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Sensitivity Analysis of Limited Actuation for Real-time Hybrid Model Testing of 5MW Bottom-fixed Offshore Wind Turbine

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Abstract

The present paper studies the effect of limited actuation for real-time hybrid model testing (ReaTHM[®] testing) of a bottom-fixed offshore wind turbine in operational, parked, and fault conditions. ReaTHM[®] testing is a new approach for conducting small-scale experimental campaigns and has recently applied to test a braceless semisubmersible floating wind turbine in MARINTEK ocean basin [1, 2, 3]. The aerodynamic loads on the wind turbine were applied based on simultaneous simulations coupled to the experiments while the wave loads and floater response were physically tested. The effects of actuation limitation on the ReaTHM[®] testing setup for the semisubmersible wind turbine were investigated previously [4] using numerical simulations, by not including some components of the aerodynamic loads or by inducing error (for example in the direction of the force actuation). In this paper, the same approach is used to investigate the sensitivity of a bottom-fixed 5MW offshore wind turbine to limited actuation. The consequences of limited actuation are also considered for fault conditions (grid loss, and blade seize with and without shutdown) due to the potential importance of fault events for the ultimate and accidental limit state analysis. For the operational turbine, most responses of interest were not strongly dependent on the studied limitations in actuation, but the aerodynamic pitch and yaw moments were important for fault cases.

Keywords: Real-time Hybrid Model Testing, Actuation, Bottom-fixed Offshore Wind Turbine, fault conditions

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1. Introduction

Model testing has a key role in design and certification of offshore wind turbines; nevertheless, there are challenges associated to physical testing accounting for both wind and waves actions. Hydrodynamic tests are generally based on Froude scaling, however a consistent scaling of the wind turbine results in low Reynolds number and normally poor aerodynamics. Although non-geometrical scaling i.e., modifications of the airfoils and chord length help improving the turbine aerodynamic performance in ocean basin testing, it is not currently possible to match the thrust, torque, and slope of the thrust curve satisfactorily [5, 6]. Accurate modeling of torque and other aerodynamic forces and moments such as the sway force and yaw moment, including the effects of wind turbine control system, may be significant in addition to correct modeling of the thrust. When the experimental goal is to qualify the global system's performance, it may be more practical to apply ReaTHM® testing (real-time hybrid model testing) approach. This implies that aerodynamic loads are actuated upon the physical model according to simultaneous (real-time) simulations of the turbine rather than being generated by a small-scale physical turbine [1, 2, 3, 4]. Figure 1 illustrates the concept of ReaTHM® testing for a bottom-fixed wind turbine (BFWT). The platform responses are measured and sent to the numerical simulator, and actuators apply proper aerodynamics and generator loads based on the results of the numerical simulations.

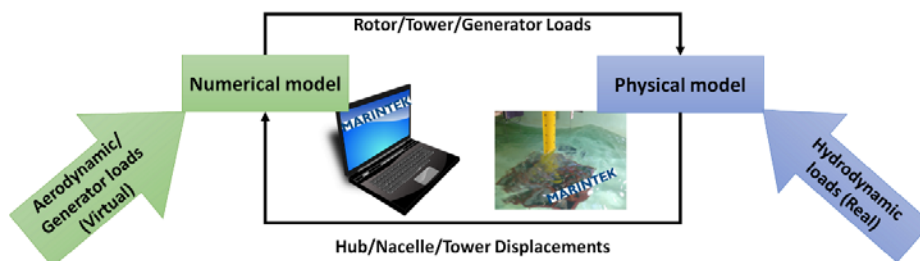


Figure 1: Real-time hybrid model testing (ReaTHM® testing) for a BFWT in a wave basin

In order to design a real-time hybrid model testing campaign of a BFWT in a wave basin, one must determine exactly which forces and moments should be actuated in order to achieve sufficiently accurate results, and how these forces and moments should be actuated. The number, required speed, and force range of such actuators are important parameters for the cost and complexity of the test campaign. This paper focuses on the question of which forces and moments should be actuated. This is studied using numerical simulations with a specially modified analysis tool. A full-scale numerical model of a BTWT with rigid blades was modeled in the coupled simulation tool SIMO-RIFLEX-AeroDyn [7].

