

Dynamic response of a novel reduced draft Spar-type FOWT with anti-motion damping structure

Pei ZHANG, Xiaoqi QU, Junhui HUANG, Jingchen ZHANG, Yougang TANG, Yan LI*

State Key Laboratory of Hydraulic Engineering Simulation and Safety,
School of Civil Engineering, Tianjin University, Tianjin, 300354, China

*Corresponding author, liyan_0323@tju.edu.cn

ABSTRACT

With regard to the offshore areas in China, the water depth is limited so that the traditional Spar-type FOWTs are not suitable to be installed in these areas. In this work, we proposed a novel reduced draft Spar-type FOWT with anti-motion damping structure. Simulations are conducted in both frequency and time domain to investigate the dynamic response of the FOWT in different scenarios. Towards this end, a coupled aero-hydro-mooring numerical model is developed. The methodology includes a blade-element-momentum model for aerodynamics, a nonlinear model for hydrodynamics, a nonlinear restoring model of SPAR buoy, and a nonlinear catenary model for mooring cables. The motions of platform, the tensions in the mooring lines and the power generation performance are documented in different cases. The dynamic performance is also compared with the classic Spar-type wind turbine. According to the results, it shows that the reduced draft Spar-type FOWT is effective to support the 5MW baseline offshore wind turbine in the limited water-depth area. The increase in diameter of the motion reducing structure can effectively reduce the motion in pitch and the mooring tension, thereby improving safety and stability of the floating turbine system.

1 INTRODUCTION

The global cumulative installed wind capacity is growing rapidly recent years. For different water depths, the types of offshore wind turbine foundation are also different. Fixed foundation is used in the shallow waters near the shore, and the applicable water depth is about 30m. When the water depth is more than 30m, the cost of fixed foundation is significantly increased, and the floating foundation is proposed. Hereby, floating foundations for wind turbine is mainly used for deep-water zone.

However, the actual area being developed for offshore wind power in China is still mainly concentrated on the continental shelf. The most characteristic of these areas is that the seabed slope is small, and most of the water depth is 50 m~70 m. This geographical condition limits the advantages of floating foundations in deep water conditions. Therefore, for the 50 m~70 m water depth, a new type of offshore wind turbine foundation type need to be proposed.

In recent years, many scholars have done a lot of research work on how to reduce the water depth and draft of floating wind turbines. Sauder^[1] et al. and Melis^[2] et al. designed new types floating foundations for supporting the respectively, and carried out preliminary numerical analysis and model experiment, but the operation ability of water depth of 50 m~70 m still cannot meet the requirements. Guzmán^[3] proposed a RDS type on the basis of classic Spar type. This type reduced the center of gravity and the draft by shortening the column and setting the ballast tank. But the impact of aerodynamic loads on the wind turbine did not be considered.

In this work, a new type of reduced draft Spar type wind turbine is proposed for the water depth of 70 m. The nonlinear coupling dynamic analysis model of aerodynamic-hydrodynamic-

mooring system is established. The corresponding numerical calculation tools are developed by Matlab to analyse the motion performance of the reduced draft Spar type floating wind turbine.

2 CONCEPT DESIGN

Among the floating foundation types, the TLP type is suitable for medium water depth, but its mooring system is intensely complicated[4]. When the water depth is shallow, the design of tension tendons is difficult and costly; semi-submersible floating foundation has large water plane area and good stability, but the heave motion response is large; the Spar type floating foundation has better motion performance when the water depth is more than 100 m~200 m, but it is not suitable for shallow waters. Based on the Spar type floating foundation, this paper adds a large-diameter cylindrical structure at the bottom, and proposes an offshore wind turbine with a motion reducing structure. The hydrodynamic and motion response analysis is carried out, and the results show the good motion performance of the new type floating wind turbine.

