COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

INFLUENCE OF FLOATER RESPONSE ON WIND TURBINE TOWER MOMENTS IN FLOATING WIND TURBINE SYSTEM

Muhammad Bilal Waris[1] and Takeshi Ishihara[2]

[1]Department of Civil and Architectural Engineering, Sultan Qaboos University
P.O. Box: 33, Muscat 123, Sultanate of Oman.
waris@squ.edu.om

[2]Department of Civil Engineering, University of Tokyo,
7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan.
ishihara@t.u-tokyo.ac.jp

Keywords: Floating Wind Turbine, FEM, Tower moment, Coupled system.

Abstract. *The study uses finite element modeling to discuss the effect of floater response on tower moments in a floating offshore wind turbine system. A semi-submersible floating platform supporting a single NREL-5MW wind turbine was investigated. In order to understand the contribution of different modes of floater motion to tower load, tension leg mooring and catenary mooring were used. The mooring systems were designed to provide similar dynamic response amplitude in surge, while the pitch response was inherently different. Wind and wave loads were considered separately and then together to identify their respective contribution to response and tower loads. Both wind and wave loads were found to be critical for tower base moment while wind loads govern the tower top moments. In comparison with catenary mooring, the tension leg mooring was found to reduce the tower base moment by up to 50 % at higher wind speeds due to restraint to pitch motion. The two types of mooring provided a similar tower top moment which indicates it is independent of pitch motion.*

1 INTRODUCTION

Wind is one of the most consistent and global form of renewable energy. Due to rapid depletion of natural resources, there is an increase in trend towards use of wind energy as an alternate and sustainable source of power generation. In the last couple of decades, there has been a rapid increase in wind farm installations. In the last five years, there was an average annual increase of almost 27.6 % in global wind power generation. Wind turbines installed worldwide till end of 2011 contribute 430 TWH of power, which is 2.5 % of global demand. Denmark has the highest national contribution from wind energy at 21%. [1, 2]

The widespread application of wind energy has some practical limitation. Rural areas with steady wind and large space for wind farms have low energy demand while urban areas with high energy demand lack the space and steady wind resource. Most of the metropolis of the world are situated near shorelines and have a huge offshore wind and space resource at hand. This potential was first recognized in early 1970's and lead to the rapid development of offshore wind farms. However, all such farms have been made in shallow water, where the water depth is less than 30 m and bottom mounted setup is possible. This constraint significantly reduces the ability to fully harness the offshore wind potential and has limited application to regions with adequate wind resource in shallow water. To exploit the rich deep offshore wind resource, floating support systems have to be developed. Marine and offshore oil industries have successfully established technical viability of floating structures but their design is safety oriented and expensive. In their design, mooring system is taken in linear range while hydrodynamic and aerodynamic dampings are ignored. In contrast, for wind energy applications, the design of the floating systems should be based on economy and needs to be optimized to achieve the lowest life cycle cost for the entire structure. Hence the purpose of this research is to investigate the effect of floater displacement on wind turbine.

Several concepts [3, 4, 5, 6, 7, 8, 9, 10, 11] were proposed for using multiple wind turbines on a single floater. Such floaters have the advantage of using a single mooring and power supply system thus reducing the cost. Owing to their large size, they are more stable but have to carry large wave current loads, while the wind turbines suffer wake effect due to close proximity to other wind turbines on the floater. Over the last decade several concepts [12, 13, 14, 15, 16] of single wind turbine floaters have been investigated, these systems would resolve issues involved in the multi-turbine system but they suffer from stronger wave induced loads. The wave loads influence the wind turbine through six degrees of freedom of the supporting floater system as shown in figure 1. Three modes are translational (surge, sway and heave) and three are rotational (roll, pitch and yaw). Out of the six surge, heave and pitch are the major modes of oscillation and are expected to contribute heavily to wind turbine tower moment. The extent of restraint in these modes depends upon the type of mooring system used for station keeping and stability of the floater in open water. The different types of mooring are catenary, taut and tension leg mooring. Catenary system provides the least restraint while the tension leg system has the highest restraint to floater response. The first is cheaper and stable in case of its partial failure while the latter is expensive and unstable in case of its partial damage.

