Long-term Extreme Structural Loads of a Triple-column Spar Floating Wind Turbine Concept

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ABSTRACT

A novelty floating wind turbine concept, which utilizes a newly developed triple-column spar platform to support the NREL 5MW baseline wind turbine, is proposed in this research. A modified environmental counter method is proposed to estimate the long-term extreme response of the novelty concept. Aero-hydro-servo-elastic coupled simulations are performed. Numerical simulations demonstrate that the triple-column Spar floating wind turbine has a better dynamic performance compared with a single-column concept, in terms of platform motion, tower base structural loads and mooring line tension. The critical environmental condition is identified with the modified environmental contour method, and it is shown that the 50-year return period extreme tower base structural load is reduced with the application of the three-column Spar platform. Nevertheless, the extreme mooring line tension which is dominated by the wind load, is not reduced. The present research reveals the prospect of the three-column Spar concept in the offshore wind energy application.

KEY WORDS: floating wind turbine; three-column Spar; long-term extreme response; environmental contour method; renewable energy.

INTRODUCTION

Powered by the increasing global pursuit of sustainable energy, the traditional wind industry is moving to deeper water to exploit the high-quality offshore wind resource. Since the proposal of the Hywind demo (Equinor, 2017), the world's first full scale offshore floating wind turbine, various floating structures have been developed for offshore floating wind turbine application. The WindFloat (Principle Power, 2015) is a semisubmersible floating wind turbine, which utilizes three columns with heaving plates to produce buoyancy force. Three floating platforms are proposed in the OC4 DeepCwind project (Koo et al., 2014). Goupee et al. (2014) conducted an experimental comparison of floating wind turbine with three supporting platforms. Li et al. (2018) numerically simulated the dynamic response a Spar-type floating wind turbine integrated with a wave energy converter (WEC) and two tidal turbines. While the short-term investigation (assuming that the stochastic environmental condition is fixed) on floating wind turbine has been fully conducted, the effort spared on long-term performance is insufficient.

During the lifetime of a floating wind turbine, the long-term environmental condition is varying rather than fixed and thereby one must address it from a stochastic point of view. Basically, a full long-term analysis approach is recommended to estimate the long-term extreme response. The full long-term analysis method integrates the short-term response with a given environmental distribution model to value the lifetime values. Coe et al. (2018) performed a full long-term analysis of the dynamic responses of a WEC. Agarwal and Manuel (2009) investigated the extreme response of an offshore floating wind turbine with the full long-term analysis (FLTA). Nevertheless, the FLTA requires massive simulations of short-term response to cover every combination of environmental parameters. It is inefficient and many alternative methods have been developed. Environmental contour method (ECM) is among these alternative methods, which assumes that the most dangerous situation happens under a critical environmental condition located on the contour surface. As not many simulation realizations are required, the ECM has been widely used to estimate the extreme response induced by wave loads. Canning et al. (2017) perform a long-term reliability analysis of a wave energy converter with ECM. Nevertheless, for the response of a floating wind turbine, the ECM may be not applicable due to the monotonic performance of wind force (Saranyasoontorn and Manuel, 2004, 2005a). Li et al. (2019) modified the ECM to consider the monotonic performance of wind force.

The primary objective of the present study is to improve the dynamic performance of offshore floating wind turbines, especially the long-term limit state, by optimizing the platform hull. For this purpose, a triple-column Spar concept is developed. A modified environmental contour method is used to estimate the long-term extreme response of the triple-column Spar. The performance of the present design will be compared with that of a single-column concept (Jonkman, 2010) to demonstrate its competence.

MODEL DESCRIPTION

Fig. 1 sketches the hull of the floating platform developed in the present study. As shown, the new concept is made up of three columns with a radius of 2.4 m to produce the buoyancy force. The three columns are connected with two discs, one of which is above the still sea level and acts as the deck to mount the wind turbine. The hull size is sketched in Fig. 1 and the main dimensions are listed in Table 1. The competence of the triple-column Spar is evaluated through comparison with a single-column design, namely the OC3 Hywind (Jonkman, 2010).