2.1 Model and parameters

The main part of the traditional Spar type floating foundation is a slender column that can keep enough displacement by a large draft. In order to reduce the applicable water depth, the column of the Spar type foundation is shortened, and a cylindrical ballast tank with a large diameter is arranged at the bottom to lower the center of gravity to ensure structural stability, and sufficient displacement is ensured under conditions of reduced draft. The basic properties of the new reduced draft floating foundation are given in Table 1. The structural form is shown in Figure 1. The foundation is mainly composed of three parts: the upper structure is 10 m high and is used for connection with the tower; the middle cylinder is 18 m high for connection with the bottom motion reducing structure; the bottom is a cylindrical type of motion reducing structure with diameter D . The upper part of the motion reducing structure is truncated cone type. The bottom part is set with a layer of damping plate. The outside of interior of the motion reducing structure is a water ballast tank (including 6 cabins); and the inside is three solid ballast tanks which filled with cement ballast. The center of the structure consists of a circular ring-shaped ballast tank with outer diameter of 12m and inner diameter of 6 m, and a circular equipment cabin with diameter of 6m.

Table 1: Properties of Reduced Draft Spar Type Floating Foundation

Draft	40/m
Diameter(D)	55/m
Displacement	50336/m ³
Mass	50821/t
Vertical Position of Center of gravity	-32.69/m
Radius of gyration about X-axis	14.07/m
Radius of gyration about Y-axis	14.07/m
Radius of gyration about Z-axis	17.91/m

The upper wind turbine of the model in this paper is a 5MW wind turbine developed by NREL^[5]. The specific parameters are shown in table 2. Part of the structure of the tower is referred to the structural form of OC3-Hywind Spar floating wind turbine^[6]. The overall model of the wind turbine is shown in figure 2.

Table 2: NREL 5 MW FOWT properties

Rotor diameter	126/m,
Hub diameter	3/m
Hub height	90/m
Cut-in,Rated.Cut-out speed	3/m·s ⁻¹ , 11.4/m·s ⁻¹ , 25/m·s ⁻¹
Rated rotating speed	12.10/rpm
Rotor mass	110000/kg
Cabin mass	240000/kg
Tower mass	249718/kg

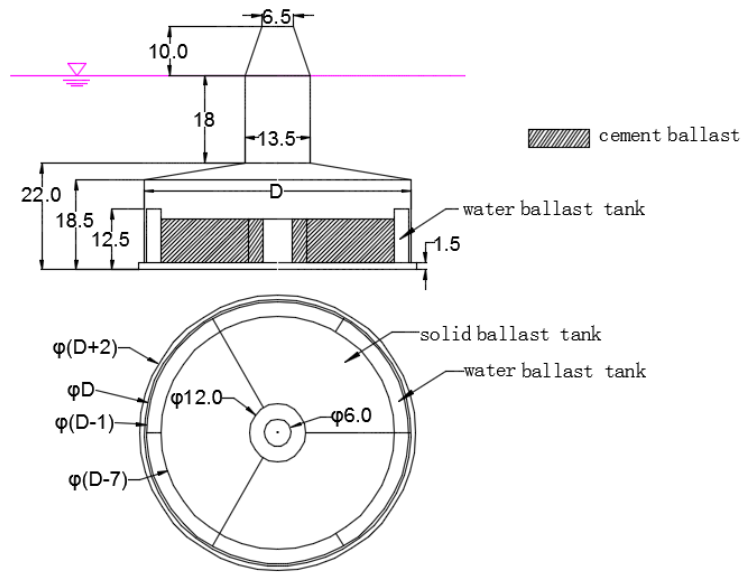


Figure 1: Structure of Reduced Draft Spar Type floating foundation



Figure 2: Overview of Reduced Draft Spar Type Floating Wind Turbine

2.2 Mooring System

Mooring system is composed of three steel cable chain of catenary type. The angle between every chain is 120 deg. The chains are connected to the floating foundation through the fairleader. The main parameters of mooring system[7] are shown in table 3.

