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Feasibility of the Application of a Spar-type Wind Turbine at a Moderate Water Depth

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Abstract

The feasibility of the application of a spar-type wind turbine at a moderate water depth is studied in this paper. In the oil and gas industries, spar-type offshore platforms are widely applied in deep water. The same idea is used in offshore wind technology to present the Hywind concept based on a catenary moored spar in deep water. The draft of the spar limits the application of spar-type wind turbines in shallow water. However, it is possible to design spar-type wind turbines for moderate water depths. The present article studies the feasibility and performance of such a design. A spar-type wind turbine at a moderate water depth called "ShortSpar" is introduced in the present article. A catenary moored spar-type support structure is applied as a base for the 5-MW NREL land-based turbine. The power performance, structural integrity and dynamic responses of a 5-MW catenary moored spar-type wind turbine in deep water (DeepSpar) have previously been studied. In the present article, the responses of the spar-type wind turbines, ShortSpar and DeepSpar, are compared. The HAWC2 code is used to carry out the coupled aero-hydro-servo-elastic analyses. Different environmental conditions are used to compare the responses. A dynamic link library (DLL) is used to feed the mooring forces at each time step into the HAWC2 code. The force-displacement relationships are obtained from the Simo-Riflex code. The comparison of the responses of ShortSpar and DeepSpar in different load cases indicates the feasibility of implementation of spar-type wind turbine in moderate water depths. The results show that the spar-type wind turbine at a moderate water depth exhibits good performance, and its responses are reasonable compared with those associated with a spar-type wind turbine in deep water. The total mass (the structural mass plus the ballast) of ShortSpar is 35% less than the mass of DeepSpar, while the statistical characteristics of the generated power are almost the same for both spars. This mass reduction for ShortSpar helps to achieve a more cost-effective solution for floating wind turbines at a moderate water depth.

Keywords: Floating wind turbine; Spar-type offshore wind turbine; Dynamic structural responses; Wave- and wind-induced analyses

1. Introduction

The good performance of spar platforms motivated the Statoil to use a spar-type support structure for the Hywind concept. Hywind is a catenary moored spar-type wind turbine in deep water. The draft of the

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spar limits the application of spar-type wind turbines in shallow water. However, it is possible to design spar-type wind turbines for moderate water depth. The present article studies the feasibility and performance of such a design. The present concept is inspired by Hywind to introduce a floating wind turbine at a moderate water depths. A spar-type wind turbine called ShortSpar is studied in the present article. The power performance, structural integrity and dynamic responses of a 5-MW catenary moored spar-type wind turbine in deep water (DeepSpar) have previously been studied [1, 2, 3 and 4]. The power performance, dynamic motions, acceleration and structural responses of an offshore wind turbine at an intermediate water depth (ShortSpar) and DeepSpar are compared for different environmental conditions.

Karimirad and Moan [1, 2 and 3] have implemented the HAWC2 code to perform the coupled aero-hydro-servo-elastic analysis of a catenary moored spar-type wind turbine subjected to wave- and wind-loads in deep water. The same approach is implemented here to carry out the analysis for ShortSpar. The Simo-Riflex [5, 6] is used to set up the force-displacement relationships for the mooring system. At each time step, the force of the mooring lines is applied at the fairleads as an external force through a dynamic link library (DLL) to the HAWC2 code. The hydroelastic model of the HAWC2 code is verified by Karimirad et al. [7] for a tension leg spar-type wind turbine through a code-to-code comparison between HAWC2 and USFOS codes. In the present article, before doing the integrated wave-wind-induced analyses, the coupled hydrodynamic analysis of the HAWC2 and Simo-Riflex codes are compared for different sea states. The agreement is very good between the codes. The HAWC2 uses the Morison formula plus the pressure integration method for the hydrodynamics [7]. The added mass coefficient of 1.0 and drag coefficient of 0.6 are chosen for the spar platform [3].