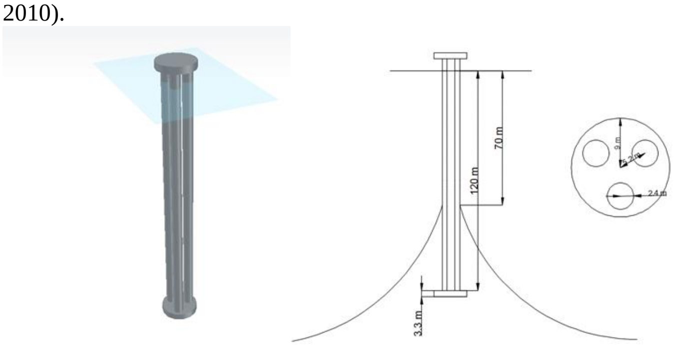

Fig. 1. Triple column Spar concept.

Table 1 Main dimensions of the triple-column Spar.

Item	Value
Draft	123.3 m
Volume	7354 m^3
Mass	6.78×10^{6} kg
CoG	(0 m, 0 m, -100 m)
I_{xx}	1.24×10^{10} kg·m^2
I_{yy}	1.24×10^{10} kg·m^2
I_{zz}	1.64×10^{8} kg·m^2

Table 2 Mooring line properties.

Item	Value
Depth to anchors	320 m
Depth of fairleads	70 m
Radius to anchors	853.87 m
Radius to fairleads	6.4 m
Unstretched mooring line length	902.2 m
Mooring line diameter	0.09 m
Equivalent mooring line mass density	77.71 kg/m
Equivalent mooring line extensional stiffness	3.84×10^{5} kN

The triple-column concept is also displaced at sea site with a water depth of 320 m and moored by three slack catenary lines. The fairleads are connected to the platform at 70 m below the still water level. The three lines are oriented at 60°, 180°, and 300° about the vertical axis. The relevant properties of the mooring lines are listed in Table 2.

The NREL 5MW baseline wind turbine (Jonkman et al., 2009) is used. The rotor diameter is 126 and the hub height is 90 m. The rated wind speed is 11.4 m/s. Please refer to (Jonkman et al., 2009) for the details of the reference wind turbine.

LONG-TERM EXTREME ANALYSIS

During the lifetime of a floating wind turbine, the environmental condition varies and follows a certain distribution model. The classic full long-term analysis takes all the possible sets of environmental parameters into account. The full long-term analysis is rather straightforward and reliable, although it requires massive simulations.

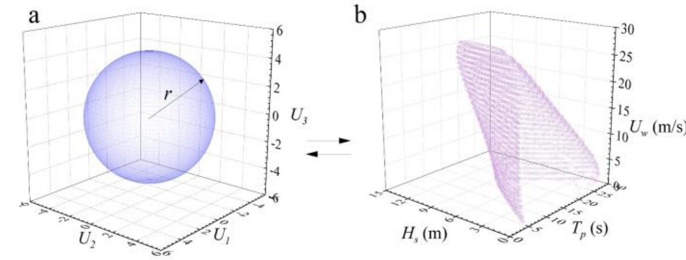

Fig. 2. Environmental contour method. (a) U-space; (b) X-space.

To save the computation effort, it is assumed that extreme response is induced by a critical environmental condition. Usually, the environmental contour method (ECM) is used to find such critical condition. The generation of the environmental contour surface is based on the Rosenblatt transformation, which transforms the environmental parameter X from the initial X-space into a nonphysical U-space. According to Fig. 2, the standard ECM merely seeks the critical environmental condition from the 50-year return period contour.

$$U = T_2(T_1(X)) \tag{1}$$

$$T_1 : Y = \begin{pmatrix} F_1(x_1) \\ \ldots \\ F_{k|1,\ldots,k-1}(x_k \mid x_1,\ldots,x_{k-1}) \\ F_{n|1,\ldots,n-1}(x_n \mid x_1,\ldots,x_{n-1}) \end{pmatrix} \tag{2}$$

$$T_2 : U = \begin{pmatrix} \Phi^{-1}(y_1) \\ \ldots \\ \Phi^{-1}(y_k) \\ \Phi^{-1}(y_n) \end{pmatrix} \tag{3}$$