Table 3: Mooring system properties

Studless cable chain diameter	142/mm
Level	R4S
Minimum breaking tension	20008/kN
Cable chain length	300/m
Distance from fairlead to sea level	-25/m
Distance from fairlead to the center of foundation	27.5/m

Distance from anchor to sea level	-70/m
Distance from anchor to the center of foundation	317.5/m

3 COMPUTATIONAL ANALYSIS METHODOLOGY

In this paper, JONSWAP wave spectrum was used to simulate the random wave, and three-dimensional potential flow theory was used to calculate the wave force on the floating foundation^[8].

Based on the theory of blade element-momentum, this paper adopts the iterative method to calculate the aerodynamic load of the wind turbine, and adopts the Prandtl blade tip loss factor correction model and the Glarert correction model^[9]. The torque generated by the total axial aerodynamic force and total tangential aerodynamic force of each local blade element after correction can be expressed as:

$$\begin{aligned} dT &= 4\pi r \rho v_0^2 a(1-a) dr \\ dM &= 4\pi r^3 \rho v_0 \omega(1-a) a' dr \end{aligned} \quad (1)$$

In this equation, r means radius of the fluid circle, dr means thickness of the fluid circle, ρ means density of the fluid, v_0 means velocity of the wind, ω means rotating speed of the rotor, a and a' means axial and tangential induction factors respectively.

After the local loads are calculated by using the blade element-momentum theory for all the control volumes, the normal and tangential load distributions can be obtained, and the overall aerodynamic loads of the wind turbines can be calculated based on this distribution.

According to the global coordinate system, the motion equation of the reduced draft Spar type floating wind turbine in time domain can be written as^[10]:

$$(M + A_\infty) \ddot{x}(t) + C(\omega) \dot{x}(t) + K(x)x(t) = q(t, x, \dot{x}) \quad (2)$$

In this equation, M means floating body mass matrix. A_∞ means the additional mass matrix when the frequency tends to infinity. C means the damping matrix. K means the restore stiffness matrix, x, \dot{x}, \ddot{x} respectively means the position, velocity and acceleration of the floating foundation in six degrees of freedom. q means the external excitation load. In this paper, we consider the aerodynamic load, first order and second order mean wave force and nonlinear restoring mooring force.

4 TIME DOMAIN DYNAMIC RESPONSE ANALYSIS

According to the time-domain motion control equation of the reduced draft Spar type floating wind turbine, the numerical calculation program is developed with MATLAB. In this paper, the hydrodynamic model of the floating foundation was firstly established by GenIE, and then the hydrodynamic characteristics of the floating foundation were calculated by WADAM. Then the initial position of the floating foundation and the environmental loading conditions were input, and the motion response of the floating wind turbine at each time step was solved by using the fourth-order Runge-Kutta method.

4.1 Free decay numerical simulation

In the environment condition without wave and wind, keep the wind turbines remains stationary, and then give the floating foundation an initial displacement. Numerical simulation of freedecay motion for each degree of freedom was carried out. The natural frequency of each degree of freedom was calculated. The calculation results are compared with the results of FAST software^[10], as shown in table 4. The results show that the results calculated by the two methods match well, which verify the reliability of the numerical program.

Table.4 Natural frequencies of Reduced draft Spar FOWT

DOF	FAST	MATLAB
Surge	0.059 rad/s	0.063 rad/s
Heave	0.100 rad/s	0.104 rad/s
Pitch	0.339 rad/s	0.336 rad/s

4.2 Operation sea state response analysis

According to the environmental conditions in the south China sea, the operating sea condition wind speed was set to be 11.4m /s, the wave height was 2.1m, the spectral peak period was 5.3s, and the simulation time was 3600s. The results of 0 ~ 1000s were taken for analysis, and the time-motion curve of motion response was compared with the calculation results of FAST. The time-motion curves were shown in figure 3, and the statistics were shown in table 5. The result shows that the calculation results of the numerical program in this paper are in good agreement with FAST. Under the operation sea state, the average of the floating foundation in surge, heave and pitch motion is 2.45 m, 0.01 m, and 3.25 °.

