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## Dynamic Analysis of a Braceless Semisubmersible Offshore Wind Turbine in Operational Conditions

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### Abstract

The development of cost effective floating type offshore wind turbines has been desired in deep sea areas. Semisubmersible platform can be considered as a very efficient design configuration among the different type proposed floating platforms. In the present paper, a preliminary assessment of the dynamic behavior of a 5-MW braceless semisubmersible offshore wind turbine with three columns and two fully submerged pontoons is presented for selected environmental operational conditions that correspond to a deep water offshore site with depth 200 m. Hydro-aero-servo-elastic time domain analysis is performed with the use of the coupled analysis tool Simo-Riflex-AeroDyn in order to calculate the dynamic behavior and response of the offshore floating wind turbine. Statistical values and spectra of time histories of response quantities are presented. The results demonstrate the feasibility of the presented deep sea floating wind turbine concept.

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### 1. Introduction

Offshore wind energy is widely recognized as a useful renewable energy capable to satisfy the increasing energy need and to increase globally the security of energy supplies. Compared to the other renewable energy resources that exist in the oceans such as waves and tides, wind energy resource exploitation and its related technology is considered as matured and rather well established mainly for bottom-fixed concepts and shallow water depths where

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several offshore wind turbines have been put into operation. For water depths larger than 50 m, the use of floating wind turbines is indicated as the most appropriate mainly due to cost related issues (Arapogianni et al. [1]). The development of offshore wind turbines in deeper waters requires further investigation. The issues related to design configuration of the support structure, installation, grid connection, operation and maintenance have significant effects on the cost of produced electricity. Hence, the feasibility of different floating concepts needs to be addressed and innovative support structures that may help maturing the offshore wind technology should be introduced and their dynamic response should be accessed and analyzed. Functionality, performance, dynamics, safety, cost and power-production of a specific design are the main parameters that define the feasibility and probability of success of a concept in industry (Karimirad [2]).

Different floating support platform configurations are possible for use with offshore wind turbines such as tension leg platforms, spar-buoys and semi-submersibles (Jonkman and Matha [3]). Among the different floating offshore wind turbines, the semisubmersible concept can be considered as very effective design configuration that relies on water plane area as well as on a fairly deep draft and ballasting to maintain stability. A semisubmersible offers a large number of advantages; one basic advantage is that it can be fabricated onshore in controlled settings where quality is more easily assured and towed to offshore site, eliminating the need for expensive construction barges and marine crane.

Common offshore wind semisubmersible designs are WindFloat and OC4 DeepCWind semisubmersible wind turbines (Roddier et al. [4], Robertson et al. [5,6]), in which, the columns of the semisubmersible are connected by braces that are slender structural elements. The braces are much prone to fatigue (Kvittem et al. [7]). The extensive hydro-aerodynamic loads on the columns will be transferred to these members. In short-crested sea conditions, the wave load applied on each column has a specific phase. This phase difference means cyclic loading at the root of the braces. The welded joints are exposed to stress concentration which results in fatigue damage in long term life. The axial forces (tension-compression) combined with periodic bending moments result in accumulated damage. Due to the large difference in diameter of the brace and columns, punching may occur as well. In order to avoid the aforementioned issues that may lead to decrease of lifetime of the offshore floating wind turbine, the columns of the semisubmersible can be connected by large dimensioned pontoons without the existence of any kind of braces. Braceless semisubmersible platforms are widely deployed in offshore oil/gas industry. The same idea is used in order to introduce braceless semisubmersible offshore wind turbines (Landbø [8], Dr Olav Olsen [9], Huijs et al. [10], Fukushima FORWARD [11] and Luan and Moan [12]). Also, braceless semisubmersible platforms are deployed for the case of combined wind and wave energy systems (Michailides et al. [13,14]).

In the present paper, the dynamic behavior of a 5-MW V-shaped semisubmersible offshore wind turbine is presented for selected environmental conditions that correspond to normal operation. A deep water offshore site with depth of 200 m is selected. The V-shaped semisubmersible consists of a semisubmersible floating platform with three columns (main column and two side columns) and two fully submerged pontoons connecting the side columns to the main column. The feasibility of the proposed offshore floating wind turbine concept is investigated.