In this paper, a previously developed numerical tool [2, 14] is used to investigate the effect of floater response modes on the wind turbine tower moments over the range of operational wind speed for wind turbine. The catenary and tension leg type mooring system are considered to account for the level of restraint to floater response. The study also investigates the influence of individual wind and wave loads on the floater response and wind turbine tower moments.

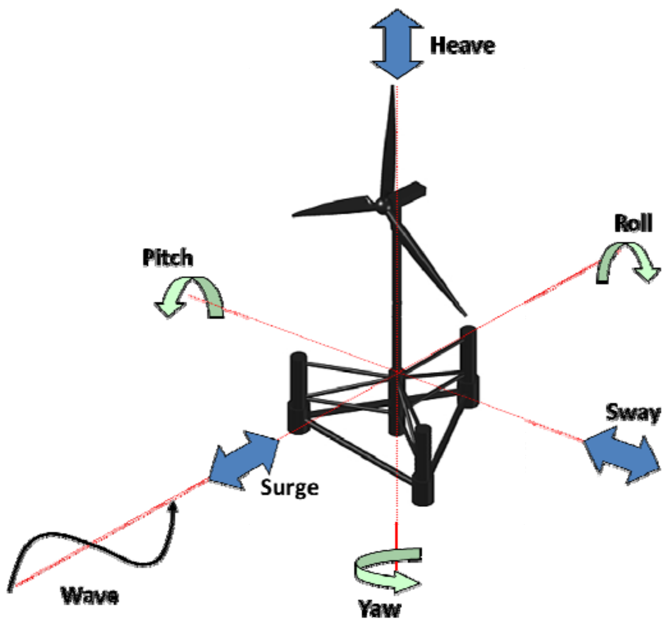


Figure 1 Degree of Freedom of a floating wind turbine

2 FLOATER WIND TURBINE SYSTEM

2.1 Wind Turbine

A modified National Renewable Energy Laboratory's (NREL) offshore 5-MW baseline wind turbine developed by Jonkman [12] was used in this study. The basic properties of the wind turbine are outlined here (table 1) with respect to some modifications that are essential for input in the numerical program. As the used scheme [2] cannot consider pitch control, wind turbine was considered as stall regulated. The aerodynamic and geometric details of the rotor blades and tower provided in Jonkman [12] were used.

Rated Power	5 MW
Rotor Orientation, Configuration	Upwind, 3-blades
Drivetrain	High Speed, Multi-stage gearbox
Rotor, Hub diameter	126, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out wind speed	5.0, 11.4, 25 m/sec
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated tip speed	80.0 m/sec
Overhang, Tilt	5.0 m, 5.0°
Rotor Mass	110,000 Kg
Tower Mass	240,000 Kg

Table 1 Details of NREL 5MW wind turbine [12]

2.2 Semi-Submersible Floater System

A triangular tri-pontoon semi-submersible floater was considered to support the NREL 5 MW wind turbine as shown in figure 1. The span in all three directions was 60.0 m. The pontoons had an overall depth of 30.0 m with a draft of 20.0 m. The floater had a mass of

5,638,760 kg for the catenary mooring system which was reduced to 75 % for tension leg mooring system to account for tether pre-tension. The details of the floater are listed in table 2.

Span		60.0 m
Draft		20.0 m
Overall Height		30.0 m
Peripheral Bracing		Φ 2.50 m
Inner Bracing		Φ 1.80 m
Corner pontoon	Top (20 m)	Φ 9.0 m
	Bottom (10 m)	Φ 10.0 m
Central pontoon		Φ 9.0 m

Table 2 Dimensions of the semi-submersible floater

2.3 Mooring System

The floater was assumed to be situated in deep water with seabed 100 m below water level. The catenary mooring system with three mooring lines each having span of 400 m was considered. The length of each line was 417.84 m. The mooring lines were separated at 120°, with front two lines having an angle of 120° and -120° with the incident wave and the third aligned in the wave direction. All the three lines had a common fairlead at the base of the central pontoon of the floater that supports the wind turbine. In tension leg mooring arrangement, three tethers are considered connected to each of the corner pontoons having length of 80 m. A buoyancy force of 25 % of the original weight of floater was considered that provided a pre-tension of 4950 KN in each tether. These values are selected to obtain similar dynamic surge response for two types of mooring systems. The mooring arrangement for tension leg is considered to eliminate pitch motion of the floater, while the arrangement for catenary magnified the pitch motion. It is essential to indicate here that the current study, does not present a comparison of the two types of mooring system but has used these systems to investigate influence of response modes on wind turbine loads.

