Impact of wind and wave induced platform motion on the aerodynamic properties of floating offshore wind turbines

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Abstract

With floating offshore wind turbines, new sources of wind energy can be used, which cannot be tapped into by bottom-fixed wind turbine systems. However, due to their design, they experience additional motion caused by wind and wave loads. The motions that are induced into the system have an oscillating course. This affects the aerodynamic properties of the wind turbine and leads to changes in the thrust force and power output of floating wind turbines compared to bottom-fixed wind turbines. Furthermore, the motions lead to an earlier breakdown of the helical wake structure behind the wind turbine and moreover lead to a decreased reliability of the rotor blades. Differences in the effects of wind and wave loads on the aerodynamic performance of floating offshore wind turbines supported by different platform systems were found.

Keywords: floating offshore wind turbine, unsteady aerodynamics, six-degree-of-freedom motions, failure probabilities, rotor blade reliability

1 Introduction

As part of the Green Deal the European Union has set itself the target of expanding the installed offshore wind power capacities to 60 GW by 2030 and 300 GW by 2050. In addition to bottom-fixed wind turbines, floating offshore wind turbines (FOWT) should also contribute to this [1]. With FOWT, wind energy can be harvested in areas with more than 40 to 50 m water depth, which cannot be reached by conventional bottom-fixed wind turbines [2]. Current floating platform systems are developed for water depth between 150 and 320 m [3–6]. They are therefore ideally suited to fully utilize the available capacities of shelf seas such as the North Sea. Nevertheless, Germany‘s EEZ[1] is less likely to come into question because here fixed systems are sufficient. But in other regions, such as Norwegian and British waters great potentials can be found. Altogether 66 percent of the North Sea water surface is located above water depths between 50 and 200 m [2]. However, the construction and operating of FOWT also creates new challenges. Through wind and wave loads the platforms experience translational (heave sway and surge) and rational (yaw, pitch and roll) motions [7]. These motions can have influence on the operating characteristics and the reliability of the rotor blades of FOWT. These review aims to summarize the effects of the influences. In particular, differences between different platform systems should also be noted.

2 Examined objects

2.1 Reference wind turbine

All studies which are mentioned in chapter 3 are based on the NREL[2] offshore 5-MW baseline wind turbine, which was defined by Jonkman et al. [8]. The main specifications of this wind turbine are listed in table 1.

Tab. 1: Specifications of the NREL 5-MW [8]

rated power	5 MW
hub height	90 m
shaft and hub tilt angle	5°
rotor orientation	upwind
number of blades	3
rotor diameter	126 m
control	variable speed, collective pitch
drivetrain	multiple stage gearbox
cut-in wind speed	3.0 m/s
rated wind speed	11.4 m/s
cut-out wind speed	25.0 m/s

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[1] Exclusive Economic Zone

[2] National Renewable Energy Laboratory

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2.2 Floating foundation

There are three primary floating platform constructions. One of them is the TLP[3], which is composed of an over-buoyant platform and moored by high tension lines. Due to the tension the system is dynamically stiff and can mitigate the dynamic stimuli from the wind and wave loads. Another system is the spar-buoy platform. It achieves its static stability due to its deep draft, combined with ballast weights. Furthermore, it is fixed by mooring lines to prevent drifting. The barge platform gets its stability from its large waterplane area and its distributed buoyancy. It is the cheapest and simplest system but due to its shallow draft is also the system with the greatest platform motions [7]. Another frequently examined platform type is, in addition to the three primary platform systems, the OC4[4] semi-submersible platform. It is made up of one main column on which the tower is attached. Three additional columns are attached to the main column with an offset of 120° through a series of pontoons and cross braces [5]. The three primary platform types and the OC4 platform are shown schematically in figure 1.

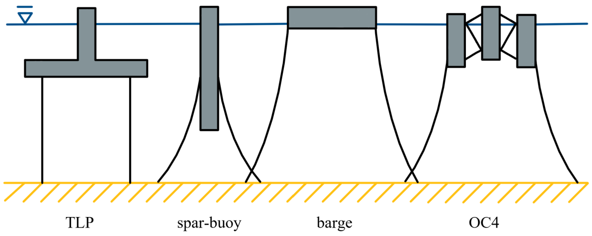

Fig. 1: Different types of floating foundations based on Lee and Lee [7] and Sebastian and Lackner [9]

3 Impact of platform motions

3.1 Impact on the aerodynamic performance

The waves on the sea exert direct forces on the platform. Simplified the waves are assumed to be periodic sinusoidal oscillations. Incoming waves pass on their periodic oscillations to the platform [7]. Due to the restrictions of the mooring lines the platform will oscillate around an equilibrium position [10]. Because platform, tower and wind turbine are rigidly connected, the motions of the waves have a direct influence on the aerodynamic performance. Just as the forces of the waves have a direct influence on the wind turbine, the forces of the wind, which are induced into the wind turbine, can also be transmitted through the tower to the platform. Here they also can lead to significant motions of the system. In comparison to the wave induced motions however, they are negligible [10]. As shown in figure 2, floating offshore wind turbine systems can experience six-degree-of-freedom motions (DoF) [7].