## 2. Description and design characteristics of the V-shaped semisubmersible offshore floating wind turbine

The V-shaped semisubmersible floating wind turbine in the present paper consists of: (a) a semisubmersible floating platform with three columns (one main column and two side columns) and two pontoons connecting the side columns to the central column making a V-shape, (b) a 5 MW wind turbine placed at the top of the central column of the semisubmersible platform and (c) three catenary mooring lines positioned at the three columns of the semisubmersible. The reference 5 MW NREL wind turbine is located at the top of one of the columns and more specifically at the column that is supported by both pontoons (Figure 2). In the same figure, the global right handed coordinate system with Z-axis upward from mean water level surface is presented. The wind and wave are considered to be aligned and to propagate in the positive X-direction. This means that in the head sea environmental conditions (zero for wave), the waves are coming from left to right. An upwind wind turbine is placed over the floater and the rotor blades of the wind turbine have negative X-value position. With regard to the geometry characteristics of the V-shaped semisubmersible platform, the three columns of the semisubmersible have the shape of cylinder; while the two pontoons that connect the three columns have rectangular shape. The two side columns have 20 m freeboard while the main column has 10 m. The draft of the semisubmersible platform is equal



Figure 1: Braceless semisubmersible of the Fukushima floating wind turbine (Fukushima FORWARD [11])

to 28 m. All the structural parts that compose the semisubmersible have thickness equal to 3 cm and have material properties corresponding to steel normally used in offshore technology. In Table 1, dimensions and characteristics of the V-shaped semisubmersible wind turbine, properties related to the required total ballast/steel mass as well as mass moment of inertia of the platform are listed. All the mass moment of inertias are given with respect to the mean water level surface (global coordinate system). For the current design, the NREL 5 MW wind turbine is applied [15] and the tower of the wind turbine is modified for floating wind turbine application [16]. As far as main properties of the tower and the wind turbine the elevation to tower base above MWL is at 10m, the elevation to tower top is at 87.6 m, the overall (integrated) tower mass is 250,000 kg, the center of mass of tower is at 43.4 m, the nacelle mass is 240,000 kg and the rotor mass is 110,000 kg.

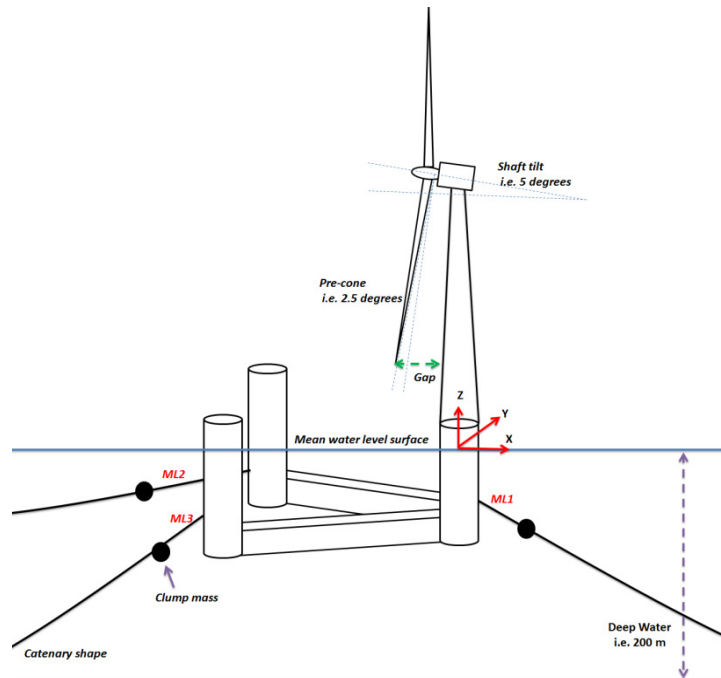


Figure 2: Schematic layout of the V-shaped semisubmersible offshore floating wind turbine in 200m water depth applying braceless platform

The mooring system of the V-shaped semisubmersible consists of three mooring lines with one clump mass for each. The clump mass is positioned 82 m far from the fairlead of each mooring line. The three mooring lines are placed in such a configuration that there exists symmetry with respect to the XZ plane. The angle between ML2 and ML3 is  $60^\circ$ ; meanwhile, the angle between ML1 and each of ML2 and ML3 is  $150^\circ$ . The length of each mooring line is 700 m, the mass per unit length is 117 kg/m, the equivalent stiffness is  $3.0E+9$  N, the diameter of the mooring line is 0.138 m, the clump mass weights 37,000 kg and has a volume  $4.4 \text{ m}^3$ . The fairlead and anchoring positions of the three mooring lines are listed in Table 2.