2. ShortSpar wind turbine

In this study, a spar-type wind turbine suitable for a moderate water depth is introduced (ShortSpar). ShortSpar is a catenary moored spar-type wind turbine inspired by the Hywind concept. The schematic layout of the ShortSpar wind turbine is shown in Figure 1. Properties of the ShortSpar offshore wind turbine are listed in Table 1. Karimirad et al. [1, 2 and 3] have previously studied the spar-type wind turbine in deep water (for more information about DeepSpar, refer to [1, 2 and 3]).

The first constraint to design a spar-type support structure is the clearance between the seabed and the bottom of the spar, which limits the application of the spar in shallow water. It is found that an adequate design can be achieved at a reduced depth. The capital cost and the displaced volume (total mass) are highly connected for spar concept. The idea is to have small displaced-volume. The mass reduction for ShortSpar helps to achieve a more cost-effective solution for offshore wind technology in moderate water depths.

The basic design of a floating wind turbine is challenging because of the variety of natural frequencies and excitations involved [8]. The wide range of characteristic frequencies of a floating wind turbine makes it difficult to design a robust system. One must ensure that the system frequencies for rigid-body motions and elastic deformations are out of the range of the wave and wind excitation frequencies.

In general, the natural frequencies of a floating platform are a function of the mooring system stiffness, hydrostatic restoring, the total mass and the added mass. For elastic eigen-modes, the distributed mass and structural stiffness should be considered as well. For a catenary moored system, the pretension forces are small compared with the buoyancy force. The added mass is a function of the shape and volume of the submerged parts. The hydrostatic restoring forces for different modes of motion are related to the mass distribution as well as the water plane area and the submerged volume. The mooring system stiffness is related to the fairlead position, depth, elastic properties of the line, line length, possible clump masses and buoyancy of buoys.

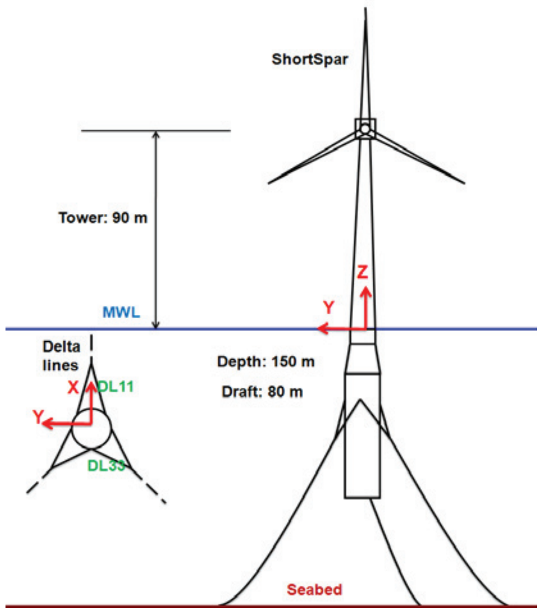

Fig. 1. Schematic layout of the ShortSpar offshore wind turbine at an intermediate water depth

Table 1. Properties of the ShortSpar offshore wind turbine

Item	Properties
Turbine	NREL 5-MW
Water depth (m)	150
Draft (m)	80
Displacement (m^3)	5245
Centre of buoyancy (m)	-42
Diameter at MWL (m)	6.5
Diameter at bottom (m)	9.4
Mass (ton)	5376
Centre of gravity1) (m)	-47.3
Mass moment of inertia, I_{XX} and I_{YY} (ton*m^2)	24.47 E+6
Mass moment of inertia, I_{ZZ} (ton*m^2)	77.62 E+3
Fairlead elevation (m)	-30

[1)] Center of gravity of the floating wind turbine, including rotor, nacelle, tower and spar (steel and ballast)