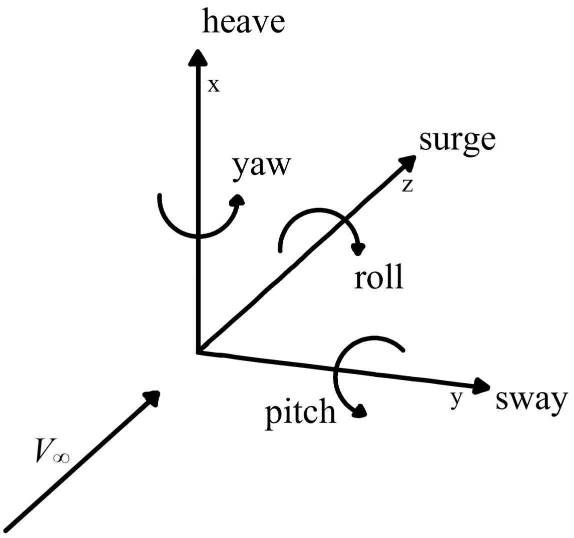

Fig. 2: Six-degree-of-freedom motions of a floating offshore wind turbine and direction of the incoming wind V_∞

Impacts of single DoF-motions

The first thing to consider is the impact of only a single DoF-motion on its own on the aerodynamic performance of a FOWT. The motions will be induced into the system at the bottom of the tower, 90 m below the hub. The focus is initially on the thrust force and the power output of the wind turbine. The examinations of Lee and Lee [7] show that only surge and pitch motions have a huge impact on the thrust force and power output of the wind turbine. In both cases the thrust force and the power output assume the sinusoidal function of the induced motions. The thrust force and power output of a FOWT under heave, sway, yaw and roll motions do not show significant differences to the thrust force and power output of a bottom-fixed wind turbine. Due to the surge and pitch motion, the power output fluctuates between the values listed in table 2. With the bottom-fixed wind turbine the power output is at a constant level of 2 MW.

Tab. 2: Fluctuation of the power output due to single DoF-motions based on Lee and Lee [7]

motion	power output
surge	0.6 MW - 3.8 MW
pitch	0.9 MW - 3.4 MW

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[3] Tension Leg Platform
[4] Offshore Code Comparison Collaboration 4

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The examinations were done with the values from table 3 at a below-rated wind speed of 8 m/s. Moreover, a comparison of several induced motion amplitudes at the same frequency showed a linear relationship between the amplitudes of the motion and the amplitudes of the thrust force and power output. In a further step the impact of the single DoF motions on the wake structure was considered under the same conditions. Behind the rotor blades of a bottom-fixed wind turbine the wake structure develops in a form of a well-defined helical geometry. The structure remains over a distance of three times the rotor diameter, where it dissolves into turbulent wake. Due to the platform motions the helical geometry behind the rotor blades dissolves after a distance of 0.5 to 1.3 times the rotor diameter. In contrast to the thrust force and power output, all DoF motions show an significant influence on the wake structure [7].

The cause of the fluctuation of the thrust force and power output and the increase of the turbulent wake is that movements of the wind turbine in the opposite direction of the incoming wind increases the effective axial wind speed on the rotor blades. This increases the aerodynamic loads, thrust force, power output and wake vorticity. It reaches its maximum when the turbine moves with its maximum speed. If the wind turbine moves back in the opposite direction, the effect is correspondingly the other way around [7, 10].

Tab. 3: Amplitude and frequency of the induced single DoF-motions [7]

motion	amplitude	frequency
heave, sway, surge	4 m	0.1 Hz
yaw, pitch, roll	4°	0.05 Hz

Impact of multi DoF-motions

Sebastian and Lackner [9] determined the platform motions, which get induced into TLP, spar-buoy and barge platforms under realistic wind and wave conditions. A distinction was made between below- and above-rated wind speed cases. According to their analysis, pitch, surge and heave motions have a significant impact on barge platforms and pitch and yaw motions on spar-buoy platforms in both cases. The TLP is influenced by surge and pitch motions in the below-rated case. In the above-rated case the surge motion is the only motion with a significant influence. Due to the different designs with different centers of gravity and buoyancy and different mooring systems the wind and wave loads also result in different motion amplitudes and frequencies for each platform type. This is also reflected in the different results for the thrust force and power output of the FOWT which were examined by Lee and Lee [7]. Their study showed that the power output of a wind turbine supported by a TLP, spar-buoy or barge platform can fluctuate between the values given in table 4. In their results the higher static stability of the TLP and spar-buoy platform becomes clear. This is already evident in the values of the amplitudes of the motions that are induced in the platforms. Here the values of the barge platform are always higher than those of the other systems. The most significant deviations between the values of the amplitudes are shown in table 5. The two amplitudes for each motion originate from two superimposed oscillation functions that were used in the model of the present study.