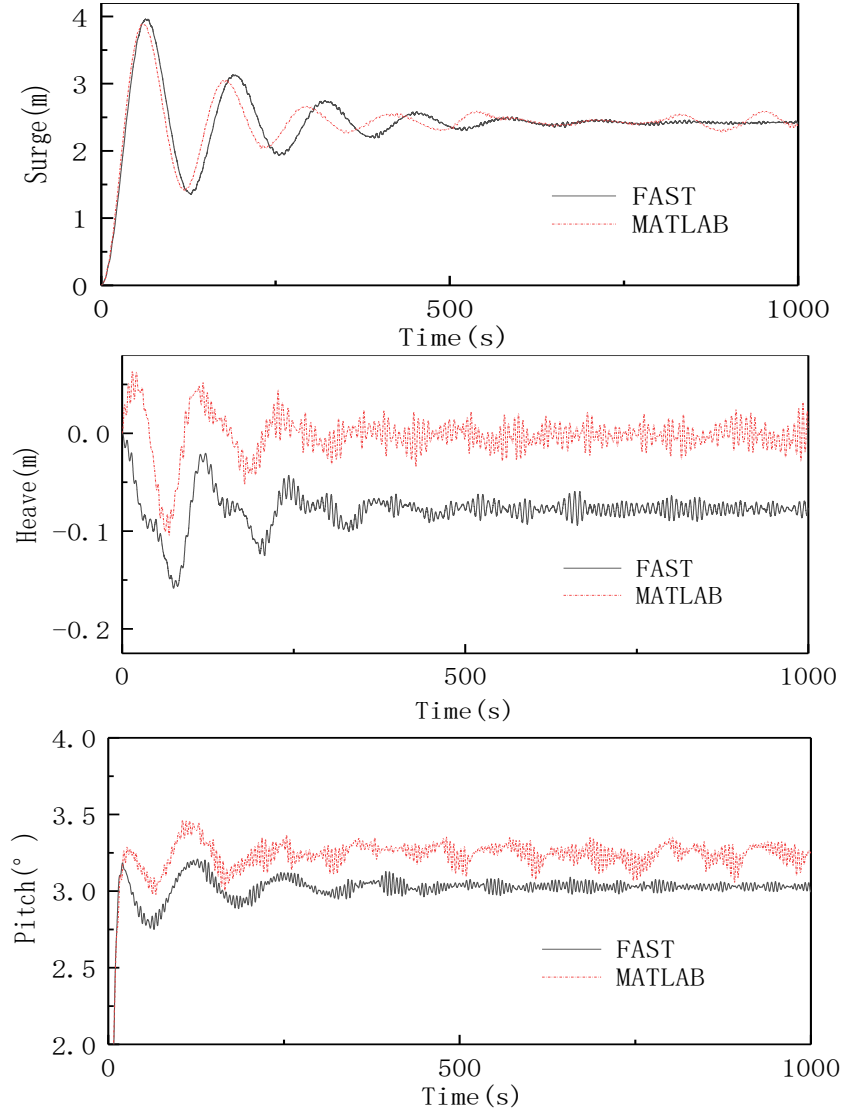


Figure.3: Motion in operation sea state

Table.4 Statistics of motion response in operation sea state

	Surge/m		Heave/m		Pitch/°	
	FAST	MATLAB	FAST	MATLAB	FAST	MATLAB
Average	2.44	2.45	0.07	0.01	3.03	3.25
Maximum	3.96	3.88	0.15	0.10	3.08	3.65
Minimum	1.34	1.34	0.00	0.06	2.97	2.99
Standard deviation	0.31	0.28	0.01	0.01	0.05	0.05

As shown in Fig.4, in the operation sea condition, the response spectrum amplitude of the surge motion is mainly concentrated at the low frequency of 0.052 rad/s, corresponding to the natural frequency of surge, and the response near the wave frequency is relatively small. The wave frequency motion response of

heave motion is significant, and there are two peaks in low frequency region, which are 0.084 rad/s and 0.052 rad/s respectively. They are close to the natural frequency of heave and surge, indicating the coupling effect of heave and surge. Pitch motion also shows obvious wave frequency motion response, and the peak value in low frequency region is 0.044 rad/s, which is between the natural frequency of surge and pitch, indicating the coupling effect between surge and pitch.