3. Mooring system

The mooring system should be designed with respect to natural frequencies, and this requires an iterative approach. Usually, the mooring system at a moderate water depth is stiffer than to that in deep water. The initial results showed that the use of clump masses for moderate water depths will end up with a mooring system that is too stiff. Therefore, the mooring system of ShortSpar does not include any clump mass. The length of the mooring line is adjusted to obtain an adequate mooring stiffness. The mooring system consists of three sets of mooring lines, which are located around the structure (Figure 2). Three fairleads are located on the circumference of the spar. Each mooring line consists of four line segments (two segments make the delta for each). The purpose of the delta line configuration is to provide yaw stiffness. The mooring lines are modeled by a force-displacement relationship in surge, sway and yaw. The influence of the mooring system on heave, pitch and roll is neglected. Damping and inertia effects are also neglected. The force-displacement relations at the fairleads of mooring system have been calculated using the Simo-Riflex [5, 6]. The dynamic effect associated with the mooring system mass has been ignored. The schematic layout of the mooring system for ShortSpar is shown in Figure 2. The properties of the mooring system components are listed in Table 2. The pretension of the mooring system is shown in Figure 3. The maximum ratio of the pretension and buoyancy force for ShortSpar is roughly 0.5%.

In Figure 4, as an example, the resulting displacement-force relation for surge is shown. Because the mooring system consists of 3 lines, the stiffness for surge motion is different in the negative and positive directions. A nonlinear FEM model of the mooring system including a clump mass and delta lines is modeled in Simo/Riflex [1, 2 and 3] for large deflections and applied as nonlinear spring stiffness in HAWC2 through a Dynamic Link Library (DLL) Interface [1, 2 and 3].

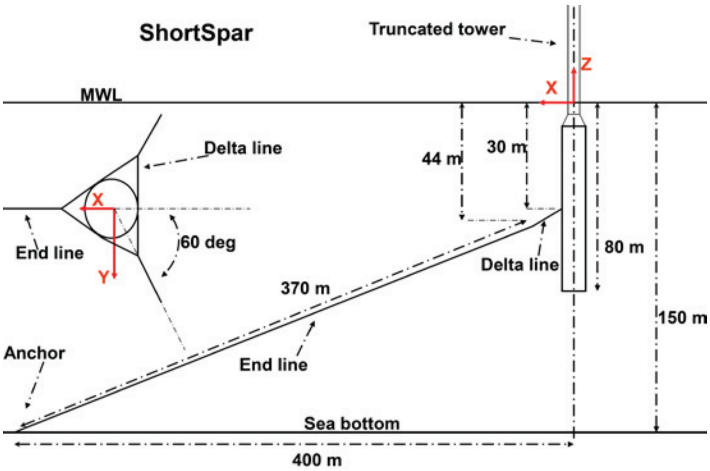

Fig. 2. Schematic layout of the mooring system for DeepSpar and ShortSpar offshore wind turbines in deep and intermediate water depths (stress-free configuration)

Table 2. Properties of the mooring system components (see Figure 2)

Property	Delta line (DL)	End line (EL)
Length (m)	50	370
Diameter (m)	0.09	0.09
Mass/Length (kg/m)	42.5	42.5
Axial stiffness[1)] (kN)	384243	384243

[1)] EA , in which E is the modulus of elasticity and A is the cross-sectional area of the component

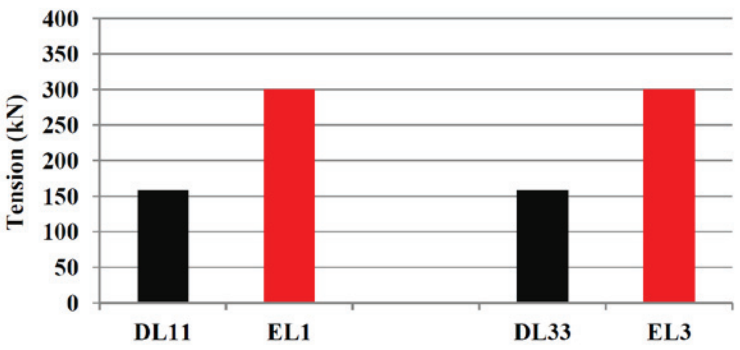

Fig. 3. Pretension in the mooring lines for DeepSpar and ShortSpar wind turbines (see Table 2)