Φ is the cumulative distribution function (CDF) of the standard normal distribution. In the U-space, all combinations of transformed environmental parameters with respect to N-year return period are located on a sphere with radius r

$$r = \Phi^{-1}\left(1 - \frac{1}{N \times 365.25 \times 24}\right) \tag{4}$$

ECM assumes the actual critical environmental condition to be close to the counter surface in X-space or the sphere in U-space with respect to the 50-year return period. Due to this assumption, which is also the limitation of ECM, ECM is not applicable to a floating wind turbine (Saranyasoontorn and Manuel, 2004; Saranyasoontorn and Manuel, 2005b). This is because the wind force is not monotonic with the wind speed, especially around the cut-out wind speed. As shown in Fig. 3, the thrust force of the NREL 5MW baseline wind turbine reaches the maximum value at rated wind speed (11.4 m/s) and drops gradually as the wind speed continues increasing. If the wind speed exceeds the cut-out speed 25 m/s, the wind turbine is parked and no wind force is applied on the rotor. In this case, the responses induced by wind force are higher in the operational state and lower in the parked state. Moreover, a discontinuity appears at 25 m/s. Consequently, the omission of response variability is not reasonable. In this circumstance, the inverse first-order reliability method (IFORM) should be used. Although the IFORM is already a simplification than the FLTA, it is still more complex than the ECM and requires massive simulations. Therefore, a modification is made to the ECM in this study, which considers the variability of response by checking multiple environmental contour surfaces.

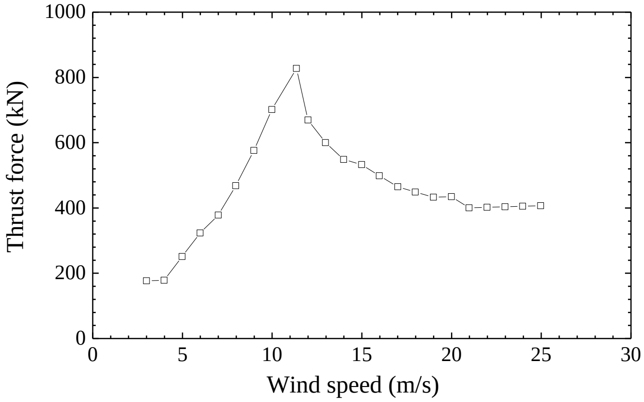

Fig. 3. Aerodynamic performance of the NREL 5MW baseline wind turbine.

Basically, the procedures of the modified environmental contour method (MECM) is similar to those of the EMC, which can be regarded as an expansion of the ECM while still a simplification of the IFORM. The main idea of the MECM is to include multiple important contour surfaces rather than the 50-year one alone. The first step is to select a set of wind speeds with respect to different return periods and the corresponding most probable wave heights and wave periods based on a joint wind-wave distribution model. Simulations are afterward performed to acquire extreme values with respect to these selected environmental parameters. The first step is introduced to find the wind speed in which the non-monotonic behavior of the wind turbine is the most significant. Subsequently, the N-year return period corresponding to a response peak and the 50-year return period are selected. A response peak is observed because the non-monotonic behavior of the wind turbine is remarkable at this wind speed. Finally, search for the critical environmental condition on the selected multiple contour surfaces (see Fig. 4). In this way, the variability of response is considered by checking multiple contour surfaces with different return periods. If all the contour surfaces within a 50-year return period are included, then the MECM will become the IFORM. If only the 50-year contour surface is identified (no response peak occurs), the MECM becomes the ECM. Please refer to (Li et al., 2019) for more details of the MECM.

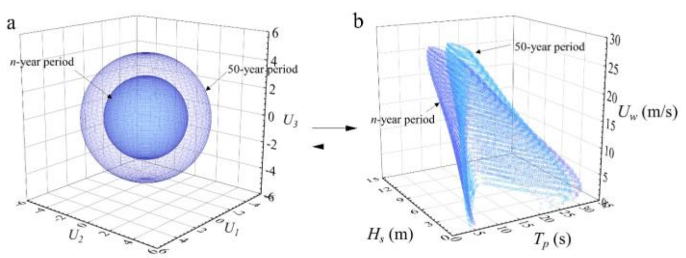

Fig. 4 Modified environmental contour method. (a) U-space; (b) X-space.