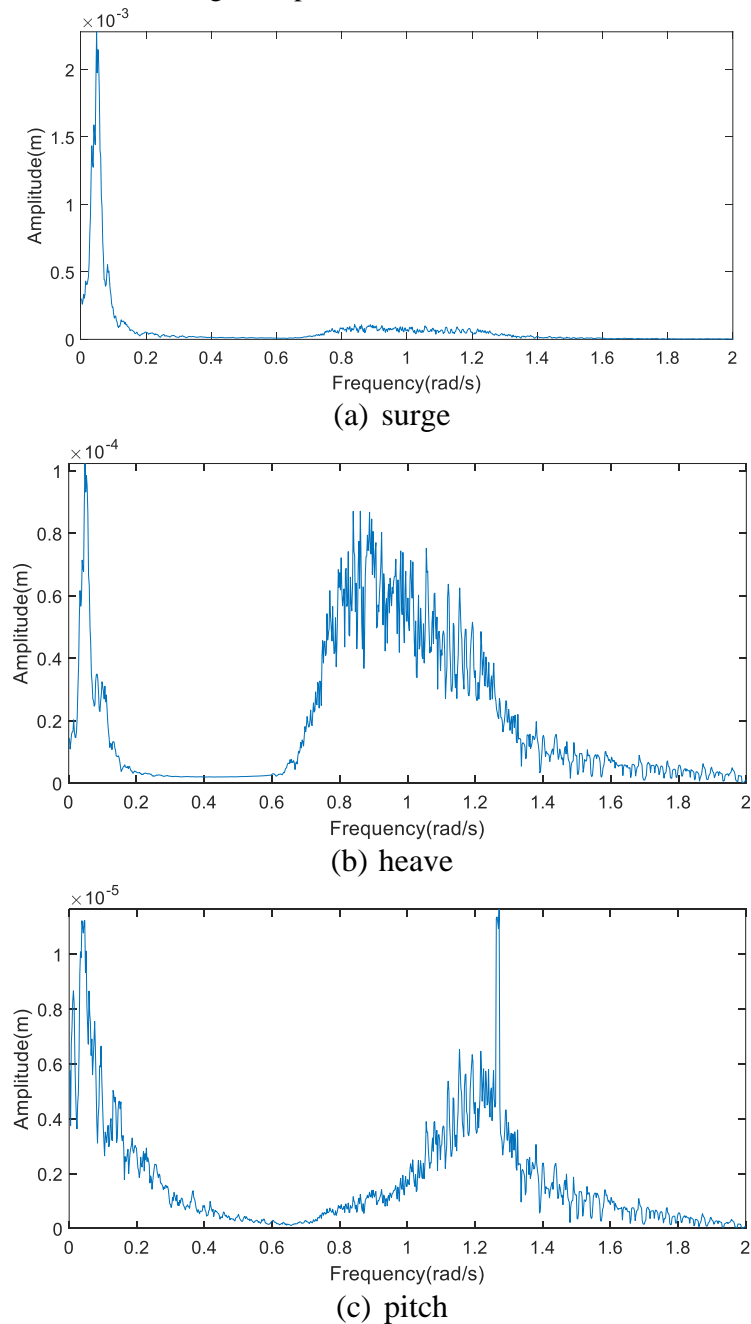


Figure.4: Spectrum of motion response in operation sea state

4.3 Optimal design of the motion reducing structure

The diameter D was selected as the optimal design parameter to study the motion characteristics. Change the diameter D from 49 m to 57 m with an interval of 2 m. The motion response of wind turbine under operation sea condition is calculated. The results of 2000s~2300s were analyzed. The time-motion curves were shown in Fig.5. The results show that with the increase of diameter D , the amplitude of the surge motion gradually increased from 1.5m to 2.5m. The amplitude of heave motion varies from 0.04m to 0.08m. When D is less than 55m, it decreases with the increase of diameter; when D is 55m, it reaches the smallest; when D is greater than 55m, it increases negatively, but the overall change is not obvious. Pitch

motion amplitude changes between 2.5° and 4.5° , and decreases with the increase of diameter. Therefore, as the diameter of the motion reducing structure increases gradually, the pitch motion of the floating foundation decreases, the surge motion increases slightly, and the heave motion first decreases and then increases. When $D=55\text{ m}$, the heave motion is the minimum.