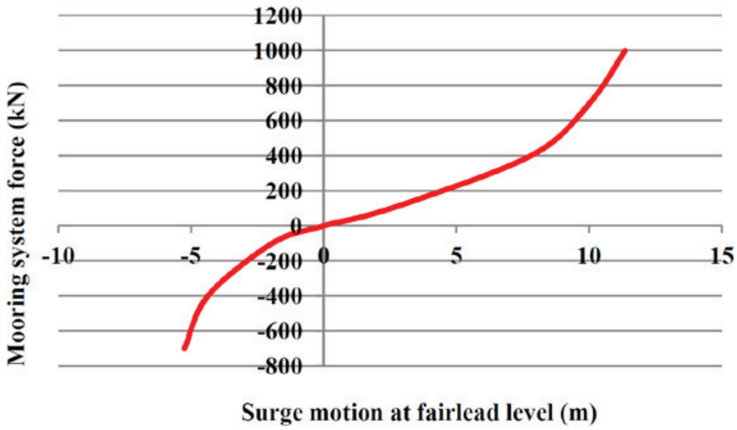

Fig. 4. Displacement-force relation for surges

4. Met-ocean

In the present study, the Statfjord site has been chosen as a representative site for floating wind turbines. Statfjord is an oil and gas field in the Norwegian sector of the North Sea operated by Statoil [1]. The Joint North Sea Wave Project (JONSWAP) spectrum was used to represent long-crested irregular waves. The peakedness parameter, which is the ratio of the maximum spectral energy to the Pierson-Moskowitz spectrum, was chosen with a default value of 3.3. In Table 3, the load cases based on the relevant met-ocean data are listed [1]. V is the 10-min averaged wind speed at the nacelle.

The selected environmental conditions are consistent with the IEC recommendations. Based on the IEC, a single value for the significant wave height (e.g., the expected value) associated with the mean wind speed should be used [9].

Table 3. Load cases for operational and survival conditions

V (m/sec)	H_S (m)	T_P (sec)	Turbulence intensity (I)	Turbine status
17	4.2	10.5	0.15	Operating
14	3.6	10.2	0.15	Operating
11.2	3	10	0.15	Operating
8	2.5	9.8	0.15	Operating

5. Hydrodynamic code-to-code comparison

In the current wave-wind-induced analysis of HAWC2, the mooring system effects are simplified, and the mooring system is modeled as a nonlinear displacement-force relationship. Hence, before completing the coupled aero-hydro-servo-elastic analysis, it is necessary to carry out the code-to-code comparison between the Simo-Riflex and HAWC2 codes. The same approach is used by Karimirad and Moan for a spar-type wind turbine in deep water [1, 2]. For more information regarding the code-to-code comparison, please refer to [4, 7]. In Figure 5, the standard deviations (stds) of the surge motion at the mean water level (MWL) are compared for different sea states. The agreement between codes is very good.

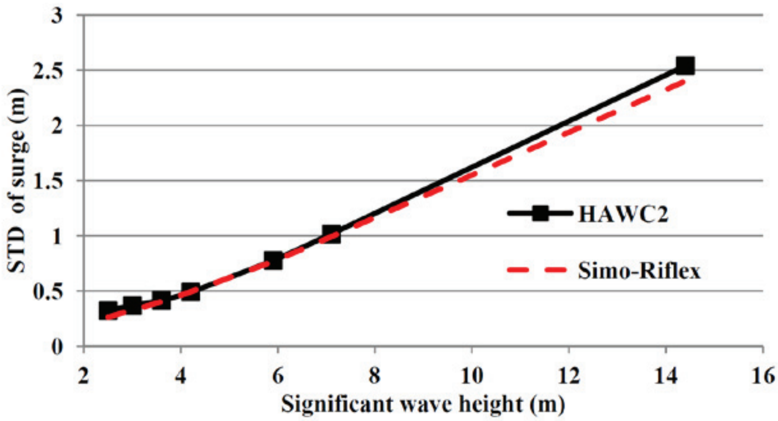

Fig. 5. Comparison of the std of the surge motion at the MWL for different sea states between the Simo-Riflex and HAWC2 codes

6. ShortSpar versus DeepSpar

In this part, the wave- and wind-induced responses of the ShortSpar and DeepSpar wind turbines are compared for different environmental conditions (see Table 3). The stochastic wind includes the steady wind plus the turbulent wind. The turbulence intensities are correlated to the mean wind speed [2] (see Table 3). The nacelle surge, nacelle acceleration, generated-power, bending moment and shear force at the tower-spar interface are shown in Figures 6, 7, 8, 9 and 10, respectively.