Tab. 4: Fluctuation of the power output of wind turbines supported by different floating platforms under the influence of multi DoF-motions based on Lee and Lee [7] (the power output is given as a portion of the power output of a bottom-fixed wind turbine)

platform	power output
barge	40 % - 190 %
TLP and spar-buoy	90 % - 110 %

Tab. 5: Most significant differences in the amplitudes of the induced platform motions into different platform systems based on Lee and Lee [7]

motion	platform	amplitude 1	amplitude 2
pitch	spar-buoy	0.084°	0.016°
	barge	1.475°	1.630°
surge	TLP	0.436 m	0.222 m
	barge	0.752 m	0.442 m

The influence of multi DoF-motions on wind turbines supported by the semi-submersible OC4 platform were examined by Cheng et al. [10]. As with the barge platform, surge, pitch and heave are the main DoF-motions. With non-identical wind speed assumed, the results cannot be directly be compared with one another. But it can be said that the range of the fluctuation of the power output of the wind turbine is similar to the wind turbines supported by the TLP or barge platform. Accordingly, waves with a height of 3.66 m, which is two times the amplitude, and a frequency of 0.1 Hz[5] lead to a fluctuation of the power output between 4.5 MW and 4.9 MW.

Lee and Lee [7] also determined differences in the stability of the wake structure between the different platform types. Under realistic wind and wave conditions the well-defined helical geometry of the wake of a bottom-fixed wind turbine dissolves after a length of 1.3 times the rotor diameter behind the rotor blades. With wind turbines supported by floating platforms the well defined wake structure dissolves earlier. The corresponding results are shown in table 6.

In both studies, which are mentioned in this chapter

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[5] original indication of the reference: wave period length in seconds

Tab. 6: Distance after which the well defined wake structure behind the rotor blades dissolves based on Lee and Lee [7]

platform	distance in times the rotor diameter
barge	0.5
spar-buoy	1.0
TLP	1.1

[7, 10] the pitch control keeps a constant pitch angle according to the velocity of the incoming wind.

3.2 Impact on the reliability of the rotor blades

The increase of the aerodynamic unsteadiness due to the multiple DoF platform motions can also lead to changes in the reliability of the rotor blades of FOWT in contrast to bottom-fixed offshore wind turbines. The causes and effects of the loss of reliability of an FOWT supported by an OC4 platform were investigated in a study of Liu et al. [11]. The examined causes of failure are

- blade root stress,
- flapwise motion of the blade tip and
- edgewise motion of the blade tip.

The resulting failure phenomena are listed in the first column of table 7. Liu et al. determined that the failure probabilities of all listed phenomena are higher on blades of FOWT than those of bottom-fixed wind turbines. The probability of failure results from the spread of the acting quantity and the spread of the resisting quantity, which are occurring in reality. In the area where the two distributions intersect, the components fail. Each occurrence of failure was examined in three different scenarios. This results in a total of nine investigations. The wind speed, wave height and peak period of wave spectrum of these scenarios are also listed in table 7. It should be noted that a wind speed of 11.4 m/s correspondents to the rated wind speed and that a wind speed of 25.0 m/s is equal to the cut-out wind speed of the wind turbine. The wind turbine in this study is still in operation at the cut-out wind speed. During the investigation at a wind speed of 51.5 m/s the wind turbine is parked. The numbers of every investigation can also be found in figure 3. The absolute failure probabilities of a bottom-fixed wind turbine and a FOWT are compared here. Furthermore, the increase of the failure probabilities is shown. Particularly noteworthy is the increase in the failure probability due to stress overload of the blade root (no. 6 in figure 3). However, the high wind speeds examined in this scenario are extremely rare in the North Sea but can occur in individual gusts [12, 13]. The occurrence of ten-minute values of wind speed of an example location, about 100 km from the Dutch coast in the North Sea, can be seen in figure 4. The graphic is intended to provide a qualitative overview of the rarity of such an event. The increase of the failure probability due to structure fatigue of the blade root is also worth highlighting (no. 2 in figure 3). Under extreme wind conditions the probability of failure due to this cause can nearly be brought back to the level of a bottom-fixed offshore wind turbine through the cut-out of the wind turbine.