3 NUMERICAL MODEL

3.1 Numerical Scheme

A finite element scheme [2, 14] that can use beam, pre-stressed beam and truss type elements and considers coupled interaction between floater, wind turbine and mooring system was used. The scheme uses Morison equation [17] with Srinivasan's Model [6] for estimation of hydrodynamic force, non-hydrostatic model [14] for restoring force and penalty method [18] for contact of mooring with seabed. The equation of motion can be written as

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F\} \tag{1}$$

Where

$$[M]=\begin{bmatrix} M_T & 0 & 0 \\ 0 & M_F & 0 \\ 0 & 0 & M_M \end{bmatrix},[C]=\begin{bmatrix} C_{TT} & C_{TF} & 0 \\ C_{FT} & C_{FF} & C_{FM} \\ 0 & C_{MF} & C_{MM} \end{bmatrix},[K]=\begin{bmatrix} K_{TT} & K_{TF} & 0 \\ K_{FT} & K_{FF} & K_{FM} \\ 0 & K_{MF} & K_{MM} \end{bmatrix},$$

$$\{X\}=\begin{Bmatrix} X_T \\ X_F \\ X_M \end{Bmatrix} \quad ;\{F\}=\begin{Bmatrix} F_T \\ F_F \\ F_M \end{Bmatrix}=\begin{Bmatrix} F_\gamma \\ F_\gamma \\ F_\gamma \end{Bmatrix}+\begin{Bmatrix} 0 \\ F_\beta \\ F_\beta \end{Bmatrix}+\begin{Bmatrix} 0 \\ F_H \\ F_H \end{Bmatrix}+\begin{Bmatrix} 0 \\ F_R \\ F_R \end{Bmatrix}+\begin{Bmatrix} 0 \\ 0 \\ F_C \end{Bmatrix}+\begin{Bmatrix} F_W \\ F_W \\ 0 \end{Bmatrix}+\begin{Bmatrix} F_B \\ F_B \\ 0 \end{Bmatrix}$$

"T", "F" and "M" refer to turbine, floater and mooring system respectively. [X] represents the unknown displacements in six degree of freedom. [M], [C] and [K] are the mass, damping and stiffness matrices of the system respectively. {F} is total external force vector changing with time. {F_γ} is gravitational force, {F_β} is buoyancy force, {F_H} is hydrodynamic force, {F_R} is restoring force, {F_C} is seabed contact force, {F_W} is aerodynamic force acting on wind turbine and floater system above sea level and {F_B} is blade element momentum force on the wind turbine rotor during operation.

3.2 Finite Element Model

The finite element model for the floating offshore wind turbine system was prepared using beam, pre-stress beam and truss elements [2]. The NREL 5 MW wind turbine was modeled using 85 beam elements, with 10 elements for the tower and 24 elements in each blade. The floater was modeled using 109 beam elements. For catenary system, each mooring line was modeled using 30 truss elements and for tension leg system each tether was modeled using 10 pre-stressed beam elements.

3.3 Environmental Conditions

In this study, wind turbulence conditions specific to offshore (Type-I) were considered. The method developed by Phuc [19] was used for the generation three dimensional wind time histories at several points considering auto spectral and cross-spectral functions. For the wind turbine tower, the wind histories were generated at nodes of the tower, while for the rotor a 7x7 square grid of points was considered that encompassed the rotor area. The sea-state was modeled using JONSWAP spectrum [20], which gives the wind-wave height and wind-wave period relationships as:

$$H_S = \frac{0.0094 \times 0.16^{-\frac{5}{3}}}{g} U^2_{1Hr|h=10m} \approx \frac{0.20}{g} U^2_{1Hr|h=10m} \tag{2}$$

$$T_P = \frac{25/4}{g} U_{1hr|h=10m} \tag{3}$$

Where 'g' is the acceleration due to gravity and '$U_{1hr|h=10\,m}$' is the hourly mean wind speed at 10 m height above the mean sea surface. Since in wind turbine analysis, the wind speed is usually considered as 10 min mean and at the hub height, equations (2) and (3) need to be modified to use this definition. The relationship between mean wind speeds for different averaging durations can be estimated based on ASCE 7-02 [21]. The wind speed at different heights is related by the normal wind speed profile with exponent value of 0.14 defined in IEC-61400-3 [22].