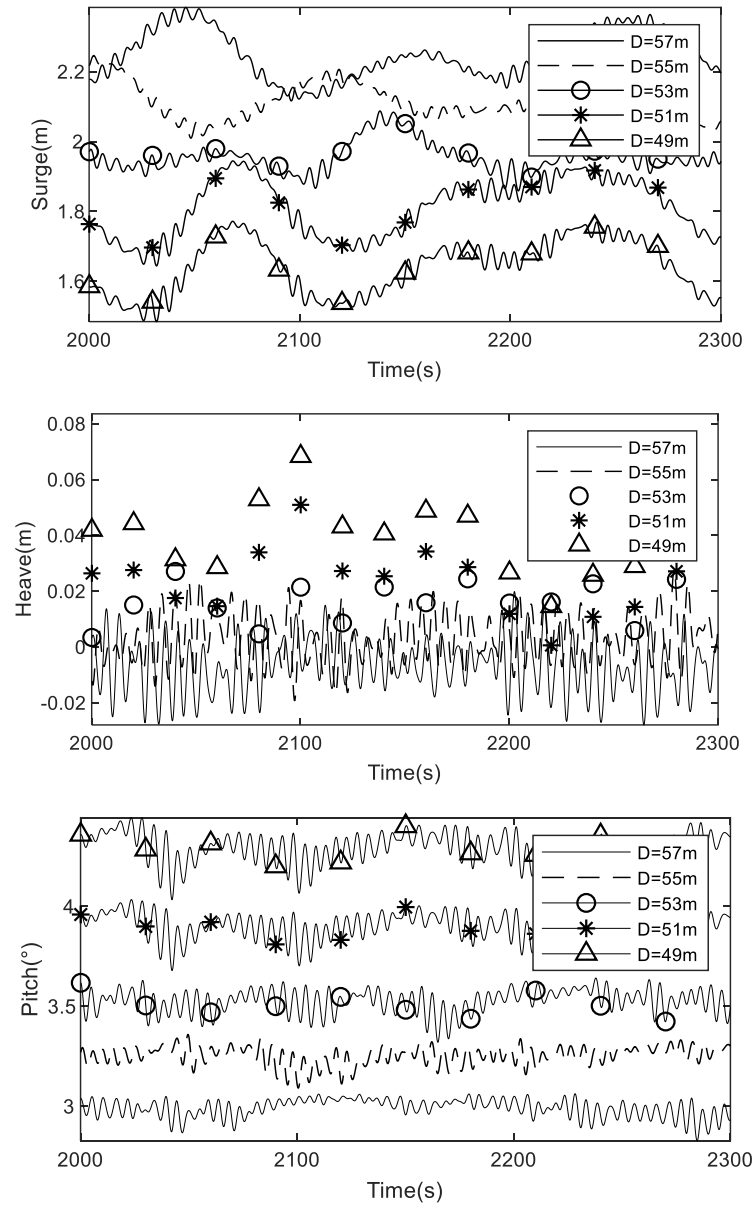


Figure.5: Motion response of floating foundation with different Diameter

For the mooring system, the no. 2 cable with the largest mooring tension is taken for the comparative statistics of the mooring tension response, and the results are shown in Fig.6. The results show that with the change of diameter D , the mooring tension varies between 1400 kN and 1550 kN, which is far less than the breaking tension, and the mean mooring tension decreases with the increase of diameter. Therefore, increasing the diameter of the damping structure is helpful to reduce the mooring tension and improve the safety performance of the floating wind turbine system.