For the critical environmental condition with respect to *N*-year return period identified by the MECM, assuming each 1-hr period is independent, the 1-hr extreme CDF of *N*-year return period can be used to extrapolate the extreme CDF of the 50-year return period

$$F^{LT}_{50-year}(x) = \left[F^{LT}_{X_{1-hr,50-year}}(x)\right]^{50\times 365.25\times 24}$$
$$F^{LT}_{X_{1-hr,50-year}}(x) = \left[F^{ST}_{X_{1-hr}|U_w,H_s,T_p}(x|u_N,h_N,t_N)\right]^{50/N} \tag{5}$$

Given that the critical environmental condition has been identified, it is assumed that the extreme response of an offshore structure converges to the Gumbel distribution

$$F^{ST}_{X_{1-hr}|U_w,H_s,T_p}(x|u_N,h_N,t_N) = \exp(-\exp(-(x-\mu)/\sigma)) \tag{6}$$

Then the most probable 50-year extreme value is given by Eq. (7). In the following part of this paper, the extreme response refers to the most probable 50-year extreme response

$$M_{50-year} = \mu + \sigma\cdot\ln\left[50\times 365.25\times 24\times(50/N)\right] \tag{7}$$

SIMULATION RESULTS

Aero-hydro-servo-elastic coupled simulation package FAST (Jonkman and Buhl Jr, 2005) is used to run the numerical simulations in time-domain. The wave kinetics are addressed within the framework of potential flow theory, assuming that the fluid is inviscous, incompressible and irrotational. Three components of hydrodynamic loads are accounted: hydrostatic force, radiation wave force (including memory effect of the free water surface), and wave excitation force. Aerodynamic calculations are based on the blade element momentum (BEM) method, where the blade is divided into a set of elements, and the elements are assumed independent from each other. The lumped-mass model is used for the dynamics of mooring lines connected to the floating platform. Please note that FAST is based on potential flow theory, which becomes less accurate in severe sea states. The nonlinearity of wave-structure in extreme waves is a complex phenomenon and to focus on the scope of the present research, FAST is still used.

The random waves are generated based on the Airy, assuming that each wave components are independent of each other. A steady wind field is considered and the wind shear effect is modeled as

$$U_z(z) = U_w\left(\frac{z}{10}\right)^{0.1} \tag{8}$$

where U_z is the wind speed at height *z* and U_w is the wind speed at 10m above the sea surface.

Hydrodynamic coefficients

Fig. 5 and Fig. 6 illustrates the linear wave excitation force transfer function for surge and pitch modes, respectively. Regardless of the wave frequency, the triple-column spar is subject to fewer wave loads in pitch mode. Meanwhile, the surge wave forces exerting on the triple-column spar is generally lower within the typical wave frequency range. Since the triple-column spar platform is exposed to lower levels of wave loads in the oceans, it can be expected to have a better dynamic performance compared with the Hywind.

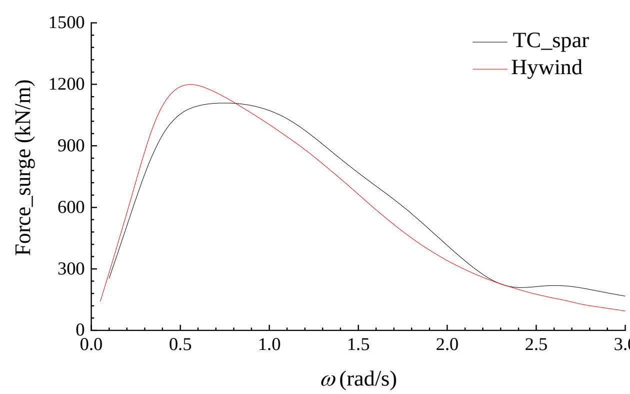

Fig. 5. Linear wave excitation transfer function.