Table 1: Dimensions and characteristics of the V-shaped Semisubmersible wind turbine

Buoyancy	10,014 m <sup>3</sup>
Centre of buoyancy, CoB (x, y, z)	(-30.6, 0.0, -19.4) m
Pontoon dimensions, width x height	9 m x 5 m
Distance between columns	60 m
Diameter of columns	9 m
Draft	28 m
Freeboard	20 m
Weight of WT	600,000 kg
Weight of floater (structural steel mass)	1,630,000 kg
Center of mass, CoG (x, y, z)	(-30.6, 0.0, -16.0) m

Table 2: Coordinate system of fairlead and anchoring points, symmetry for XZ plane

Fairlead for line 1 (x, y, z)	(4.5, 0, -18) m
Fairlead for line 2 (x, y, z)	(-55.8, 32.3, -18) m
Fairlead for line 3 (x, y, z)	(-55.8, -32.3, -18) m
Anchor pint for line 1 (x, y, z)	(650, 0, -200) m
Anchor pint for line 2 (x, y, z)	(-618.7, 357, -200) m
Anchor pint for line 3 (x, y, z)	(-618.7, -357, -200) m

The static configuration and the effective tension of the applied catenary mooring lines for prescribed offset are presented in Figure 3 and Figure 4. The stability of the semisubmersible platform can be considered as a very basic design performance criterion for offshore floating wind turbines since the platform is expected to undergo large heeling moments in the lifetime of the wind turbine. Moreover, the waves can propagate in different directions compared to wind direction and as a result, they can introduce large heeling moments in different directions.

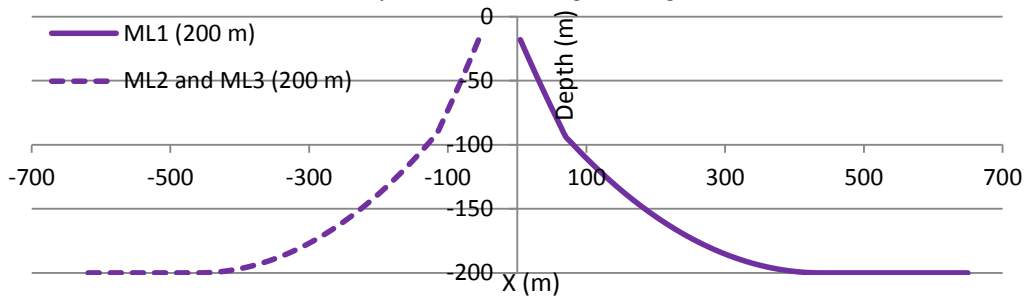


Figure 3: Static equilibrium configuration of catenary mooring lines

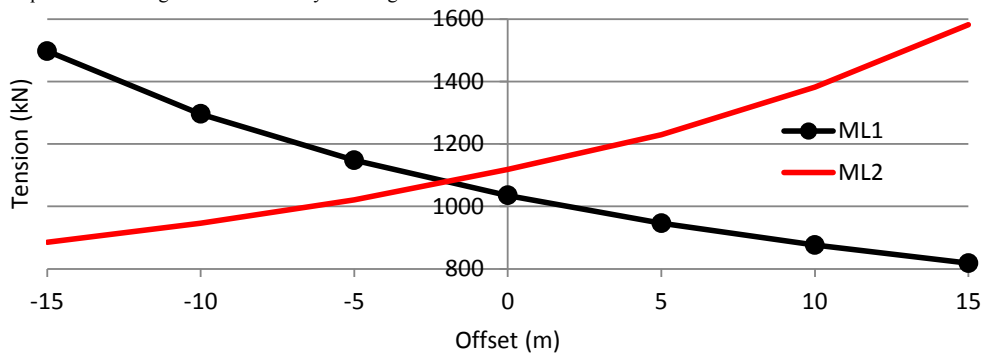


Figure 4: Axial effective tension in mooring lines ML1 and ML2 for given offset of the platform in surge (X-direction)