$$U_{1Hour|h=10m} = \frac{U_{10\min|h=10m}}{1.08} \tag{4}$$

$$U_{10\min|h=10m} = U_{hub} \left(\frac{h}{H_{hub}} \right)^{0.14} = U_{hub} \left(\frac{10}{H_{hub}} \right)^{0.14} \tag{5}$$

'U_{hub}' represents the 10 minute mean wind speed at the hub height 'H_{hub}' above the sea level. Using these relationships (equation 2-5), the significant wave height 'H_S' and peak wave period 'T_P' were estimated using the 10 minute mean wind speed at hub height 'U_{hub}'

over a range of 5 ~ 25 m/sec as shown in figure 2. The wave time history was generated using JONSWAP spectrum [20] for the respective value of significant wave height and peak wave period. A wave current velocity of 2.0 m/sec was considered to account for the effect of current.

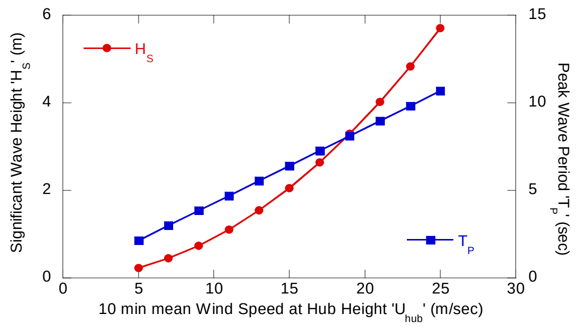


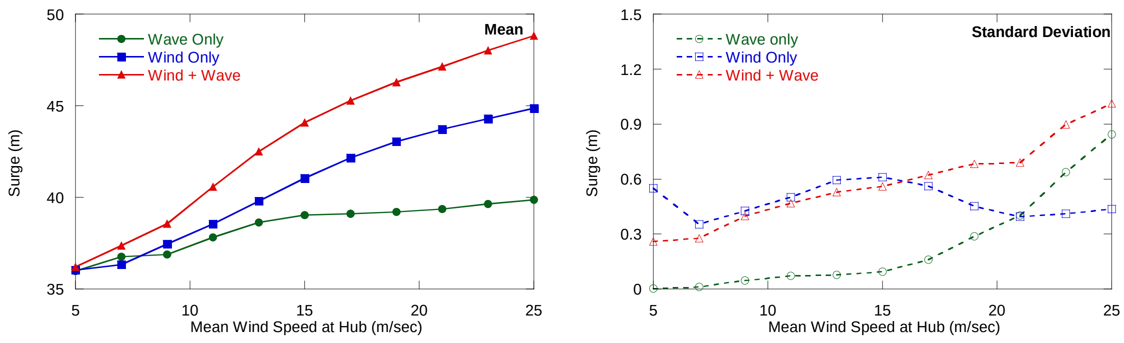
Figure 2 Relationship of wind speed at hub height with significant wave height and peak wave period

4 RESULTS AND DISCUSSION

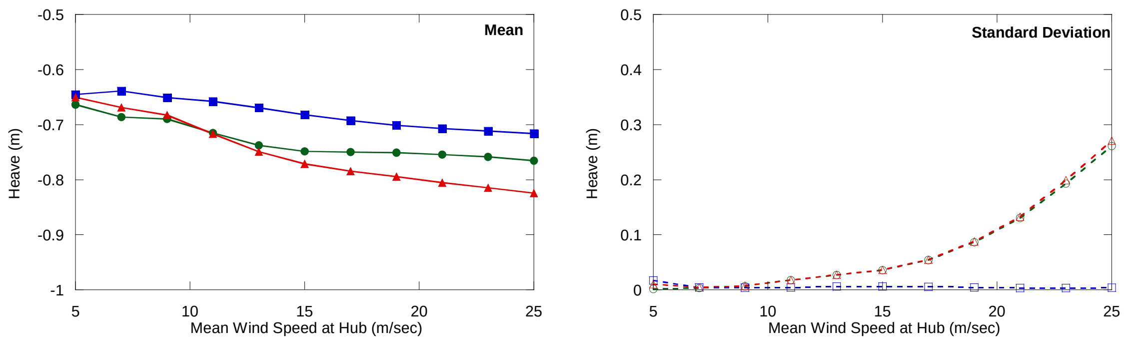
Three types of loading scenarios were considered; wave only, wind only and wind and wave combined. The effect of wave current was considered in all cases. For each load scenario, 11 simulations of 20 min duration were run for wind speed from 5 to 25 m/sec. For the wave only cases, the waves were modeled using the respective wind speed but the wind was ignored. To account for the drift due to currents, initial 600 seconds of the simulation have been removed for statistical estimation. The results are presented as the mean and standard deviation of surge, heave and pitch response of the floating wind turbine system for respective mean wind velocity. The wind turbine loads are presented as the tower base and tower top moments.

