The benefit of the teetering rotor in an offshore wind turbine and floating platform system

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SUMMARY

The paper investigates the dynamic behavior of two-bladed, teetering-hinge, yaw-control wind turbine, on top of a concrete semi-submersible floating platform (Figure 1). The paper discusses the role of the turbine on the pitch (roll) damping of the offshore floating system and focuses on the turbine loading trade-off between offshore and onshore.
The work addresses three questions:

- Does the operation at wind speed above the rated cause negative damping of the platform pitch (roll) mode leading to amplified tower deflection, and turbine and tower loading [1]?
- Does the platform pitch (roll) mode amplify the rotor loads compared to onshore?
- How does the teetering hinge affect the system loading?

The study has been conducted for an offshore turbine of 6.2 MW (Seawind 6) and it was verified that the conclusions are also valid for a larger wind turbine of the same type (Seawind 12).
The findings of this paper are:

- The offshore rotor of two-bladed teetering hinge wind turbines with a concrete floating support structure, like the OO-Star Wind Floater by Olav Olsen, properly optimized, doesn't add negative damping to the system and counteracts the floating foundation motion reducing platform oscillations caused by waves.
- The teetering rotor and the high inertia of the concrete floating platform play an important role in lowering the offshore system loading. Offshore UL and DEL loads are slightly higher than onshore.
- The rotor bumper is never hit, except for parking in extreme conditions and wind-wave misalignment.
- The teetering hinge leads to symmetrical flapping loads on the two blades, irrespectively of the rotor-wind misalignment.

Figure 1 The offshore system subject of the investigation

1. CHARACTERISTICS OF WIND TURBINE SYSTEM

The two-bladed teetering hinge turbine considered in this work has a size optimized for hurricane areas. Its rotor diameter is 126m although the rated power is 6.2 MW (Seawind 6, Figure 2). Due to the degree of freedom introduced by the elastic hinge (Figure 3), the turbine is no more a gyroscopic system (Figure 4); the yaw torque is small, and the power is controlled by yawing rather than by pitching (Figure 5). Due to the hinge, the blades are subjected the same flapping moments, irrespectively of the rotor-wind misalignment. The hinge is equipped with a damping bumper. However, generally the bumper is never hit; a hit can be expected in parked conditions under extreme wind speed (70 m/s) and waves-wind misalignment. The turbine characteristics in terms of power, torque, running speed, thrust,

versus wind speed, are depicted in Figures 6 & 7. Beyond the rated wind speed the thrust remains constant.
The main data of the system and of the reference site considered in the analyses are given in Table1.