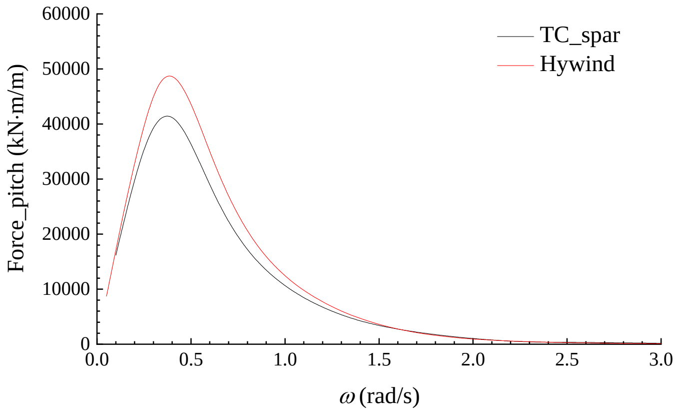

Fig. 6. Linear wave excitation transfer function.

Platform Motions

Firstly, the short-term dynamic responses at three joint wind-wave environmental conditions (below-rated, rated, over-rated) are presented. The environmental conditions are listed in Table 3. The JONSWAP wave spectrum is used to specify the random wave elevations. The simulation runs sufficiently long time until the transient response damps out, and the last 3600 s simulation data are collected for analysis

Table 3 Environmental conditions

	U_{hub}	H_s	T_p
Env1	8 m/s	3 m	6 s
Env2	11.4 m/s	4 m	8 s
Env3	14 m/s	5 m	10 s

Table 4~6 summarize the standard deviations of platform motions in the environmental conditions concerned. It is favorable to see that the platform motions of the triple-column spar platform are reduced, especially the heave motion. This is because the bottom disc behaves like a heaving plate, producing more vertical damping. It is worth noting that the mean inclination of the TC_spar is much smaller than that of the Hywind, implying that the rotor could harvest more energy form the wind flow (Tsalicoglou et al. 2012). Fig. 7~8 illustrate the feature of platform motion responses. The platform motions of the triple-column spar at the resonant frequency and the wave energy frequency are both reduced compared with the Hywind.

Table 4 Statistics of platform surge motion

		Max (m)	Min (m)	Mean (m)	Std.dev (m)
Env1	TC_spar	12.52	11.63	12.06	0.124
	Hywind	12.37	11.50	11.92	0.124
Env2	TC_spar	23.35	21.10	22.24	0.317
	Hywind	23.08	20.67	21.91	0.342
Env3	TC_spar	18.42	14.18	16.17	0.546
	Hywind	18.40	13.79	16.00	0.602

Table 5 Statistics of platform heave motion

		Max (m)	Min (m)	Mean (m)	Std.dev (m)
Env1	TC_spar	-0.25	-0.27	-0.26	0.002
	Hywind	-0.12	-0.21	-0.17	0.013
Env2	TC_spar	-0.39	-0.48	-0.44	0.014
	Hywind	-0.32	-0.61	-0.46	0.045
Env3	TC_spar	-0.27	-0.39	-0.31	0.015
	Hywind	0.09	-0.69	-0.27	0.100

Table 6 Statistics of platform pitch motion

		Max (deg)	Min (deg)	Mean (deg)	Std.dev (deg)
Env1	TC_spar	2.32	1.88	2.09	0.061
	Hywind	2.71	2.22	2.45	0.070
Env2	TC_spar	4.34	3.29	3.86	0.146
	Hywind	5.10	3.82	4.52	0.179
Env3	TC_spar	3.79	1.91	2.79	0.239
	Hywind	4.53	2.17	3.28	0.300

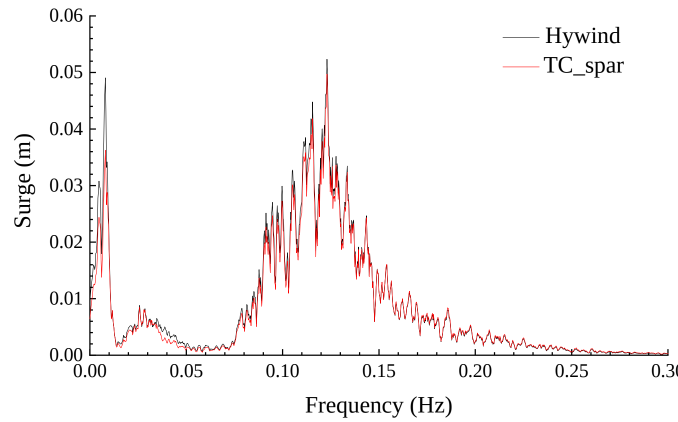

Fig. 7. Surge motion in Env2.