In general, the standard deviations of the responses are close for both spars. This is because the wave loads for both designs are the same order of magnitude. The main contribution from the wave loads come from the upper part of the spar; the lower part of the spar is not significantly affected because the wave kinematics die out far below the water surface.

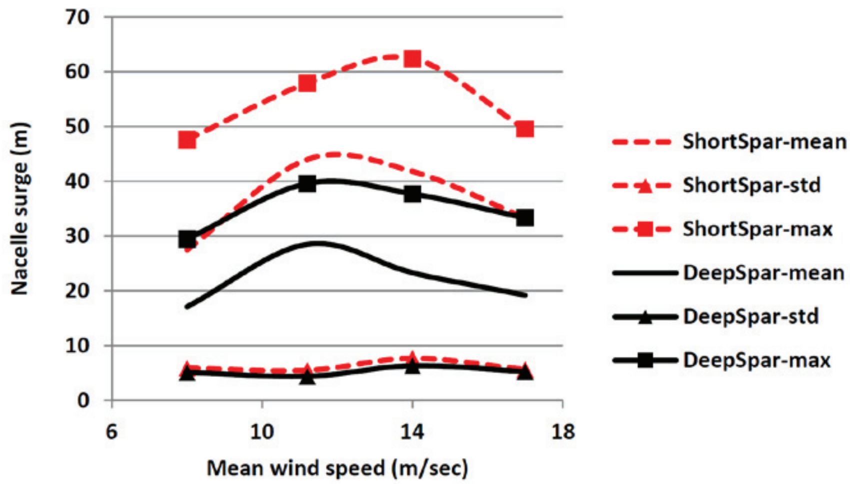

Fig. 6. Statistical characteristics of the nacelle surge motion. Mean wind speed refers to the load cases in Table 3 and the corresponding environmental conditions (wave and stochastic wind)

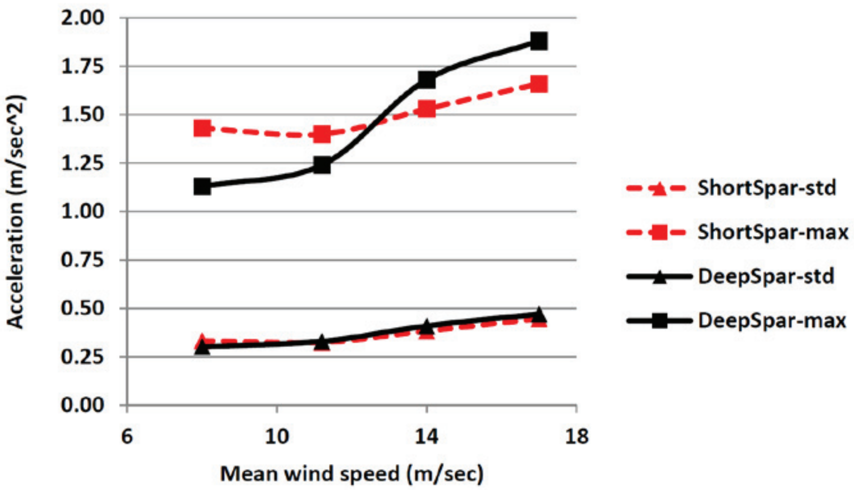

Fig. 7. Statistical characteristics of the nacelle surge acceleration. Mean wind speed refers to the load cases in Table 3 and the corresponding environmental conditions (wave and stochastic wind)