SIMO-RIFLEX-AeroDyn contains three integrated numerical codes. SIMO (MARINTEK) [8] models the rigid body hydrodynamics of the hull. RIFLEX (MARINTEK) [9] includes the finite element solver, flexible elements for the mooring lines (or tendons), tower, shaft, and blades, and the link to an external controller. AeroDyn (NREL) [10] provides the forces and moments on the blades based on Blade Element/Momentum (BEM) or Generalized Dynamic Wake (GDW) theories, including dynamic stall, tower shadow, and skewed inflow correction. The generator torque and blade pitch control system is implemented in Java. To study the effects of limited actuation, modifications were applied into the AeroDyn module of SIMO-RIFLEX-AeroDyn [4]. The blade loads are modified within the aerodynamic module before being applied as distributed loads in the structural module. Basically, the differential aerodynamic loads on each element are first calculated in the tower-fixed rotor coordinate system, then modified for example by removing the aerodynamic yaw component. Afterward, aforementioned aerodynamic loads are calculated in their local frame before AeroDyn returns the forces to the structural solver (RIFLEX).

In order to make the numerical model more similar to the proposed experimental model, the piled section of the monopile was replaced with a tuned torsional spring. After establishing the baseline behavior of the model, modifications to the numerical model were included in order to examine the effects of incomplete actuation of the rotor loads. The complete rotor loads which are transferred to the platform include three aerodynamic forces, two aerodynamic moments, the generator torque, and inertial (gyroscopic) effects. This study considers the effects of removing the: (a) dynamic variation of generator torque, (b) pitch moment, (c) sway force and (d) yaw moment. Furthermore, for parked conditions, the effect of removing the aerodynamic forces completely is considered. It is assumed that the effect of thrust directionality (vertical and horizontal), gyroscopic moments, and heave force can be

neglected for the BFWT due to the limited motions of the rotor-nacelle-assembly (RNA) and the relatively small importance of vertical aerodynamic forces on the axial loads on the structure.

Fault cases influence the design of wind turbines due to their transient effects. Therefore, testing the performance and structural integrity of the offshore wind turbines under fault cases is important. This paper investigates which forces and moments should be actuated when considering fault cases. The sensitivity of limited actuations for a bottom-fixed 5MW offshore wind turbine considering grid loss, blade seize with and without shutdown.

2. Baseline design

In this article, a 5MW bottom-fixed offshore wind turbine in 30 m depth is considered, see Figure 2. The NREL 5-MW reference wind turbine is considered together with the OC3 monopile design [11,12]. The main characteristics of the BFWT are listed in Table 1. The structural model of the BFWT in RIFLEX consists of beam elements, as well as nodal masses and spring elements distributed along the structure, see Figure 2. The distributed nonlinear soil springs along the pile represent the soil-pile interaction in dynamic analysis. Figure 3 shows the deflection-force relation for distributed soil springs along the pile [12].