Figure 2 The turbine configuration

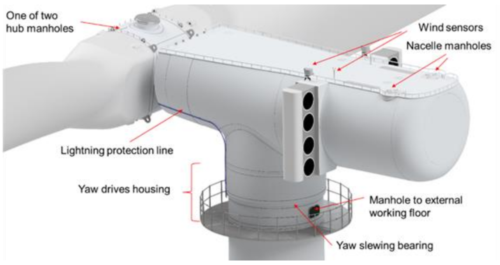


Figure 3 The teetering hinge

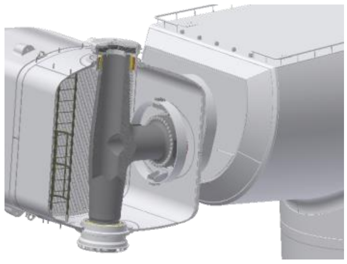


Figure 4 The conceptual control by yawing

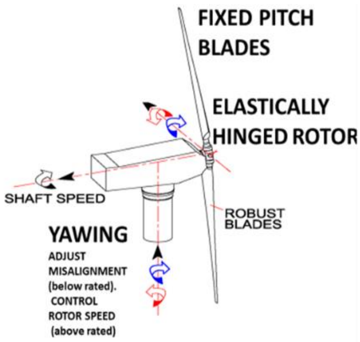


Figure 5 The control loops

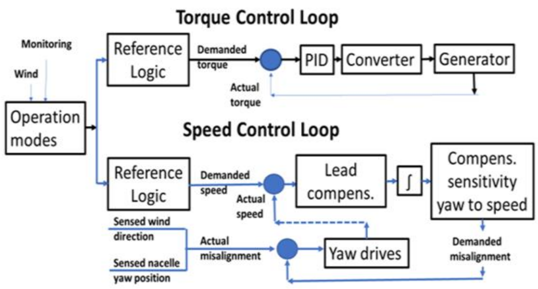


Figure 6 Turbine power, torque, thrust

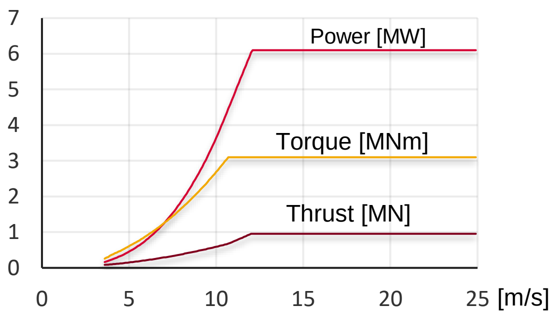


Figure 7 Turbine running speed

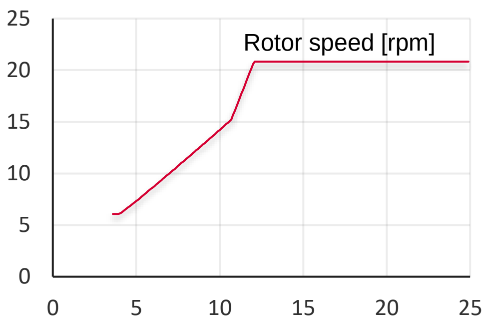


Table 1

System		Reference site K3[1]			
Rated power	6.2 MW		Wind [m/s]	Hs [m]	Tp [s]
Cut in; Cut out	3.5 m/s; 25 m/s	Normal operating	3.5 to 25	1.2 to 3.5	5.8 to 7.8
Rotor diameter	126 m				
Hub height	89 m from WL	Extreme 50-year Parking	56	12.9	16
Tower frequency	0.5 Hz (between 1P_2P)				
Support structure	OO-Star Wind Floater by Olav Olsen				

[1] K3 coordinates 53°13'04" north and 3°13'13" east

2. EXTENSION OF ANALYSIS

2.1. LOAD CASES

The analyses were carried out, with Bladed software [2], to:

- Study the behaviours of the offshore system (in terms of displacements and loads) for
  - Fatigue cases: DLC 1.2 (normal production) NTM
  - Ultimate load cases: DLC 1.3 (extreme turbulence); DLC 6.1 (parking with 50-year wind); DLC 6.2 (parking for maintenance with 1-year wind)
- Examine the situations of waves coming from any radial direction of the floating platform with and without wave-wind misalignment
- Compare the results with those of the same turbine having a bottom-fixed tower with the same modal frequency
- Test the benefit of the teetering hinge by finding how the loads would change if the rotor were rigid
- Substantiate the benefit of the teetering hinge in balancing the rotor blades flap moments
- Confirm that the larger the turbine size, the lower is the amplitude of the teetering hinge angle.

Although, for wind speed @ 20 m/s, the values of Hs and Tp of the reference site are about 3.5m and 7.8 s, the analysis was made with waves of 6 m and 5_20 s period. Table 2 lists the cases examined for the sensitivity analysis. Wind and waves are aligned in direction J (Figure 8). The cases 1off-2off (and 1off$_a$-2off$_a$) are studied to investigate how the platform oscillations change when a constant wind is added to waves of different periods. The cases 3off- 4off- 5off analyse the effect of waves period Tp with turbulent wind; the worst of these cases (5off) is compared with the relevant onshore case 5on. The cases 6off- 6on, refer to a turbine shutdown. The cases 7off-7on refer to the operating condition with wind extreme turbulence. The cases 8off-8on refer to the extreme 50-year wind with parked turbine. The case 9off, compared with 5off, is added to examine how the loads would change with a rigid rotor.