Karimirad and Moan [1] have shown that the standard deviation of the responses are mainly wave-induced, while the mean of the responses are wind-induced. Therefore, the dynamic responses of ShortSpar and DeepSpar are close, in general. The mean of the nacelle surge motion and the bending moment are increased because of the increased tilt, and consequently, the bending moment is increased because of the gravitational effects (Figures 6 and 9). The restoring forces of ShortSpar are lower because of the decreased GM, which results in a higher mean value of pitch motion (tilt). The shear force is dominated by wave loading, while the bending moment is dominated by wind loading. So, the shear force of ShortSpar and DeepSpar are very close (Figure 10).

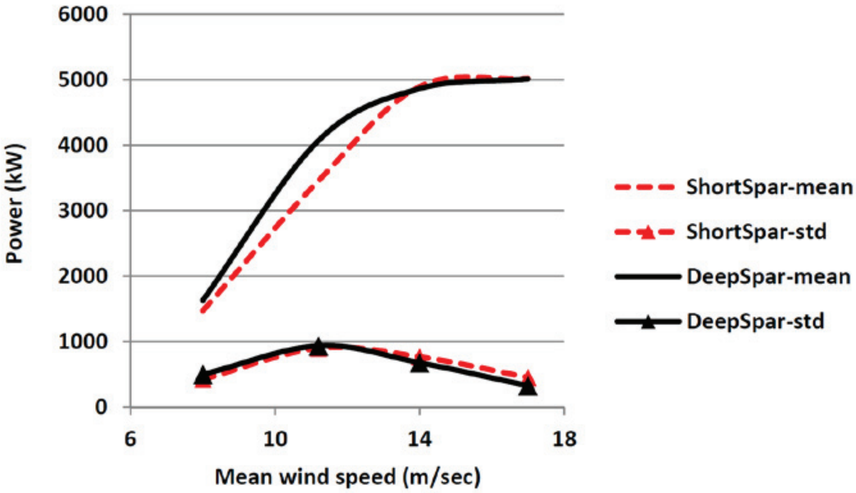

Fig. 8. Statistical characteristics of the generated power. Mean wind speed refers to the load cases in Table 3 and the corresponding environmental conditions (wave and stochastic wind)

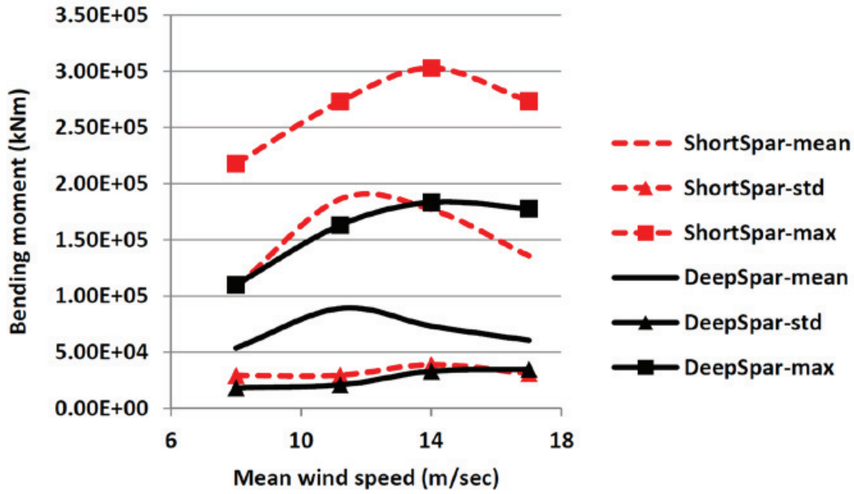

Fig. 9. Statistical characteristics of the bending moment at the spar-tower interface. Mean wind speed refers to the load cases in Table 3 and the corresponding environmental conditions (wave and stochastic wind)