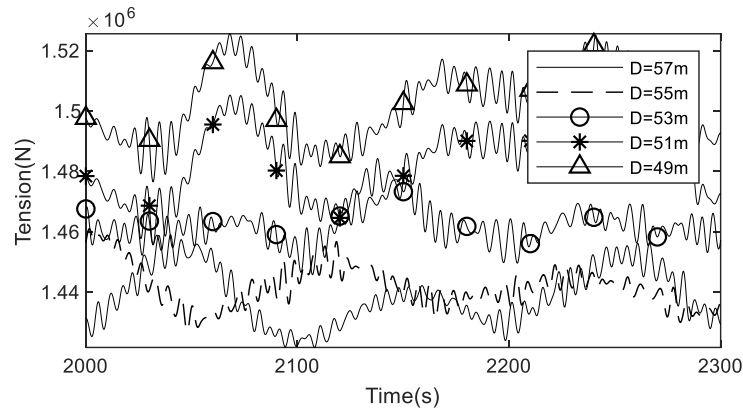


Figure.6: Tension of floating foundation with different Diameter

5 CONCLUSION

In this paper, a new type of reduced draft Spar type floating wind turbine is proposed, which is suitable for water depth of 70 m. The nonlinear dynamic analysis model of the coupling of aerodynamic force, hydrodynamic force and mooring system is established. The corresponding numerical calculation tool is developed with MATLAB. The main conclusions are as follows:

1) The time domain response results calculated by the program in this paper are in good agreement with the calculation results of FAST. The motion response of the new type of reduced draft Spar type floating wind turbine in the operating sea condition meets the safety operation requirements which could be found in previous investigations on the FOWTs [11]. This reflects the good applicability of the structure to the shallow sea.

2) Increasing the diameter of the motion reducing structure can reduce the pitch motion of the floating foundation and lead to a small increase in surge motion. The heave motion is the smallest when the diameter is 55 m.

3) Increasing the diameter of the motion reducing structure can reduce the mooring tension, so as to improve the safety performance of the floating wind turbine system.

ACKNOWLEDGEMENTS

This work is financially supported by the Project funded by China Postdoctoral Science Foundation (No.2019M651042).

REFERENCES

- [1] Sauder T, Chabaud V, Thys M, et al. Real-Time Hybrid Model Testing of a Braceless Semi-Submersible Wind Turbine: Part I—The Hybrid Approach[C]//ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers, 2016.
- [2] Melis C, Caille F, Perdrizet T, et al. A Novel Tension-Leg Application for Floating Offshore Wind: Targeting Lower Nacelle Motions[C]//ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers, 2016.
- [3] De Guzmán S, Marón D, Bueno P, et al. A Reduced Draft Spar Concept for Large Offshore Wind Turbines[C]//ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers, 2018.
- [4] Natvig B J, Teigen P. Review of hydrodynamic challenges in TLP design[J]. International Journal of Offshore and Polar Engineering, 1993, 3(04).
- [5] Jonkman J, Butterfield S, Musial W, et al. Definition of a 5-MW reference wind turbine for offshore system development[R]. National Renewable Energy Laboratory, Golden, CO, Technical Report No. NREL/TP-500-38060, 2009.
- [6] Jonkman J. Definition of the Floating System for Phase IV of OC3[R]. National Renewable Energy Lab. (NREL), Golden, CO (United States), 2010.
- [7] The International Association of Classification Societies. IACS UR W22 Offshore mooring chain - Rev.6[S]. 2016.
- [8] Journé J M J, Massie W W. Offshore hydrodynamics[J]. Delft University of Technology, 2001, 4: 38.
- [9] Leishman G J. Principles of helicopter aerodynamics with CD extra[M]. Cambridge university press, 2006.

[10] MARINTEK, SIMO 4.8.5 Theory Manual[Z] 2016.10

[11] Casale, C., Lembo, E., Serri, L., & Viani, S. (2010). Preliminary design of a floating wind turbine support structure and relevant system cost assessment. *Wind Engineering*, 34(1), 29-50.