Table 2- Cases examined for displacements and loads comparison

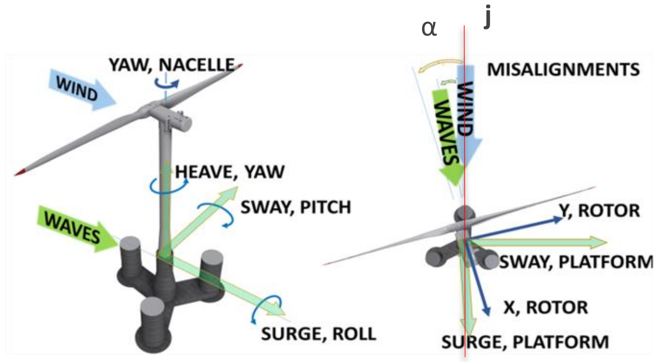
Offshore cases	Waves		Wind		Onshore cases
Label	Hs [m]	Tp [s]	Speed [m/s]	Condition	Label
1off	6	20	-	-	-
2off	6	20	20 constant	Normal operation	-
1off$_a$	6	10	-	-	-
2off$_a$	6	10	20 constant	Normal operation	-
3off	6	5	20 turbulent[2]	Normal operation	-
4off	6	10	20 turbulent	Normal operation	-
5off	6	20	20 turbulent	Normal operation	5on
6off	6	20	20 turbulent	Shutdown	6on
7off	6	20	20 turbulent	Normal operation. Extreme turbulence	7on
8off	12.9	16	56 turbulent	50-years parking	8on
9off	6	20	20 turbulent	Normal operation. Rigid rotor	-

2.2. COORDINATE SYSTEM

The coordinate system used for the simulation is in Figure 8.

[2] Turbulent 20 m/s, covering a range of 12_28 m/s and a variation of 30° of wind direction

Figure 8 Coordinate system



3. RESULTS

3.1. OFFSHORE DISPLACEMENTS

3.1.1. WAVES AND WIND ALONG THE REFERENCE DIRECTION (J, FIGURE 8)

All cases examined show that the offshore system (as it is now) is characterized by a pitch (roll) modal frequency of about 25 s and a yaw natural modal frequency of about 350 s. The cases $1off_a$-$2off_a$ (Figures 9 & 10) show that: the system oscillates with the period of the waves (10 s); the constant wind added to the waves reduces the platform oscillation amplitude. On the contrary, the time histories of the cases 1off-2off (Tp 20 s) reveal that, if the system modal period is close to waves period, the waves-system dynamic interaction leads somehow to amplify the oscillations even with only waves.
Table 3 gathers the pitch, roll and yaw of the offshore and onshore cases 3 to 9. The cases 3off to 5off show that the *average* pitch, roll and yaw don't change passing from 5 to 20 s of wave period; the max ranges of pitch and roll increase with the waves period, while the yaw range remains constant. The cases 6off and 7off show that in shutdown, and in extreme turbulence, the oscillation amplitudes are not higher than in normal operation. The case 8off shows higher roll amplitudes, being the turbine parked with the rotor disk virtually parallel to the wind direction. The case 9off reveals that a rigid rotor would only slightly affect the amplitude of the platform oscillations[3].

Figures 9 Displacements with waves only (case $1off_a$)