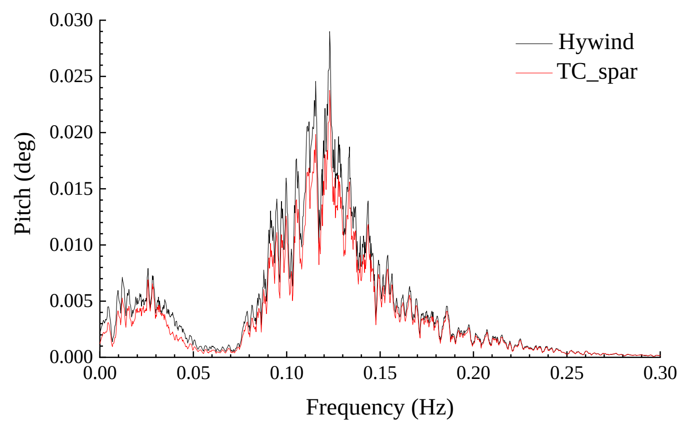

Fig. 8. Pitch motion in Env2.

Short-term structural responses.

Table 7~9 list the statistics of the structural loads at several critical connections. According to the statistical results, the structural responses at the tower based and the tower top are reduced with the proposed TC_spar platform. This can also be proved by the time-series (see Fig. 9~10). However, it seems that the mooring line tension force is hardly varied.

Table 7 Statistics of tower top shear force

		Max (kN)	Min (kN)	Mean (kN)	Std.dev (kN)
Env1	TC_spar	907	77	499	114
	Hywind	941	90	521	118
Env2	TC_spar	1451	401	943	152
	Hywind	1537	389	981	166
Env3	TC_spar	1443	-32	657	196
	Hywind	1576	-63	688	220

Table 8 Statistics of tower base bending moment

		Max (kN·m)	Min (kN·m)	Mean (kN·m)	Std.dev (kN·m)
Env1	TC_spar	79830	118	40809	10983
	Hywind	82920	1742	43008	11286
Env2	TC_spar	125100	25680	76520	14503
	Hywind	133300	25110	80274	15886
Env3	TC_spar	129700	-9692	84746	18590
	Hywind	142200	-12220	57791	20886

Table 9 Statistics of mooring line tension

		Max (kN)	Min (kN)	Mean (kN)	Std.dev (kN)
Env1	TC_spar	1020	1010	1016	4
	Hywind	1050	1040	1047	4
Env2	TC_spar	1171	1148	1158	3
	Hywind	1195	1172	1182	4
Env3	TC_spar	1092	1056	1072	5
	Hywind	1121	1084	1101	5

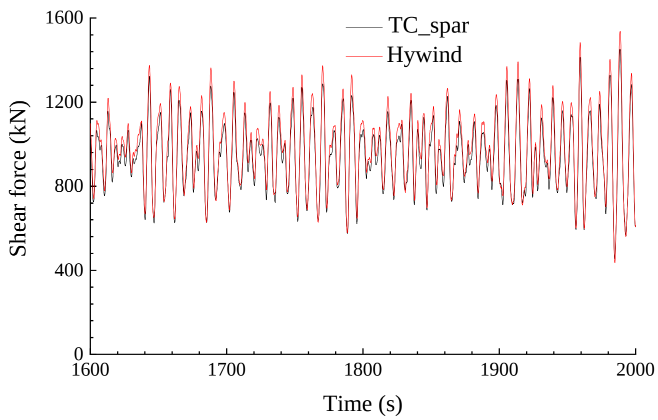

Fig. 9. Time series of tower top shear force, Env2.

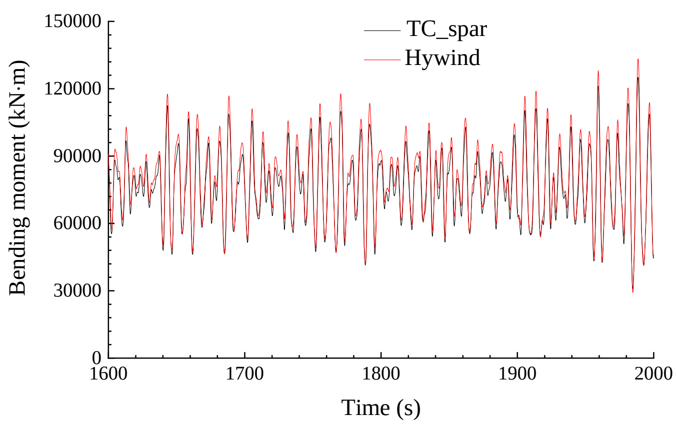

Fig. 10. Time series of tower based bending moment, Env2.