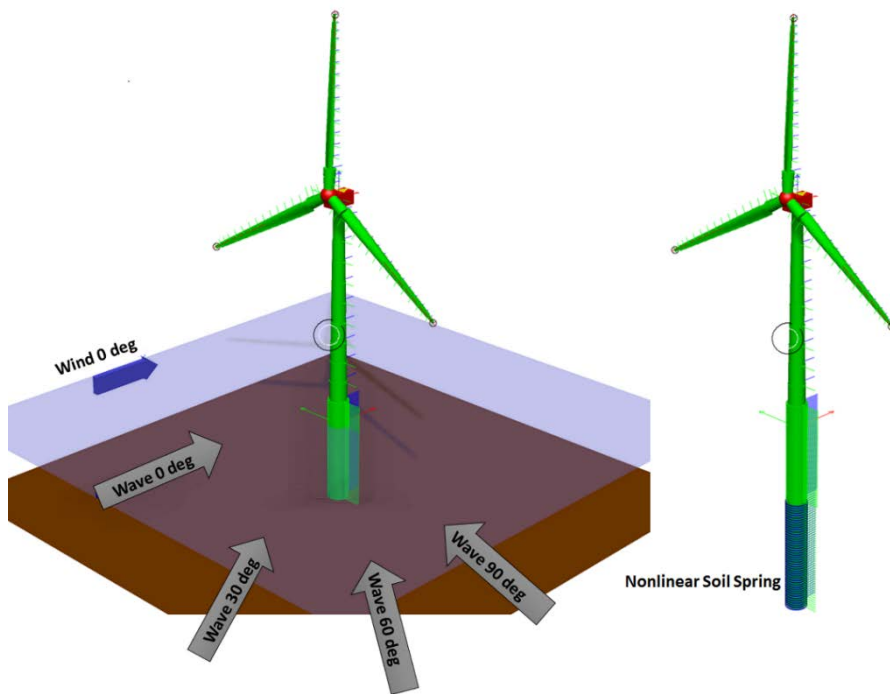


Figure 2: Bottom-fixed wind turbine model in SIMA, also showing wind and wave directions.

Table 1: Main characteristics of the bottom-fixed wind turbine

Water depth (m)	30
Pile diameter (m)	7
Thickness of pile (cm)	6
Embedded length of pile (m)	46
Turbine (tower + RNA) mass (kg)	600E3
Pile mass (from seabed to tower, dry) (kg)	450E3
Pile mass (below seabed, dry) (kg)	500E3
Torsional spring stiffness* (Nm/deg)	1.4 E+09

*See Section 3.

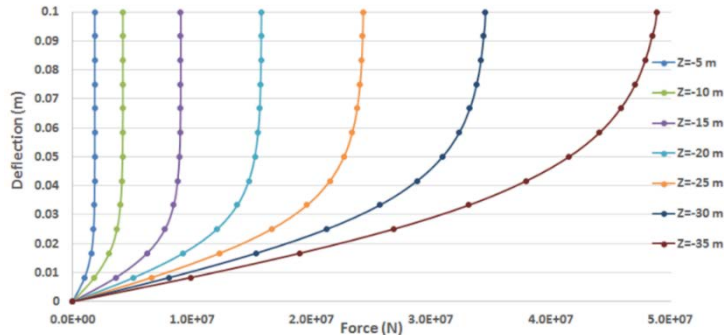


Figure 3: Deflection-force relation for distributed nonlinear soil-pile spring along the pile (Z-axis is upward at seabed), refer to [12]

3. Simplified model

In order to make the study more relevant for the planned model tests, the effect of the distributed soil stiffness was replaced with a single linear torsional spring, with the stiffness given in Table 1. The first two mode shapes and eigenfrequencies were compared to ensure that the simplified modelling could approximate the more complex model. Figure 4 presents the comparison of the mode shapes, while natural frequencies are presented in Table 2. As it is clear, the eigen-modes and eigen-frequencies agree well.

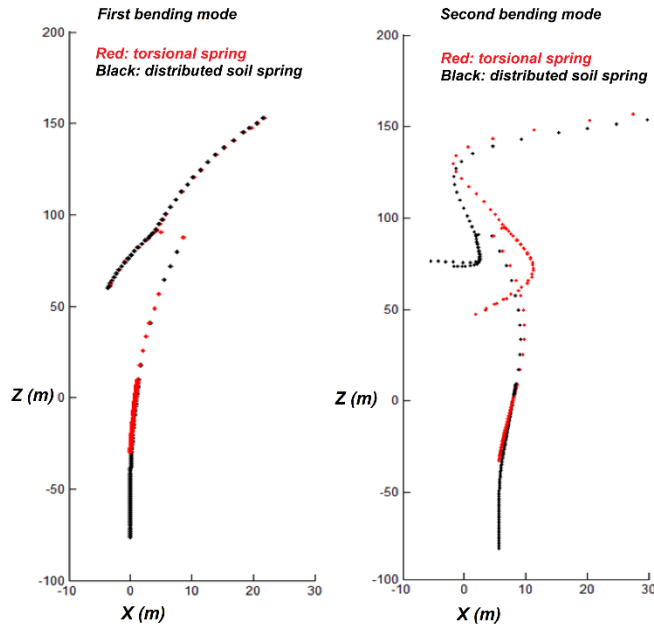


Figure 4: First and second bending fore-aft mode shapes of the monopile bottom-fixed wind turbine.