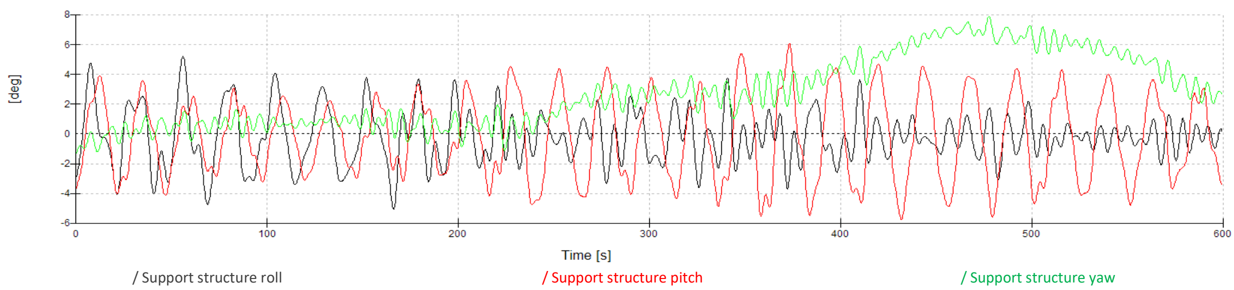
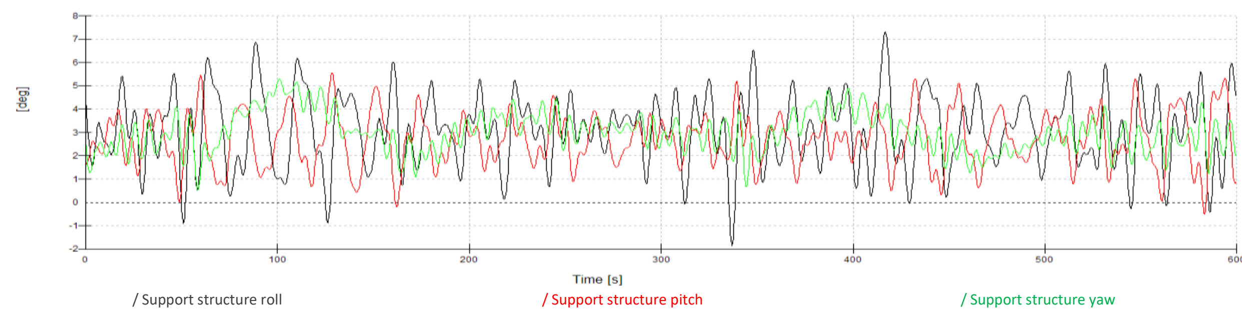


Figure 10 Displacements with waves and constant wind (case $2off_a$)



[3] A rigid rotor would affect the loads instead, as displayed below

Table 3- Displacements with waves and turbulent wind

Case	Pitch (Roll) Platf. [deg]		Pitch (Roll) Top Tower [deg]		Yaw Platf. [deg]	
	Ave	Half amplitude	Ave	Half amplitude	Ave	Half amplitude
3off	2.7 (3.0)	4.5 (5.3)	4.3 (0.6)	4.6 (4.8)	2.2	5.6
4off	2.6 (3.0)	3.7 (5.5)	4.3 (0.6)	4.9 (4.4)	3.2	4.0
5off	2.6 (2.9)	7.2 (7.4)	4.1 (0.5)	8.0 (6.1)	2.2	5.4
6off	0.6 (1.2)	4.0 (5.1)	1.1 (0.6)	5.4 (3.8)	1.3	1.7
7off	2.6 (3.0)	4.5 (4.5)	4.2 (0.7)	5.2 (3.5)	2.7	1.9
8off	-0.3 (2.3)	5.7 (17.4)	-0.3 (2.3)	5.6 (17.5)	-0.7	8.6
9off	2.3 (2.8)	7.4 (8.8)	3.8 (0.6)	6.0 (9.7)	4.4	6.5

3.1.2. WIND-WAVES DIRECTION DIFFERENT FROM THE REFERENCE J

With a wind direction different from the reference direction J (Figure 8) by ± 60°, and a wind-waves misalignment of ± 15%, the response of the system changes, also due to the platform asymmetrical configuration, with some effects on displacements (and loads) for waves period close to the system modal period and without significant effects for waves period lower than the system period. The issue is acknowledged as a key point for the optimization of the support structure.

3.1.3. DISPLACEMENTS FOR THE REFERENCE SITE K3

In the condition of the site K3, where the waves period (7.8 s) is well uncoupled from the system modal period, the oscillation amplitudes are quite lower (Figures 11 & 12), and they change little versus the wind-waves direction. Moreover, the nacelle oscillates with the velocities of Figure 13.