Long-term Extreme Structural Loads

In order to investigate the long-term extreme response, the joint wind-wave distribution model developed by Li et al. (2015) is used. The model is based on the field measurement in the North Sea center from 2001 to 2010, which consists of a marginal distribution of wind speed at 10 m above the mean sea level U_w, a conditional distribution of wave height H_s given U_w, and a conditional distribution of wave period T_p given U_w and H_s. Please refer to (Li et al., 2015) for the details of the joint distribution model.

We first investigate the long-term extreme structural loads at the tower. The critical environmental condition identified by the MECM is shown in Fig. 11. Since the structural loads applied the tower are more dominated by the hydrodynamic loads, the non-monotonic effect of the wind force is not significantly and the identified critical environmental condition is located on the 50-year contour surface. Please note that the wind speed 24.5 m/s refers to that at the 10 m height, and it corresponds to 30.5 m/s at the hub height according to the wind shear model Eq. (8).

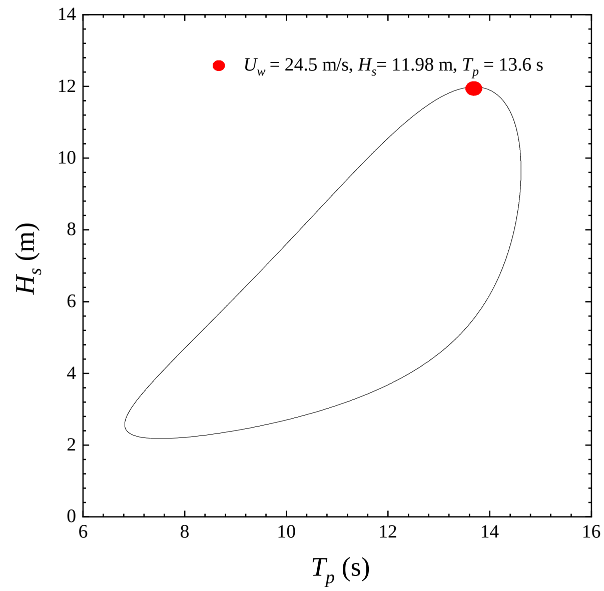

Fig. 11. Identified critical environmental condition for shear force and bending moment.

Fig. 12~13 demonstrate the cumulative distribution function of the extreme tower top shear force and the extreme tower base bending moment corresponding to the 50-year return period, respectively. According to the CDF of the extreme structural load, one can find that the wind turbine is safer with the application of the triple-column spar platform. For example, the extreme tower base bending moment just has a 25% probability to exceed $3{\times}10^5$ kN·m over a 50-year period with the triple-column platform. However, the probability rises to nearly 100% with the Hywind. Based on Eq. (7), the most probable extreme structural loads of the two concepts happen in 50 years are listed in Table 10. It is obvious that the triple-column spar platform is less likely to exceed the limit state.

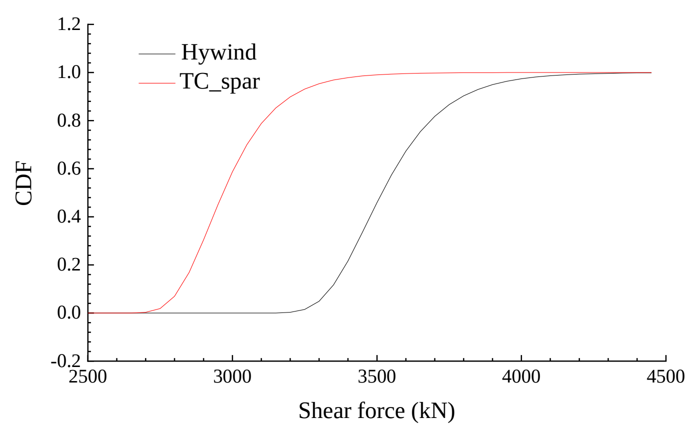

Fig. 12. CDF of the 50-year extreme tower top shear force.