4.1 Response of the floating wind turbine system

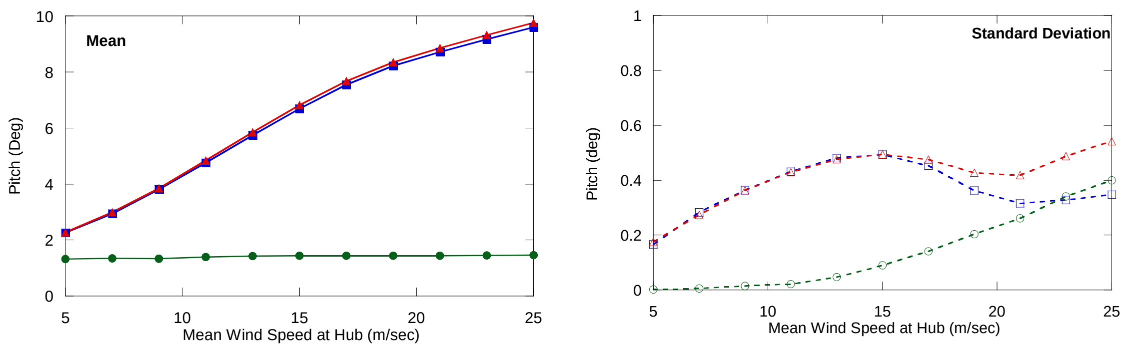
The response of the two types of mooring systems are discussed separately and observed for similarity. Mean and standard deviation of surge, heave and pitch response at the tower base for catenary and tension leg mooring are shown in figures 3 and 4 respectively. For the catenary mooring in figure3(a), mean surge indicates that the wave current results in a mean drift of nearly 35 m. The response had a monotonic increase with wind speed and wave height. The wind loads had stronger effect on mean surge relative to wave loads this is be because of large aerodynamic load on the wind turbine. The mean surge for wind + wave load is almost the arithmetic sum of the individual response for wind and wave that indicates the floater system behaves like a linear spring. The standard deviation of surge shows that the dynamic behaviour is more sensitive to wave load showing monotonic increase, while the wind load shows no clear relationship. In figure3(b), the mean heave response is not sensitive to wind load while the wave load has an overall sinking effect on the floater. The negative values indicate increase in draft. The standard deviation shows that the dynamic component of heave is sensitive to wave load only with negligible contribution from wind. The system again shows a linear behavior when the two loads are combined. The mean pitch response in figure 3(c) is sensitive to wind load only, due to the thrust on the wind turbine rotor while the dynamic part is sensitive to the both the wind and wave load. The pitch response does not show a linear behavior, the values for the wind only and combined cases were the same till 15 m/sec while the latter gets larger afterwards and contribution from wave loads increased.