Figure 11 Platform pitch, roll, yaw in normal operation @20_24 m/s

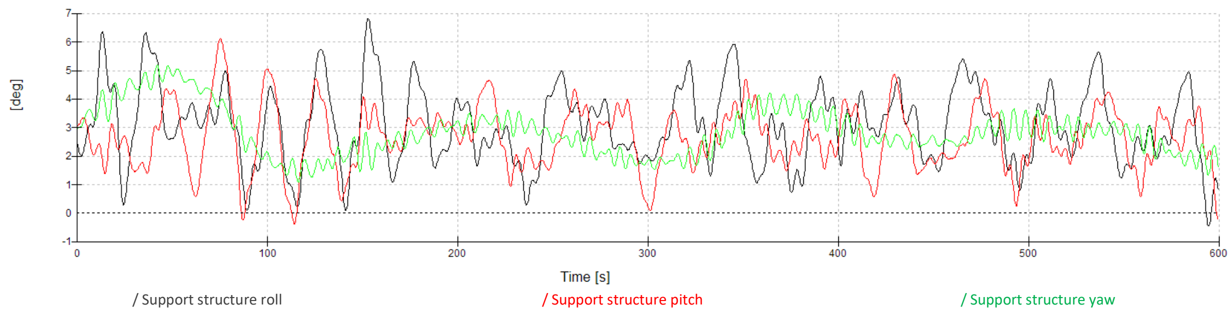


Figure 12 Nacelle pitch, roll and yaw in normal operation vs. onshore @20-24 m/s

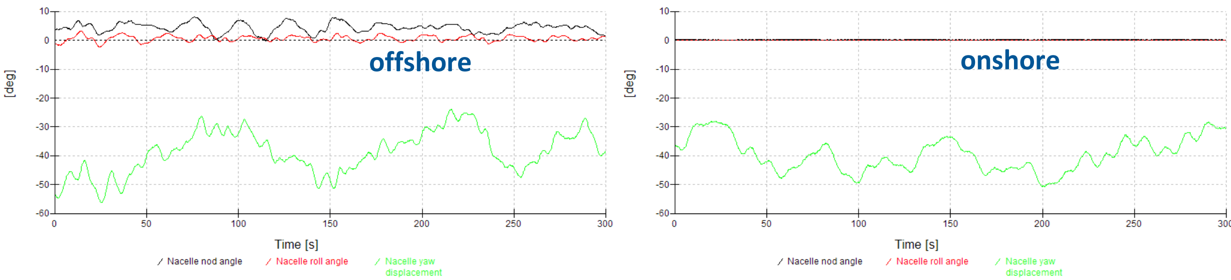
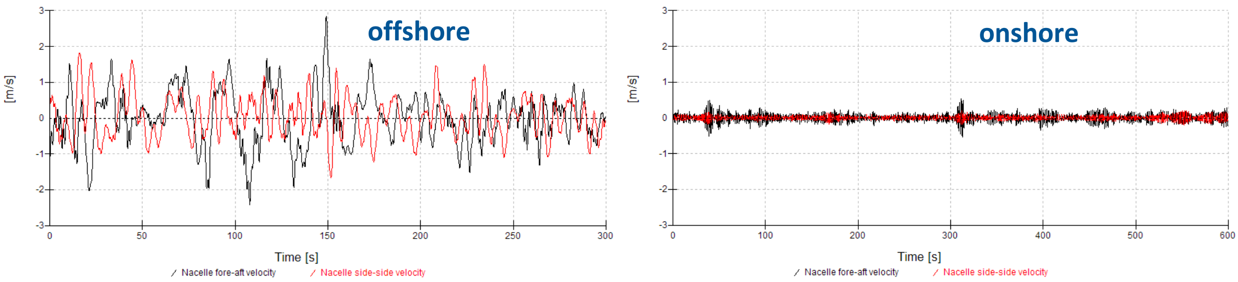