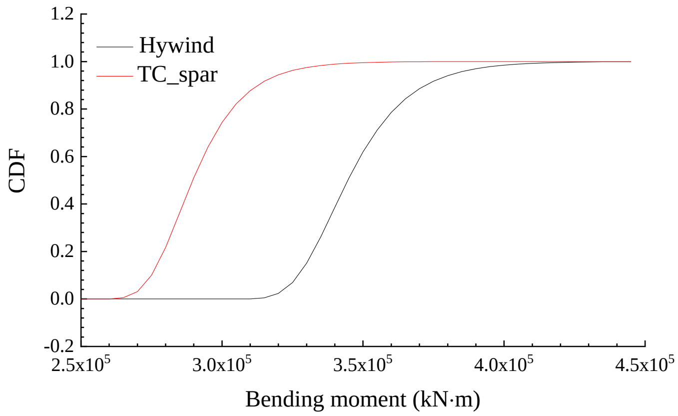

Fig. 13. CDF of the 50-year extreme tower base bending moment.

Table 10 50-year most probable extreme structural loads

	Tower top shear force (kN)	Tower base bending moment (kN·m)
TC_spar	2921	2.9×10^5
Hywind	3463	3.4×10^5

The identified critical environmental condition for the fairlead tension is located on the 0.04-year contour surface, as shown in Fig. 14. The MECM seeks the critical environmental condition from the 0.04-year contour surface because the wind force plays a dominating role on the average fairlead tension. Based on the identified environmental condition, the 50-year most probable fairlead tension is calculated, and the result is listed in Table 11. As shown, the extreme fairlead tensions of the two platforms are similar. It is because the extreme fairlead tension is mainly dominated by the wind load so that the optimization of the platform has a very small effect.

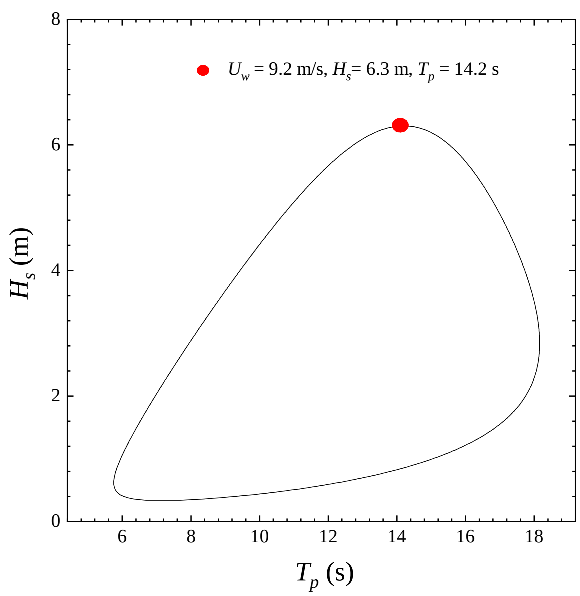

Fig. 14. Identified critical environmental condition for fairlead tension.

Table 11 50-year most probable fairlead tension

	Hywind	TC_spar
Fairlead tension (kN)	1361	1342

CONCLUSIONS

A triple-column Spar platform is proposed in the present study as the floating platform for offshore floating wind turbine application. Comparisons are made against the Hywind concept, a single-column Spar platform.

Compared with the Hywind, the wave loads exerting on the triple-column Spar platform are reduced implying that the platform will have a better dynamic response under the joint excitation of wind and waves. According to the time-domain coupled analysis results, the global motions of the proposed platform are smaller than those of the Hywind.

The extreme responses of the two concepts are estimated with a modified environmental contour method, which seeks the critical environmental condition from multiple contour surfaces. The estimated extreme structural loads at tower base and tower top for the triple-column Spar platform are much smaller than those of the Hywind so that the proposed concept is less likely to exceed the limit state. However, the extreme mooring line tension force is hardly reduced.

According to the simulation results presented, the proposed triple-column Spar platform has a better dynamic performance than the Hywind concept.

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