It can be assumed that the failure probability of an FOWT supported by a TLP or spar-buoy platform increases in a similar range as the failure probability of an FOWT supported by an OC4 platform, since they also achieved similar results in chapter 3.1.

Tab. 7: List of the examined failure phenomena and wind and wave scenarios in the study of Liu et al. [11]

event	wind speed m/s	wave height m	peak frequency[5] Hz	no.
structure fatigue of the blade root	11.4	3.24	0.10	1
	25.0	6.02	0.09	2
	51.5	12.90	0.07	3
stress overload of the blade root	11.4	3.24	0.10	4
	25.0	6.02	0.09	5
	51.5	12.90	0.07	6
excessive displacement of the blade tip	11.4	3.24	0.10	7
	25.0	6.02	0.09	8
	51.5	12.09	0.07	9

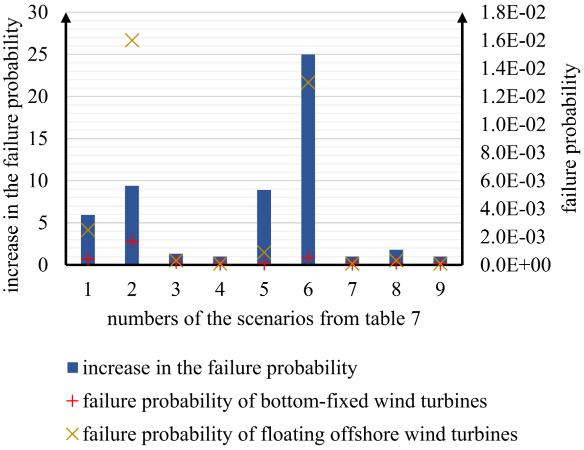

Fig. 3: Failure probabilities of rotor blades from bottom-fixed on floating offshore wind turbines based on Liu et al. [11]

4 Conclusion

In summary it can be said that the platform motions caused by wind and wave loads lead to a variety of

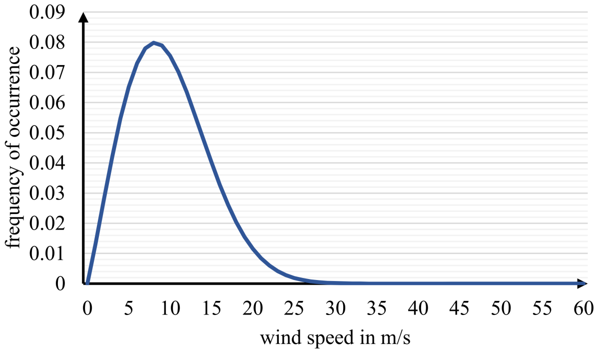

Fig. 4: Frequency of occurrence of ten minute mean values of wind speed in the north sea at location 53°13'04.0"N 3°13'13.0"E at a height of 74.8 m above the mean sea level based on Coelingh et al. [12]

changes in the operational properties of a FOWT. The following changes were noted in this review:

- The thrust force and power output of FOWT are fluctuating in the same frequency as the platform motions.
- The fluctuations of the thrust force and power output are almost exclusively based on surge and pitch motions of the platform.
- The TLP, spar-buoy and OC4 platform are less affected by wind and wave loads than the barge platform.
- Platform motions lead to an increase of the failure probability of the rotor blades of an FOWT compared to a bottom-fixed wind turbine.
- The wake structure behind the rotor blades of an FOWT is experiencing an earlier breakdown than the wake structure behind a bottom-fixed wind turbine.

The highly unstable wake might also lead to additional problems in floating offshore wind farms. Due to the unsteady wake the wind turbines, which are located downstream of another wind turbine are exposed to unsteady inflow conditions. This puts additional stress on their rotor blades [7]. Additional studies of how high these effects are would be desirable. Moreover, further studies on the failure probability of the FOWT rotor blades would be useful, as the data available so far is very limited.
All studies mentioned in this review, which take a critical look at the effects of platform motions are based in theoretical models. It can be assumed that practical data from current test systems will be added in the future.

5 Outlook

It is almost impossible to eliminate platform motions induced by wind and wave loads. Nevertheless, it is possible to decrease their influences on the operational properties of the wind turbine. Individual blade pitch control could be one possible solution. It was already shown that the power fluctuation of a FOWT, operating at above-rated wind speed conditions, supported by a barge platform, can be decreased by up to 44 % due to such a system. The pitch and roll motions were also decreased by 39 and 43 % respectively [14]. Further improvements could be reached due to a coating of a piezoelectric ceramic at the first quarter of the blade root, which is activated when root stress reaches its limitation. The failure probability due to the failure phenomena listed in table 7 could be decreased by up to 89 % [11].

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