Figure 13 Nacelle velocity in normal operation versus onshore @20-24 m/s



3.1.4. INFLUENCE OF THE HYDRAULIC COEFFICIENTS

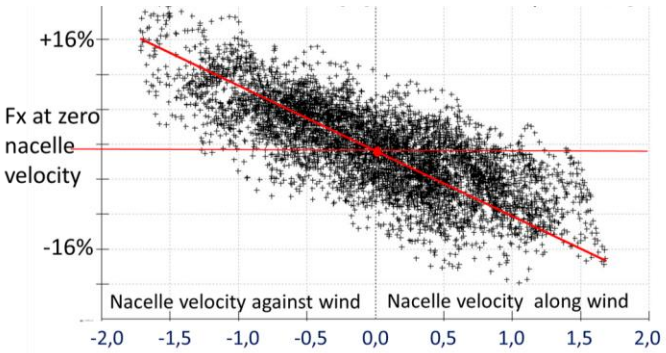
A sensitivity analysis of the hydraulic coefficients reveals the importance of the heave coefficients which, therefore, are a second key point to be considered for the optimization of the support structure.

3.1.5. HOW THE NACELLE SPEED AFFECTS THE ROTOR THRUST

Figure 14 shows that when the nacelle moves with a velocity against the wind direction, the wind speed seen by the rotor increases and the relevant thrust increases. Vice versa if the nacelle moves along the wind direction.

This characteristic of two-bladed yaw-controlled turbines introduces into the system a positive damping, as can be seen from the comparison of the above cases $1off_a$ and $2off_a$.

Figure 14 Rotor thrust Fx [%] versus nacelle speed [m/s]



3.2. OFFSHORE LOADS COMPARED TO ONSHORE

The following pictures show the ratio of offshore loads to onshore loads *ceteris paribus,* for the conditions of the reference site. Figure 15 refers to the DEL, for fatigue.

The following two figures refer to the driving DLC, for UL. Figure 16 is for extreme turbulence DLC.

Figure 17 is for 50-year wind DLC, with extreme waves (Hs12.9m and Tp 16s). This is the case of turbine parked with horizontal blades pointed to the wind ± 15°and yaw and shaft locked.

Figure 18 points out the critical loads for the turbine parking lock devices.

Figures 15 - DEL-Ratio offshore to onshore

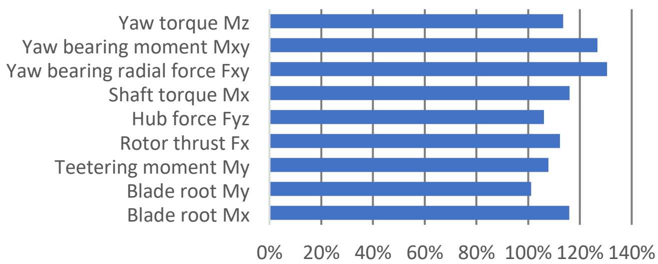
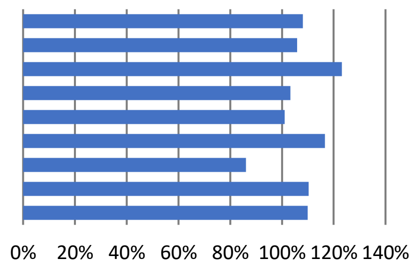


Figure 16 - Extr. Turb.-Ratio offshore to onshore



Figures 17 - 50y -Ratio offshore to onshore

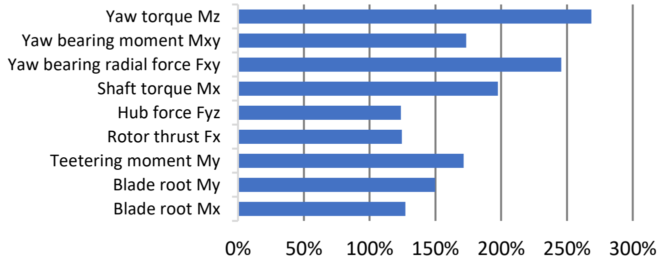
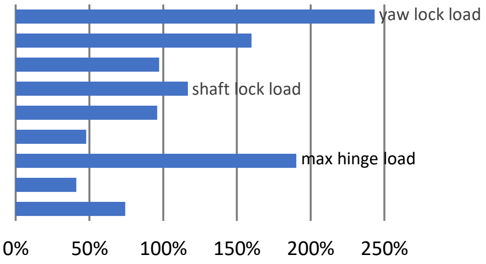