Table 2: Comparing the effect of the distributed springs versus single torsional spring on the bending modes

Mode	Nonlinear distributed springs (below the seabed)	Single torsional spring (at seabed)
First bending mode (Hz)	0.261	0.261
Second bending mode (Hz)	1.239	1.423

4. Selected load cases

Four basic environmental conditions (ECs) were considered for the sensitivity study, as shown in Table 3. These conditions were based on the joint wind-wave distribution for Site 15 presented in [13]. For each condition, the mean wind speed U_w , significant wave height H_s , peak wave period T_p , and turbulence intensity I are shown, based on one-hour mean wind speed at 10m height and one-hour sea states. The normal turbulence model (NTM) for class C

turbines according to the IEC-61400-1 guideline [14] was selected. The four conditions were chosen in order to examine responses in below-rated (EC 1), rated (EC 2), above-rated (EC 3), and storm (EC 4) conditions. EC4 represents the 50-year return period mean wind speed, while the most probable H_s and T_p given were used for the other conditions. For each of the ECs, four wave directions were considered, as illustrated in Figure 2. The wind direction was always taken to be 0° , and the turbine rotor was always aligned with the wind. For the dynamic simulations, the long-crested waves were generated according to a two-parameter JONSWAP spectrum, with time step $dt=0.1$ s and frequency resolution 0.001 rad/s. The wind field was generated in TurbSim [15] for a 32 x 32 grid covering an area of 150 m x 150 m, with step $dt=0.05$ s.

Table 3: Environmental conditions

	EC 1	EC 2	EC 3	EC 4
Uw (m/s)	8	11.4	20	31.5
Hs (m)	1.2	1.8	3.6	9.5
Tp (s)	5.8	6.5	8.2	12.3
I% (NTM)	17.1	14.0	11.5	11.0

This paper also investigates which forces and moments should be actuated when considering three particular fault cases, defined in the same way as in [16]. During grid loss, the generator torque is lost, and the turbine is shut down by pitching all three blades quickly to feather. Blade seize indicates that one of the blades loses the ability to pitch and stays fixed at its instantaneous orientation. Blade seize may be followed by shutdown, where the two remaining blades are pitched to feather. The fault cases were only considered for EC2, and are summarized in Table 4.

Table 4: Fault cases (EC 2)

Fault case	time of occurrence (sec)	time delay before shutdown (sec)
Grid loss (with shutdown)	1000	0.1
Blade seize (without shutdown)	1000	-
Blade seize (with shutdown)	1000	0.1

5. Baseline platform performance

The performance of the BFWT as predicted by SIMO-RIFLEX-AeroDyn (without the imperfections or artifacts induced by the ReaTHM® testing setup) is summarized in this section. These results are considered the baseline results for further comparison. Figure 5 shows the variation of the standard deviation of selected responses as a function of the wave direction. $\zeta_1, \zeta_2, \zeta_4, \zeta_5, \zeta_6$ stand for nacelle motion responses: surge, sway, roll, pitch and yaw, respectively. These motions represent the deflection at the top of the tower. In Figure 5, BMT and SFT are the bending moment and shear force at the bottom of the tower while BMP and SFP are the bending moment and shear forces of the pile at the seabed. In addition, FA and SS subscripts stand for the direction of the load, fore-aft or side-side, respectively.

The torsional moment is not shown in Figure 5, but the yaw motion and torsion are highly correlated. The lowest point on the tower is fixed in yaw rotation, the only stiffness in yaw comes from the monopile and tower cross sections (i.e., no torsional soil stiffness is modelled), and there is no hydrodynamic excitation in yaw. For small angles of rotation (yaw), the yaw at the nacelle is thus linearly related to the torsional moment.

As shown in Figure 5, the side-side motion and loads such as roll, sway, BMT_{SS} , BMP_{SS} , SFT_{SS} and SFP_{SS} increased with increasing wave angle while the fore-aft motion and responses decreased. The responses are largest in EC4.

