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Stability and dynamic response analysis of a submerged tension leg platform for offshore wind turbines

Yanqing Han[a,b,c], Conghuan Le[a,b,c,*], Hongyan Ding[a,b,c], Zhengshun Cheng[d,**], Puyang Zhang[a,b,c]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] Key Laboratory of Coast Civil Structure Safety (Tianjin University), Ministry of Education, Tianjin 300072, China
[c] School of Civil Engineering, Tianjin University, Tianjin 300072, China
[d] Department of Marine Technology, NTNU, Trondheim, Norway

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ABSTRACT

This paper proposed a submerged tension leg platform (STLP) for an offshore wind turbine in moderate water depth (70–150 m). During the transportation, the platform is semi-submersible and self-stabilized because it has a relatively large water plane area. Therefore, it can be wet-towed out together with the wind turbine from the quayside to the offshore installation site. During the operation phase, the platform is submerged with a relatively small water plane area, which improves its hydrodynamic performance. Hence, this STLP wind turbine requires low transportation and installation cost. It can also achieve a potentially good dynamic behavior during the operation phase. In this paper, the stability of the STLP wind turbine during the transportation phase is first assessed without considering the mooring lines. The results show that the STLP wind turbine has a good stability to ensure a safe wet towing. The dynamic responses of the STLP wind turbine during the operation phase are then studied with emphasis on the effect of second-order wave loads, wind-wave misalignment and water depth. Based on fully coupled time domain simulations, it is found that the effect of second-order wave loads on the dynamics of the STLP wind turbine is slightly larger in an extreme sea state than that in a moderate sea state. The standard deviations of the surge, sway, roll and pitch motions and the tower base bending moment are dependent on the wind-wave misalignment, while those of the heave and yaw motions, the blade root bending moment are not. In addition, a larger water depth leads to larger standard deviations of the platform motions and a smaller standard deviation of the tower base bending moment. The effect of water depth on the blade root and tower top bending moments is negligible.

1. Introduction

Recently, offshore wind turbines have become an attractive solution to harvest offshore wind energy resources. In shallow water (< 50 m), bottom-fixed foundations are usually used to support offshore wind turbines, such as monopiles, gravity-based structures, jackets and buckets (Ding et al., 2015; Peire et al., 2009). However, when offshore wind farms move towards deep water, (> 50 m), where the wind is stronger and less turbulent, floating supporting platforms are an alternative worth considering from an economic perspective. A number of floating wind turbine concepts have been proposed. Based on how they achieve static stability, they are mainly divided into three categories: spar, barge and tension leg platform (TLP) (Jonkman and Matha, 2011). The spar concept is usually ballast stabilized with a small water plane area (Skaare et al., 2011). The barge concept is often water-plane stabilized due to its large water plane area. The TLP concept is usually stabilized with tendons or taut mooring lines and is resistant to wave induced motions; consequently, it can decrease the variation in the generator power and alleviate the impact on the grid.

A number of studies on comparing and optimizing the designs of these three floating platforms were conducted (Goupee et al., 2014; Myhr et al., 2011). In some of these studies, TLP wind turbines were proposed as a possible solution for moderate water depth (100–200 m), since the tendon system may be better suited for these depths, where the design of a catenary mooring system is challenging and limited platform motions are expected to reduce the structural loading on the tower and blades compared to other floating concepts (Adam et al., 2013; Bachynski, 2014). Design considerations for TLP wind turbines in intermediate water ranging from 100 m to 200 m were presented by Bachynski and Moan (2012). A parametric study on the

** Corresponding author.
* Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China.
E-mail addresses: leconghuan@163.com (C. Le), zhengshun.cheng@ntnu.no (Z. Cheng).

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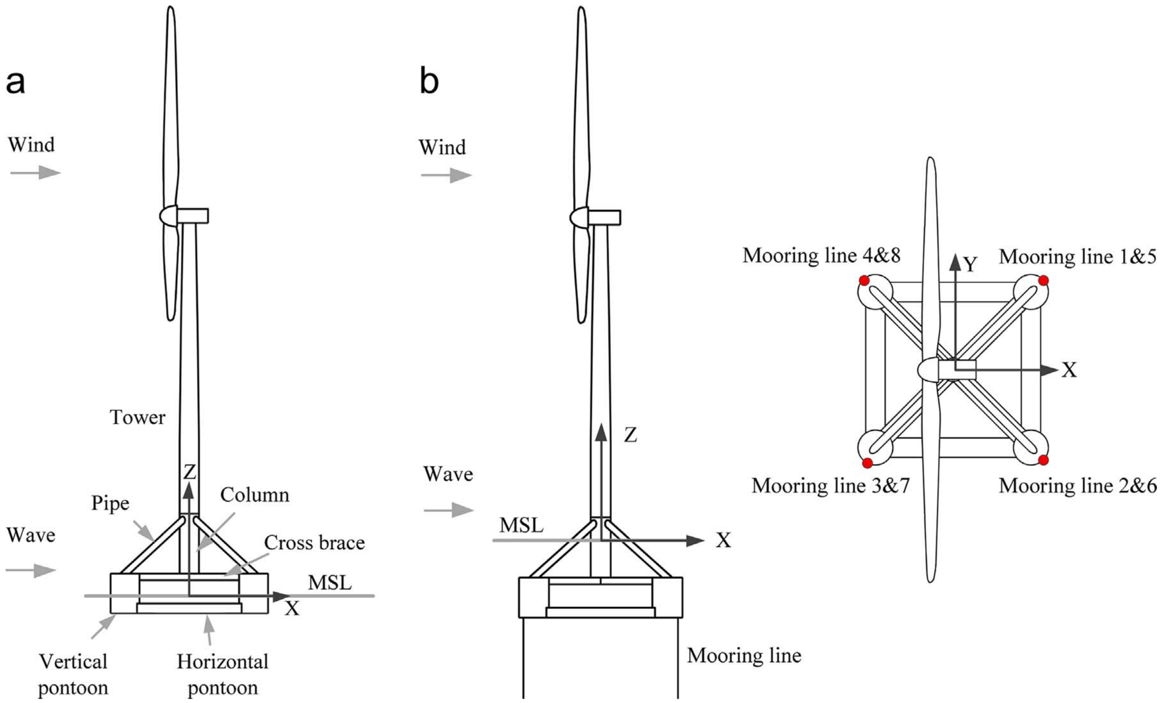