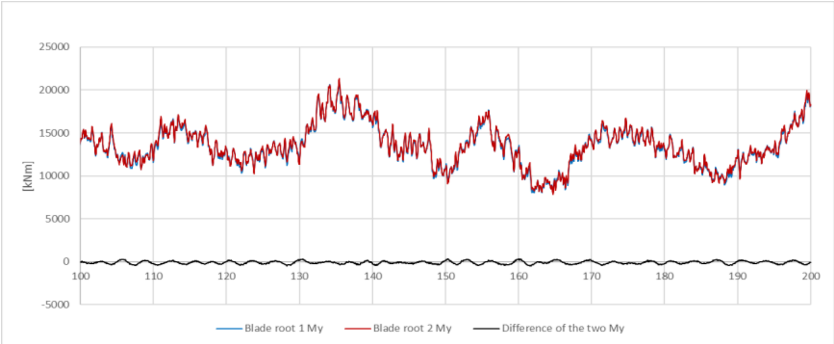
Figure 18 - Offshore -Ratio 50y to Extr. Turb.



3.3. BLADES BALANCING IN THE TEETERING HINGE ROTOR

The role of the teetering hinge is not only to introduce a degree of freedom into the system to minimize the yaw torque (gyroscopic loads) and to eliminate the aerodynamic moments entering the rotor shaft, but also to balance the flap moments of the two blades (Figure 19).

Figure 19 Offshore loads of teetering rotor blade roots



3.4. LOADS OF TEETERING ROTOR VERSUS RIGID ROTOR

The following pictures show the load ratios between teetering rotor and theoretical rigid rotor. The major benefits are for the turbine shaft moment, blade moment, yaw bearing.

Figure 20 Case of rotor into constant wind

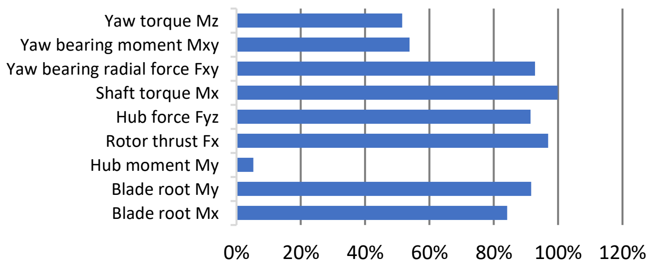
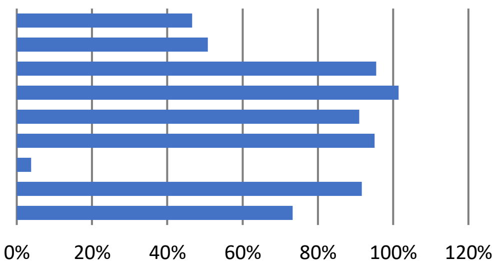


Figure 21 Operating condition @ cut-out



3.5. TEETERING ANGLE VERSUS ROTOR DIAMETER

The following picture compares the amplitude of the rotor hinge teetering of the turbine considered in this study (Seawind 6) with the same parameter for a larger turbine Seawind is developing (Seawind 12). The larger turbine is characterized by a smaller teetering amplitude. The main reason lies in the Lock number (which represents the ratio of aerodynamic forces, which act to lift the blade, to inertial forces, which act to maintain the blade in the plane of rotation) that is higher for the larger rotor. The angles are well within the bumper clearance, except for one-two hits in parking 50-year DLC.