(a) Surge



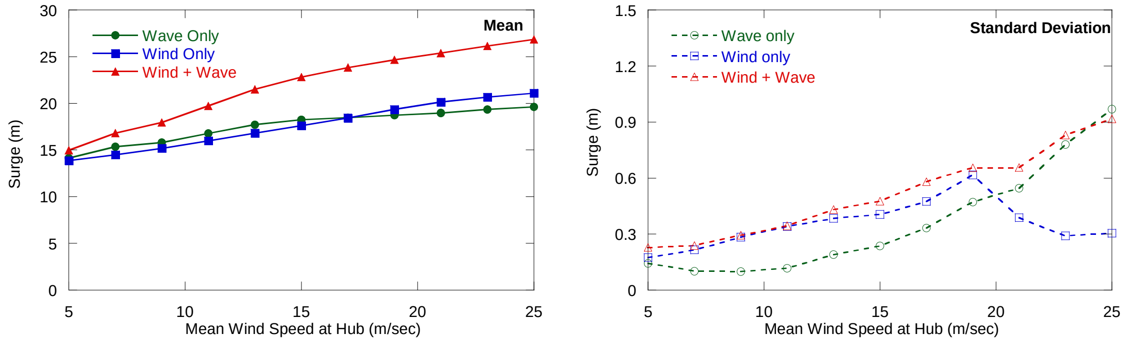
(b) Heave



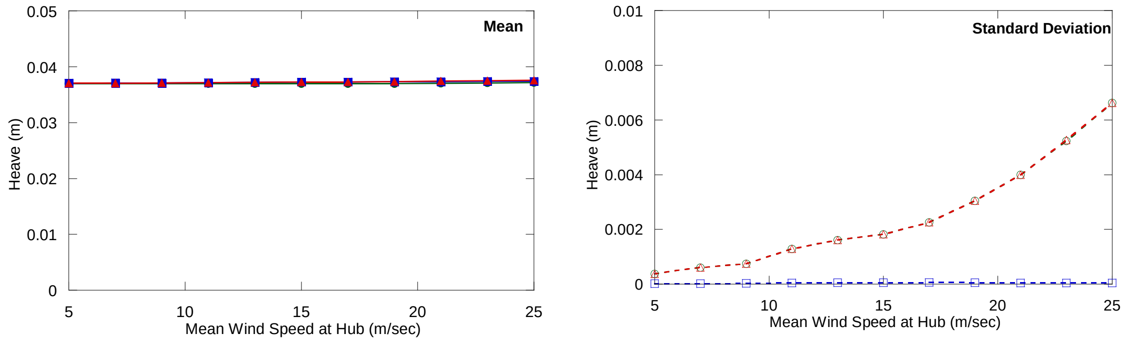
(c) Pitch

Figure 3 Response of floater with catenary mooring

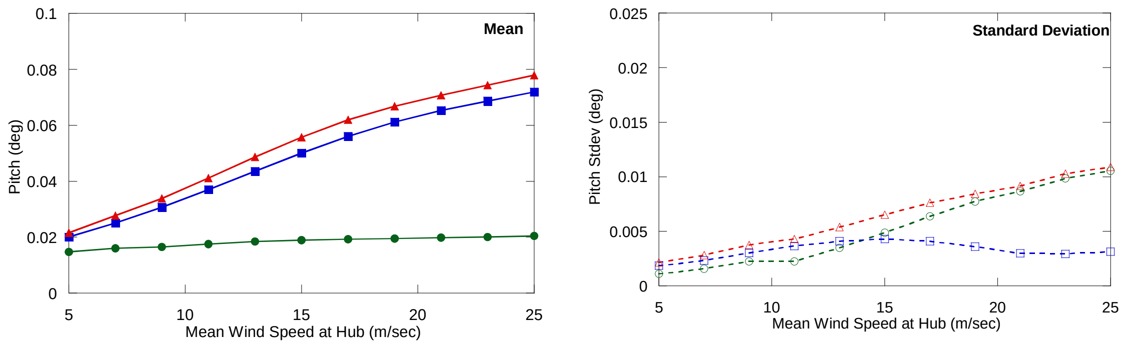
For tension leg mooring in figure 4(a), the mean surge drift under currents is nearly 14 m that is around 40 % of that catenary mooring. The wind and wave loads have similar effects on mean surge response as seen in case of catenary mooring. However, comparative effect of the two is almost similar. The mean heave response is independent of the environmental load because of the strong restraint. The mean pitch though infinitesimal is more affected by wind load as observed in case of catenary mooring. For dynamic component (standard deviation), the wind and wave again showed similar contribution to surge response, the heave response was dependent on wave loads while contribution from wind loads was very small. The pitch response had monotonic increase with wave loads. Comparing the two types of mooring system, it can be observed that because of the pitch and heave restraint the floater response becomes less sensitive to load from the wind turbine. Though the mean responses for the two types are very different, the standard deviation of surge is quite similar as was intended. Considering this similarity of dynamic surge, it can be said that contribution of surge to wind turbine loads for the two types of mooring would be nearly similar and the difference in loads would be because of the pitch response of the floater in case of catenary mooring system.