In Figure 5, the righting moment curve of the V-shaped platform as calculated from an appropriate stability analysis is presented. The stability analysis was performed with the HydroD software of the DNV SESAM package [17]. In order to examine and evaluate the stability performance of the V-shaped semisubmersible platform a specific inclining moment threshold related to the heeling moment is considered; the threshold is defined to be equal to  $\pm 67.5$  MNm which is equal to the maximum induced heeling moment due to the wind turbine steady force at

rated wind speed at the top of the tower. Considering the stability of the V-shaped platform (Figure 5) and for positive heel angle, the interception of the righting moment curves with the defined threshold is 5 degrees. This means that it is expected the rotor swept area to have just a 0.4 % reduction for the rated wind speed loading in calm sea. Due to wave and wind loads and dynamic responses, the tilt angle will increase having as a result the decrease of the rotor swept area and consequently the power production of the offshore floating wind turbine. This is further investigated by dynamic analysis and studying the platform pitch angle and turbine power production in coupled wave and wind loading.

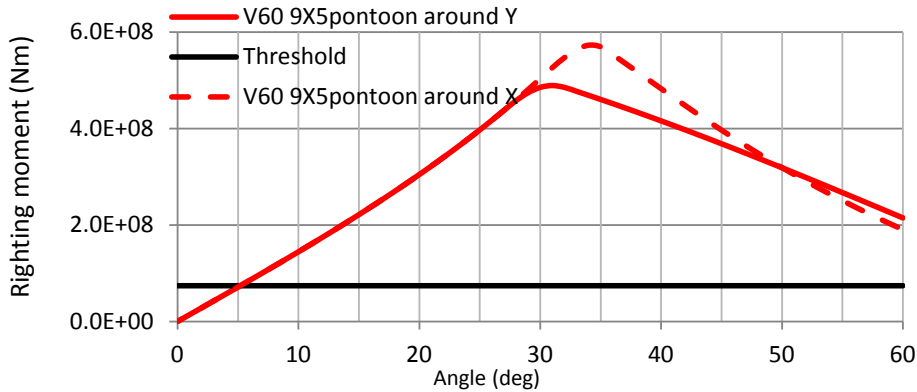


Figure 5: Transversal and longitudinal righting moment curve of the V-shaped semisubmersible platform.

### 3. Numerical modeling and examined environmental conditions (Load cases)

In order to estimate the dynamic behavior of the offshore floating wind turbine in different environmental conditions a hydro-aero-servo-elastic time domain numerical analysis model has been developed and applied with the use of the coupled analysis tool Simo-Riflex-AeroDyn which was developed by Marintek [18] and Centre for Ships and Ocean Structures (CeSOS) in Trondheim, Norway. The aforementioned coupled tool further extends the capabilities of the Simo [19], Riflex [20] and AeroDyn [21]. Simo is used to model the hydrodynamic loads on rigid-body floating structures in time-domain, including the first-order, second-order and higher order wave loads. The calculation of the time-domain hydrodynamic loads is based on frequency domain hydrodynamic loads that are calculated using the panel method (potential theory). Convolution integrals have been implemented to account for the memory effects. AeroDyn reads a turbulent wind field and calculates the aerodynamic loads on the blades based on Blade Element Momentum theory. Riflex is the main component of the coupled analysis tool since it is the Finite Element Solver and also with the Riflex and through beam elements, the simulation of the mooring lines, tower, shaft and blades of the wind turbine is performed. Simo-Riflex-AeroDyn has been successfully used for the analysis of different type of offshore floating wind turbines [22].

The examined wind and wave environmental conditions represent a range of possible expected operational conditions for given hub-height mean wind speed,  $U_{w,s}$ , and are presented in Table 3.  $H_s$  is the significant wave height and  $T_p$  is the wave peak period of the JONSWAP spectrum that is used in order to simulate irregular waves. For all the examined spectra, the peakedness factor is assumed to be 3.3. Both wind and wave are considered aligned with mean direction that is parallel to the X-axis (see Fig. 2).