Figure 21- Teetering hinge angles of 6.2 MW turbine (Seawind 6) in normal operation

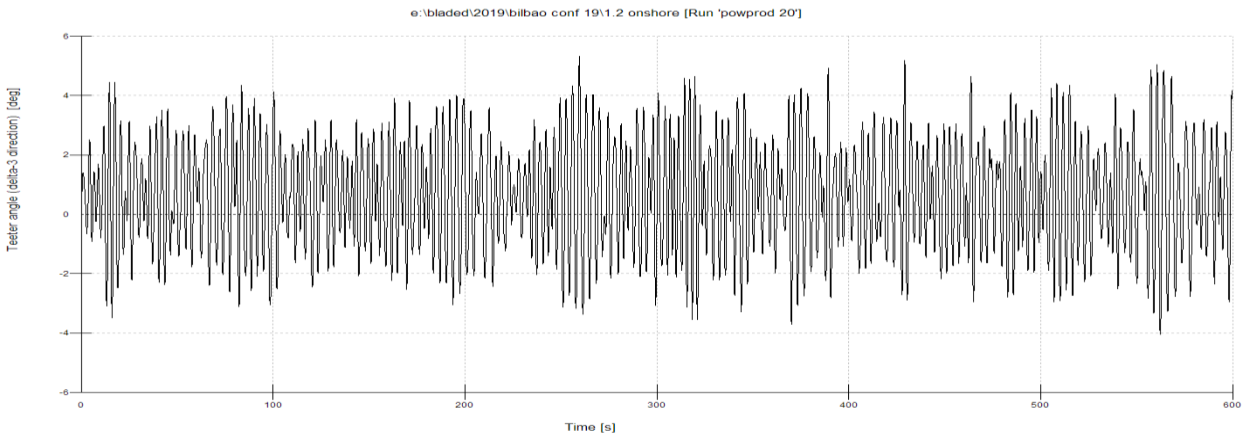
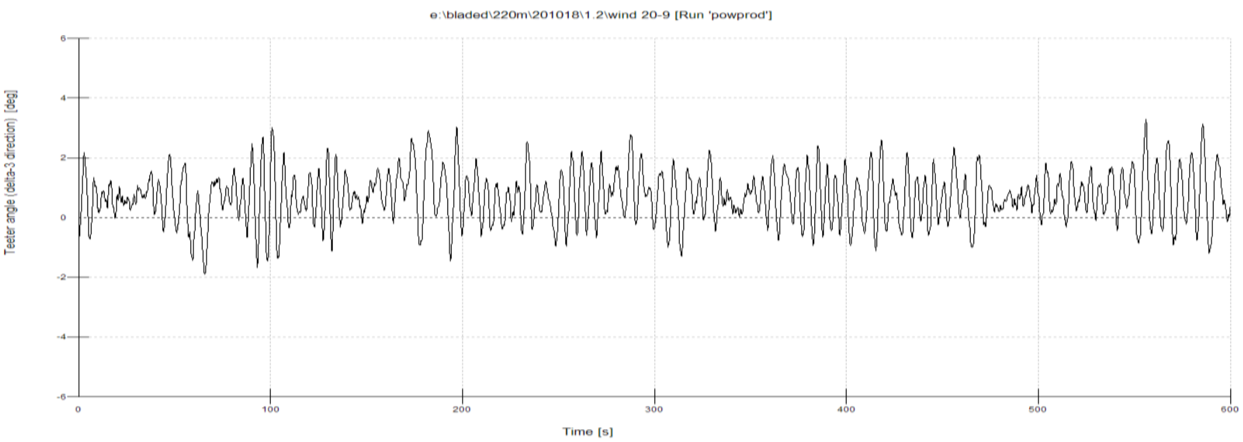


Figure 22- Teetering hinge angles of 12 MW turbine (Seawind 12) in normal operation



4. PLANNED FURTHER INVESTIGATION

Further work shall be carried out to investigate the system behaviour by improving the support structure (e.g. tuning the size). The results of the simulation model and the critical inputs (e.g. hydraulic coefficients) will be substantiated by physical model test in basin.

5. REFERENCES

[1]. J.M. Jonkman, Dynamics Analysis Offshore Floating WT, 2007

[2]. Bladed, Version 4.5