(a) Surge



(b) Heave

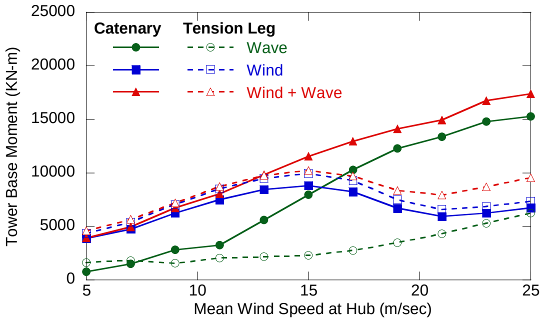


(c) Pitch

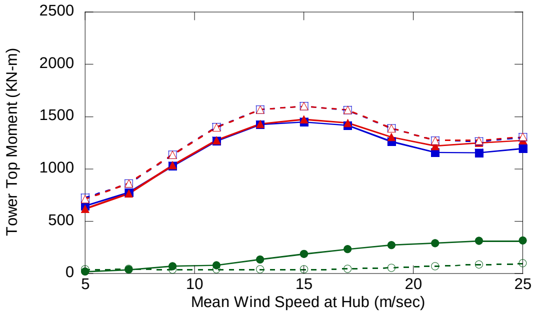
Figure 4 Response of floater with tension leg mooring

4.2 Wind turbine tower loads

In the previous section, the response for the two types of mooring systems has been discussed and contributions of wind and wave loads to the significant modes of response (surge, heave and pitch) were identified. To discuss the contribution of the these loads and effect of pitch motion the wind turbine loads, two critical points for design of wind turbine are considered i.e. tower base moment for support structure and tower top moment for the yaw system. Figure 5 shows these two loads for the two types of mooring systems. The results show that both the wind and wave loads are critical for tower base (support system), while wind loads govern the tower top (yaw system) for both types of mooring system. Further, the combined wind and wave loads do not result in much larger loads and a simple summation of loads due to wind only and wave only will give conservative results. Considering the comparison of the tension leg mooring and Catenary Mooring system, it can be observed that tension leg mooring results in reduction of tower base moment due to wave loads at higher wind velocities. Since the two types have dynamic surge component of the same order, this difference can be only attributed to pitching motion in case of catenary mooring system. The tower base moment due to wind load only is slightly smaller in catenary mooring, because of increased aerodynamic damping arising from the pitching motion that aggravate the rotor disc displacement. Finally, both types of mooring systems have similar tower top loads which indicate that the top load is not sensitive to pitching motion but depend on the surge displacement of the floater which is similar for the two types of mooring systems.



(a) Tower Base Moment



(b) Tower Top Moment

Figure 5Wind turbine moments in a floating wind turbine system

5 CONCLUSIONS

A numerical study was carried out to investigate contribution of environmental loads and floater response mode on wind turbine loads. Catenary and tension leg mooring system with similar surge component were used. It is observed that the contribution of environmental loads to modes of motion is independent of mooring system. The mean and dynamic surge response is more sensitive to wave loads, while the mean pitch response is sensitive to wind loads and dynamic pitch is influenced by wave loads. Both wind and wave loads are found to be critical for support system (tower base) and wind loads are critical for yaw system (tower top). Comparison of wind turbine loads for tension leg and Catenary mooring systems show that tension leg mooring results in reduction of wave loads at tower base because of the pitch restraint. The yaw system load (tower top moment) is of the same order for the two types of mooring system, which indicates that this load is independent of floater pitching motion, and depend upon the surge displacement similar for the two types of mooring systems.