Table 3: Load cases: LC1, LC2 and LC3 (examined environmental conditions)

Examined load case	$U_w$ (m/sec)	$H_s$ (m)	$T_p$ (sec)
Below rated wind speed (LC1)	8.0	1.7	9.5
Rated wind speed (LC2)	11.4	3	10
Over rated wind speed (LC3)	18.0	4.2	10.5

### 4. Wave-wind-induced dynamic analyses

In the following, the mooring line tension responses, global motion of the semisubmersible platform and the wind turbine performance are presented for the examined load cases. Coupled stochastic waves and winds have been applied in the integrated aero-servo-hydro-elastic time domain simulations. Statistical characteristics of the response quantities data are obtained from time domain analyses and are presented. In Figure 6, statistical characteristics of the tension forces of the mooring lines ML1, ML2 and ML3 as well as of the motions of the platform in global translational motions (surge, sway and heave) and rotational motions (roll, pitch, yaw) are presented for LC1, LC2 and LC3. It should be noted that min, max, std and mean symbolizes the minimum, maximum, standard deviation and average values of the one hour time series of each response. It is noted that significant maximum values of the surge motion are presented and fatigue related problems of the power take-off cable should be further investigated.

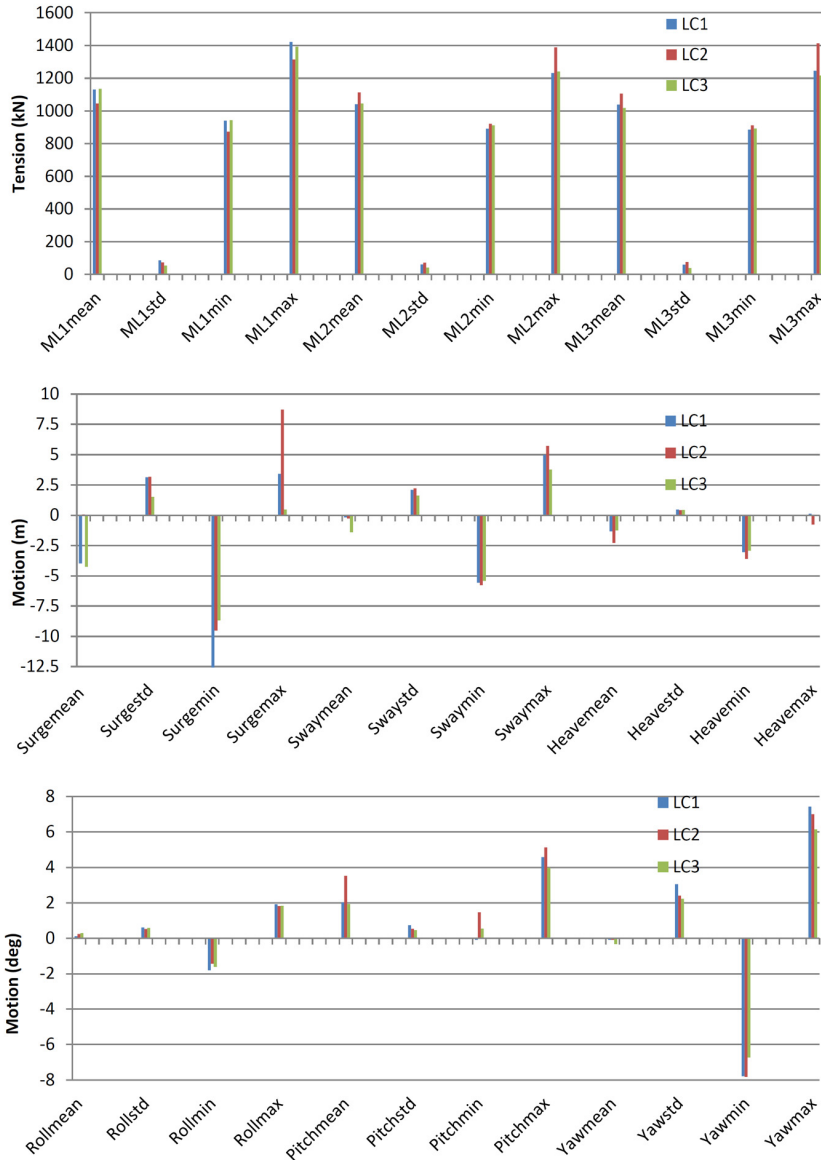


Figure 6: Statistical data of effective tension forces and motions of the V-shaped semisubmersible wind turbine in LC1, LC2 and LC3.