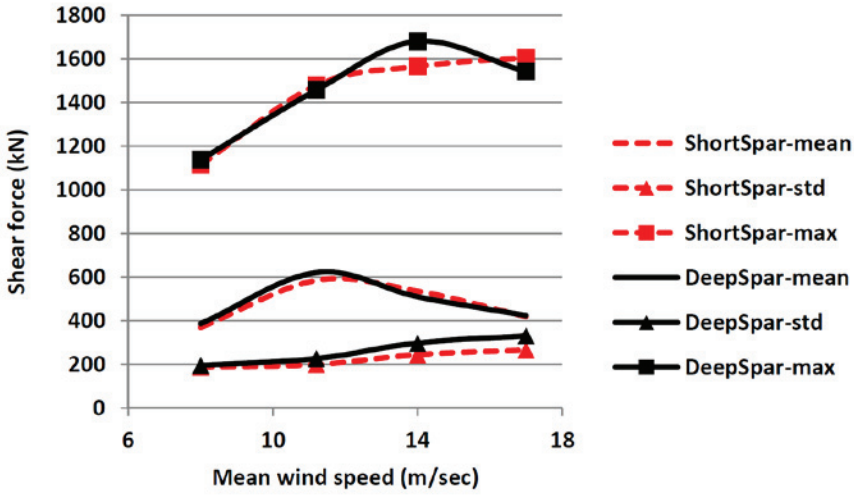

Fig. 10. Statistical characteristics of the shear force at the spar-tower interface. Mean wind speed refers to the load cases in Table 3 and the corresponding environmental conditions (wave and stochastic wind)

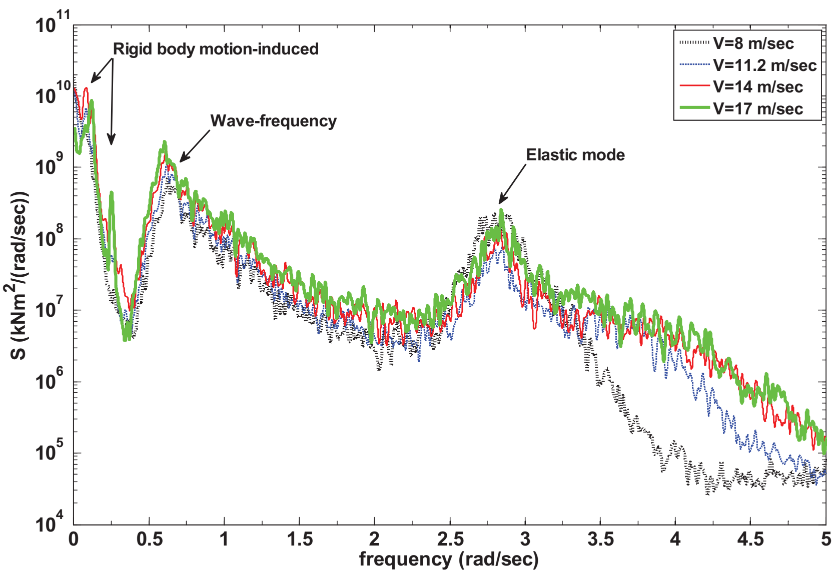

Fig. 11. Spectra of the bending moment at the spar-tower interface based on 1-hour time domain analysis for ShortSpar. Mean wind speed (V) refers to the load cases in Table 3 and the corresponding environmental conditions (wave and stochastic wind)

The nacelle acceleration for the operational cases is less than 2 m/sec^2, which indicates the possibility of application of the current rotor-nacelle assembly for the ShortSpar design. The generated power (Figure 9) is close for both spar-type wind turbines, which indicates the possibility of applying the spar-type wind turbines at a moderate water depth. The maximum nacelle acceleration of ShortSpar and DeepSpar is close, which confirms the possibility of implementing the same rotor-nacelle assembly for ShortSpar. The aero-hydro-servo-elastic analysis of ShortSpar in different load cases shows that the implementation of the spar-type wind turbine at a moderate water depth is feasible to produce adequate electricity.