REFERENCES

1. *World Wind Energy Report*, World Wind Energy Association, 2012.
2. M.B. Waris, *Dynamic response prediction of floating offshore wind turbine system using fully nonlinear model*, Ph.D. Dissertation, The University of Tokyo, Tokyo, 2010.
3. T. Utsunomiya, E. Nishida, On sea experiment of a hybrid SPAR for floating offshore wind turbine 1/10 scale model, *Proceedings of the ASME 29th International Conference on Ocean*, Offshore and Arctic Engineering, Shanghai, 2010.
4. B. Skaare, T.D. Hanson, F.G. Nielsen, R. Yttervik, A.M. Hansen, K. Thomsen, T.J. Larsen, Integrated dynamic analysis of floating offshore wind turbines, *Proceedings of European wind energy Conference and Exhibition*, Milan, 2007.
5. T.P. Fuglseth, M. Undeland, Modelling of floating wind turbines for simulation and design of axial thrust and power control strategies, *Renewable Energy*, Chiba, 2006.
6. N. Srinivasan, S. Chakrabarti, R. Radha, Damping controlled response of a truss pontoon semi-submersible with heave plates, *Proceedings of the 24th International Conference of OMAE*, Halkidiki, Greece, 2005.
7. M. Murakami, M. Takada, M. Fujiyoshi, T. Katada, S. Nagata, T. Fujita, The Hitz concept of an offshore floating-type wind turbine generation system, *Offshore Wind Energy Forum*, Tokyo, 2004.
8. K. Yago, Y. Ohkawa, H. Suzuki, T. Sawai, A basic study on the floating wind power system, *17th Ocean Engineering symposium – The society of Naval Architects of Japan*, Yokohama, 2003.
9. B. Skaare, T.D. Hanson, F.G. Nielsen, Integrated dynamic analysis of floating offshore wind turbines, *Wind energy Conference and Exhibition*, Athens, 2006.
10. P.V. Phuc, *Dynamic Response Analysis of Floating Offshore Wind Turbine System in the Parked Condition*, Ph.D. Dissertation, The University of Tokyo, Tokyo, 2008.
11. D. Roddier, C. Cermelli, A. Weinstein, Wind Float: A Floating Foundation for Offshore Wind Turbines, *Journal of Renewable and Sustainable Energy,* **2(3)**, 1-34, 2010.
12. J.M. Jonkman, *Dynamic Modeling and Load Analysis of an Offshore Floating Wind Turbine*, Ph.D. Dissertation, University of Colorado, Colorado, 2007.
13. S.H. Jeon, M.W. Seo, Y.U. Cho, W.G. Park, W.B. Jeong, Sloshing Characteristics of an Annular Cylindrical Tuned Liquid Damper for Spar-type Floating Offshore Wind Turbine, *Journal of Structural Engineering and Mechanics*, **47(3)**, 331-343, 2013.
14. M.B. Waris, T. Ishihara, Dynamic response analysis of floating offshore wind turbine with different types of heave plates and mooring systems by using a fully nonlinear model, *Coupled Systems Mechanics*, **1(3)**,247-268, 2012.
15. B. Wang, S. Rahmdel, C. Han, S. Jung, S. Park, Hydrodynamic Response of Alternative Floating Substructures for Spar-type Offshore Wind Turbines, *Journal of Wind and Structures*, **18 (3)**, 267-279, 2014.
16. N. Alati, V. Nava, G. Failla, F. Arena, A. Santini, On the Fatigue Behavior of Support Structures for Offshore Wind Turbines, *Journal of Wind and Structures,* **18 (2)**, 117-134, 2014.

17. J. R. Morison, M. P. O'Brien, J.W. Johnson, S.A. Schaaf, The force exerted by surface waves on piles, *Petroleum Transactions*, AIME, **189**, 149-154, 1950.

18. S.H. Ju, J.J. Stone, R.E. Rowlands, A new symmetric contact element stiffness matrix for frictional contact problems, *Computers and Structures*, **54(2)**, 289 – 301, 1995.

19. P.V. Phuc, *Numerical and Theoretical Study on the Wind Response of Wind Turbine in the Strong Wind Condition*, M.Sc. Thesis, Department of Civil Engineering, The University of Tokyo, Japan , 2005.

20. S.K. Chakrabarti, *Hydrodynamics of offshore structures*, Computational Mechanics Publications, Southampton, 1987.

21. ASCE 7-02, *Minimum Design Loads for Buildings and Other Structures*, Revision of ASCE 7-98, 2002.

22. IEC 61400-3, *Wind turbines – Part 3: Design requirements for offshore wind turbines, 1st Edition*, IEC, 2007.