In Figure 7, statistical characteristics of the rotor rotational speed, generator speed, blade pitch angle, produced electrical power and rotor aerodynamic power are presented for LC1, LC2 and LC3. As far as the tension of the mooring lines, same magnitude of max and min tension forces presented for all the three mooring lines ML1, ML2 and ML3, see Figure 6. In general, the tension responses of mooring lines in different operational conditions (LC1, LC2 and LC3) are found to be similar.

As far as the motions of the semisubmersible platform, surge obtains larger max value for LC2 load case and smaller min value for LC1; this is attributed to the initial static equilibrium of the platform. As far as the pitch motion of the platform, the larger max value is observed for LC2 load case (associated to the rated wind speed). The largest pitch value is 5.5 degrees. It should be noted that yaw max angle equal to 7.8 degrees is observed for LC2. The yaw motion of the presented concept is slowly-varying which does not significantly affect the power performance of the turbine. As far as the quantities that are related with the functionality of the wind turbine (Figure 7) the produced power for all the examined environmental load cases has mean values that are very close to the provided values of the reference 5MW wind turbine. Note that there is no feathering of the blades for below rated wind speed load case (LC1).

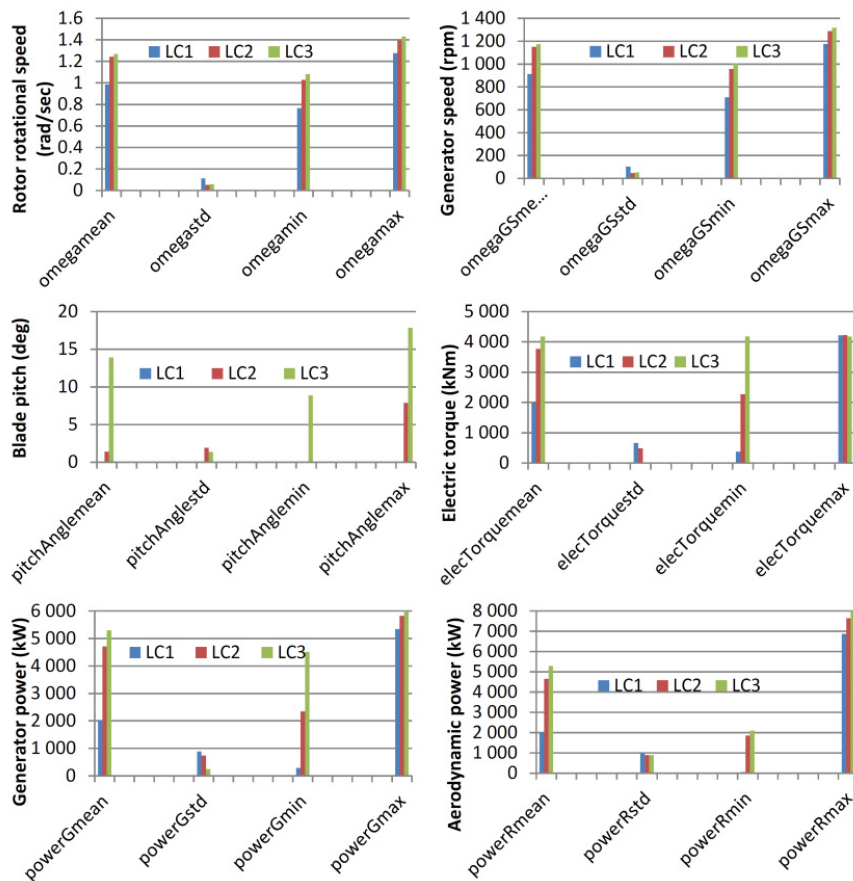


Figure 7: Wind turbine parameters including the rotational speed of rotor, generator speed, blade pitch angle, electrical torque, generated power and aerodynamic power of the V-shaped semisubmersible wind in LC1, LC2 and LC3.