Fig. 1. Schematic layout of the STLP wind turbine: (a) transportation phase, and (b) operation phase.

Table 1
Properties of the STLP wind turbine.

Characteristics	Value
Column diameter (m)	6.5
Diameter of vertical pontoon (m)	9.0
Height of vertical pontoon (m)	12.0
Distance between vertical pontoons (m)	40.0
Width and height of horizontal pontoon (m)	5.0, 3.0
Platform mass (kg)	2.7342E6
Moment of inertia in roll about the CM (kg m^2)	7.818E8
Moment of inertia in pitch about the CM (kg m^2)	7.818E8
Moment of inertia in yaw about the CM (kg m^2)	1.359E9
COG of the platform during tansportation phase (m)	(0, 0, −2.55)
COB of the platform during tansportation phase (m)	(0, 0, −3.70)
Water plane area during transportation phase (m^2)	252.8
COG of the platform during operation phase (m)	(0, 0, −16.75)
COB of the platform during operation phase (m)	(0, 0, −14.08)
Water plane area during operation phase (m^2)	51.45

CM: center of mass; COG: center of gravity; COB: center of buoyancy

Table 2
Main characteristics of the NREL-5 MW wind turbine.

Characteristics	Value
Turbine control	Variable speed, collective pitch
Cut-in, rated, cut-out wind speed (m/s)	3, 11.4, 25
Cut-in, rated rotor speed (rpm)	6.9, 12.1
Turbine mass (kg)	697,500
COG of the turbine (m)	(−0.2, 0.0, 64.0)

Table 3
Properties of the mooring system.

Number of the mooring lines	8
Fairlead distance from center (m)	32.78
Diameter of the mooring lines (m)	0.127
Mass of per length (kg/m)	116.074
Equivalent axial stiffness (N)	2.5E9

design parameters of single-column TLP wind turbines was carried out using fully coupled simulations in order to evaluate the platform motions as well as structural loads in the turbine components and tendons. The Blue H concept with a submerged TLP was installed in Italy (Bilgili et al., 2011). On top of that, a commercially available Blue H concept for 5–7 MW wind turbines based on the proven TLP technology is planned for 2016. Moreover, significant works on TLP wind turbines were performed by Massachusetts Institute of Technology (MIT) and the National Renewable Energy Laboratory (NREL). The MIT/NREL TLP, a cylindrical platform ballasted with concrete and moored by four pairs of vertical mooring lines, was developed for a floating wind turbine (Matha, 2010). The PelaStar TLP that features a simple design, minimal platform motions, economical transportation and installation, and low levelized cost of energy, was designed by Glosten Associates Company to support 5–10 MW turbines in water depth ranging from 50 m to 200 m (Vita et al., 2015). More recently, an innovative concept, GICON® SOF, was designed for water depths of 17–500 m with high and homogeneous wind speeds (Adam et al., 2013; Dahlhaus and Großmann, 2015; Hyland et al., 2014).

Although numerous researchers have suggested possible designs, there still exist several challenges for the design of TLP wind turbines. For example, there is very little consensus on the transportation of a TLP wind turbine. Self-stable transportation and installation seem to be a profitable technology for floating wind turbines (Roddier et al., 2010). Among the aforementioned TLP wind turbine concepts, the MIT/NREL TLP has the possibility of self-stable transportation and installation. Because of the heave ballast, the MIT/NREL TLP can be towed together with the wind turbine from the harbor to the offshore site (Matha, 2010). However, the heavy ballast also contributes to a deep draft (approximately 35 m), which makes the transportation inappropriate in shallow water. For the GICON concept, a new technology that used the gravity anchor as the ballast of the floating platform was proposed. Hence, both the platform and the gravity anchor can be towed to the installation site together (GICON, 2015). Nevertheless, more studies are still required to ensure the stability of the entire structure during the sinking process of the gravity anchor.

Second-order wave forces were found to be relevant for fatigue damage and extreme responses for TLP wind turbines (Bachynski and