Figures 11 and 12 show the spectra of the bending moment and the shear force at the tower-spar interface, respectively. The rigid body motion-induced (low-frequency resonant responses) wave frequency, as well as the elastic bending mode of the tower-spar, are present in the spectra of the bending moment and the shear force. The spectra of the bending moment are dominated by the low resonant responses due to the effect of the turbulent wind from the aerodynamic loading, while the spectra of the shear force are governed by the wave-frequency part through the linear hydrodynamic loading.

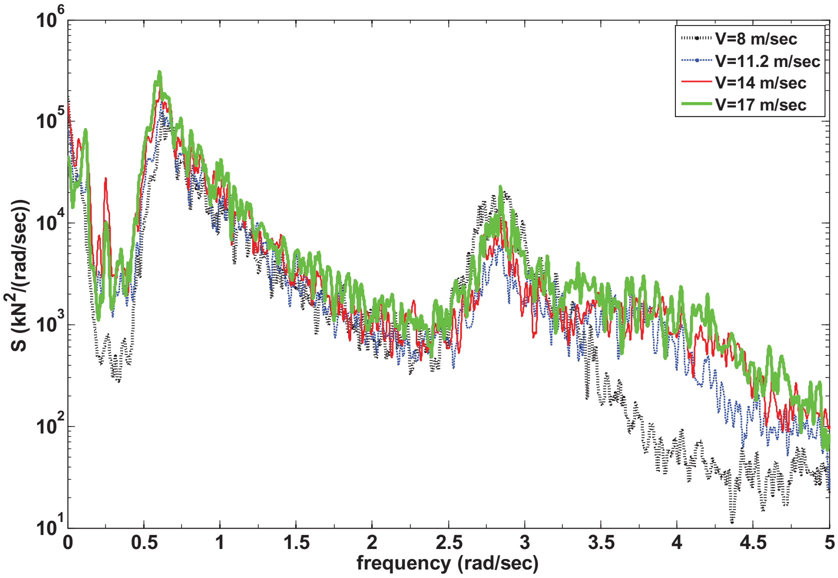

Fig. 12. Spectra of the shear force at the spar-tower interface based on 1-hour time domain analysis for ShortSpar. Mean wind speed (V) refers to the load cases in Table 3 and the corresponding environmental conditions (wave and stochastic wind)

7. Conclusion

The feasibility of using a spar-type wind turbine at a moderate water depth is studied in this paper. A spar-type wind turbine suitable for a moderate water depth is presented (ShortSpar). It is found that an adequate design can be achieved by a reduced depth. The smaller mass used in ShortSpar helps to achieve a more cost-effective solution for offshore wind technology at a moderate water depth.

The aero-hydro-servo-elastic analysis of ShortSpar and DeepSpar for different load cases shows that the implementation of the spar-type wind turbine in moderate water depth is feasible. The results show that the spar-type wind turbine at a moderate water depth exhibits good performance, and its responses are reasonable compared with those associated with a spar-type wind turbine in deep water. The nacelle acceleration for the operational cases is less than 2 m/sec^2, which indicates the possibility of application of the current rotor-nacelle assembly for this design.

In general, the standard deviations of the responses are close for both spars, as is mentioned above. This is because the wave loads for both designs are of the same order of magnitude. The standard deviations of the responses are mainly wave-induced, while the mean of the responses are wind-induced.

Therefore, the dynamic responses of ShortSpar and DeepSpar are close, in general. The means of the nacelle surge motion and bending moment are increased because of the increased tilt, and consequently, the bending moment is increased because of the gravitational effects. The shear force is dominated by wave loading, while the bending moment is dominated by wind loading. Therefore, the shear-force of ShortSpar and DeepSpar are very close.

The maximum of the nacelle motion and bending moment is governed by the mean values, while the shear force is governed by the standard deviation (the dynamic part). The low-frequency resonant responses, wave frequency responses and the elastic bending mode of the tower-spar present in the spectra of the bending moment and the shear force. The spectra of the bending moment are dominated by the low-frequency resonant responses caused by the effect of the turbulent wind through aerodynamic loading, while the spectra of the shear force are governed by the wave-frequency part through the linear hydrodynamic loading.

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