In Figure 8, the blade-tip elastic-deflection (with respect to the blade-root), both flap-wise and edge-wise deflections, are shown for rated wind speed. The maximum thrust loads are associated with rated wind speed load case. The time series of the aforementioned quantities as well as the corresponding spectra are presented. The rotor harmonics 1P, 2P and 3P are presented for flapwise deflections while only the first harmonic (1P) is presented in edgewise blade deflections. Also, the slowly-varying motion of the platform affects the flapwise elastic deflection of

the blade. According to Jonkman et al. [15] and for the case of the V-shaped braceless semisubmersible wind turbine the overhang, shaft tilt and pre-cone of blades are 5 m, 5 and 2.5 degrees, respectively. The diameter of the tower at the base is 6.5 m and the blade-tip distance from the rotor-center accounting for the hub-radius is 63 m. Hence, the clearance between the blade-tip and tower for calm water (no-wave and no-wind) and wave-wind-induced load case are:

$$\begin{aligned} \text{Gap}_{\text{calm}} &= 63 \times [\sin(5) + \sin(2.5)] + 5 - 6.5/2 \cong 10 \text{ m} \\ \text{Gap}_{\text{dynamic}} &= \text{Gap}_{\text{calm}} - \text{blade}_{\text{deflection}} \cong 5 \text{ m} \end{aligned}$$

Therefore, the gap between blade and tower,  $\text{Gap}_{\text{dynamic}}$  accounting for the dynamic and elastic deflection of the blade in coupled analysis, which is an important parameter for wind turbines is reasonable for the current concept.

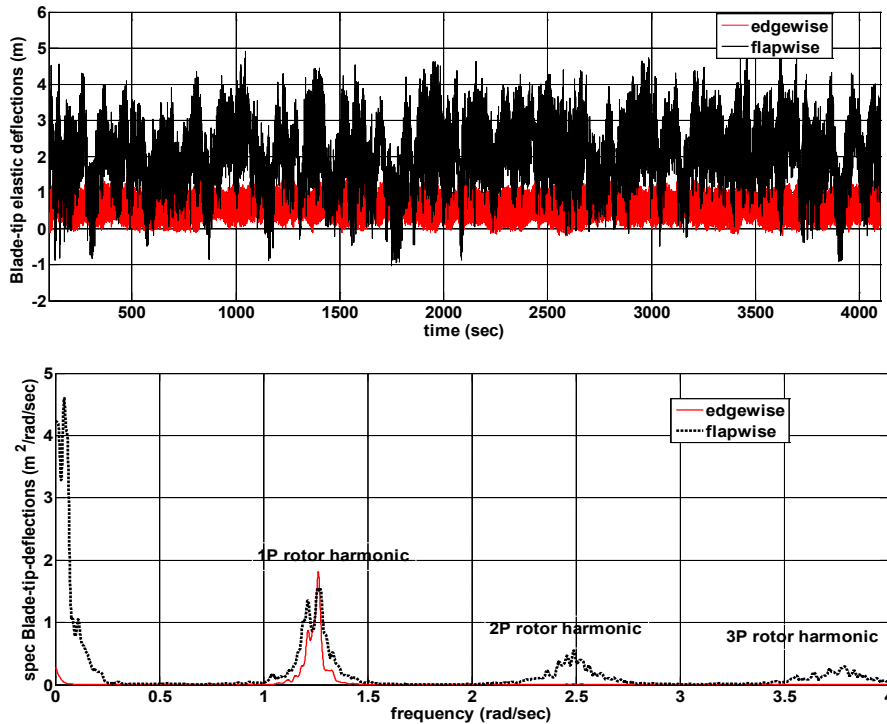


Figure 8: Time histories and spectra of flap- and edge-wise blade-tip elastic-deflection (relative to blade-root) for rated wind speed case, LC2.

## 5. Conclusions

Dynamics of a 5-MW V-shaped semisubmersible offshore wind turbine in normal operational conditions is presented in this paper. Considering the stability of the V-shaped platform and for positive heel angles in both X and Y axes, interception of the righting moment curves with a defined threshold that corresponds to the maximum induced heeling moment due to the wind turbine steady force at rated wind speed at top of tower is 5 degrees. In order to estimate the dynamic behavior of the offshore floating wind turbine in different environmental conditions, a hydro-aero-servo-elastic time domain numerical analysis model has been developed and applied with the use of the coupled analysis tool Simo-Riflex-AeroDyn. The coupled wave- and wind-induced analyses have been carried out for a specific number of normal operational conditions in order to highlight the feasibility of application of the V-shaped braceless floating semisubmersible wind turbine in deep water depth of 200m. The maximum observed pitch angle in coupled wave- and wind-induced motions is equal to 5.5 degrees and as a result the rotor swept area has a reduction of 0.4%. The overall global motions of the platform, mooring line tension responses and wind turbine data show that the presented concept is suitable for offshore wind application in deep water.



## 6. Acknowledgements

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