power and large power-to-weight ratios would be especially attractive for use with the TLB or TLP floaters. Concluding, the low costs of the TLB and TLB floaters and the availability of offshore wind sites with capacity factors in excess of 40%, water depths up to a few hundred meters and moderate or oceanic wave conditions underscore the attractiveness of investments in utility scale offshore wind farms based on the TLP and TLB floating wind turbine technologies.

7. Acknowledgements

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8. References

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