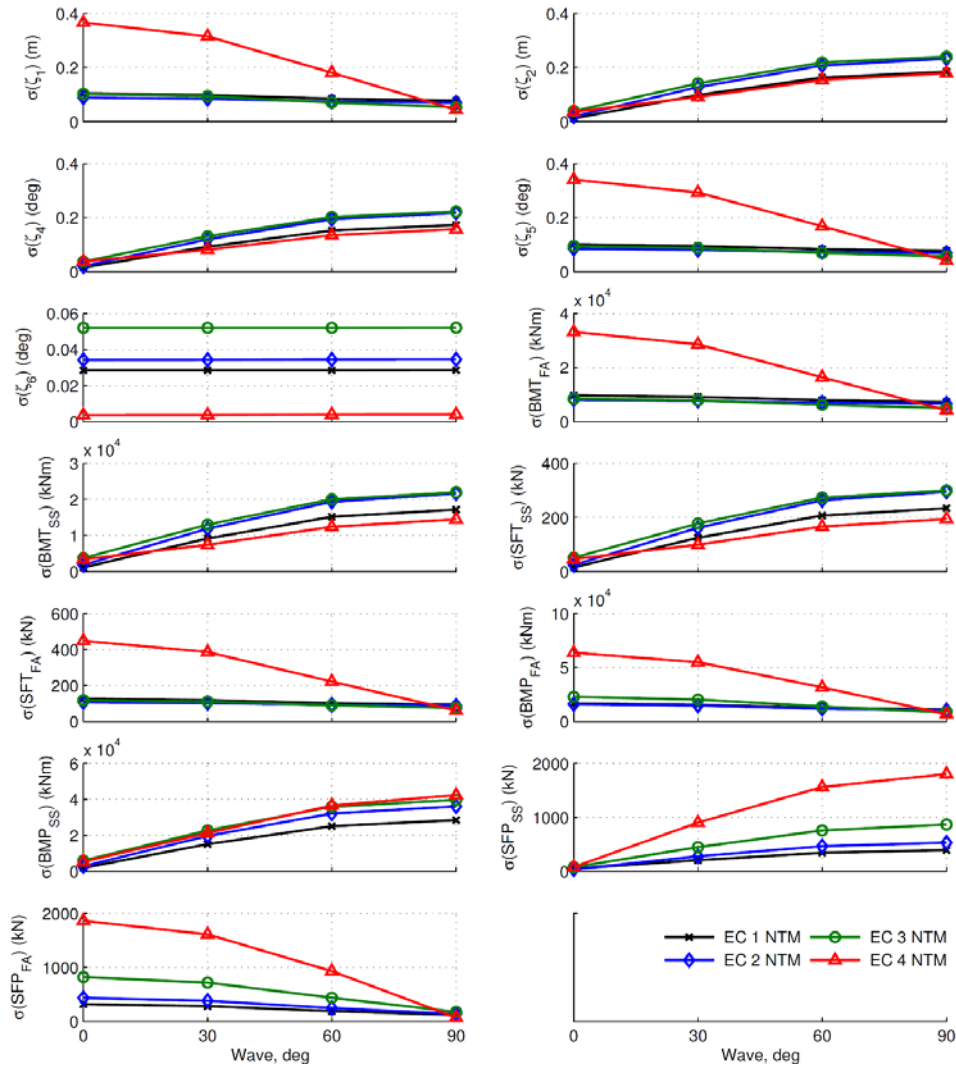


Figure 5: Standard deviation of selected responses of the BFWT, baseline case (note variations in vertical scale).

6. Effects of limited actuation in operational and parked conditions without fault

6.1. Wind loads in storm conditions

When the wind turbine is parked in extreme weather conditions, one may hypothesize that the aerodynamic forces become negligible compared to the wave-induced responses. In that case, it could be reasonable to perform a pure hydrodynamic test. In order to determine whether or not the aerodynamic loads should be included in storm conditions, simulations were carried out with and without the wind loads. As shown in Figure 6, the standard deviation of the responses was smaller for the wave-wind case than for the wave-only case. Even in a parked condition, aerodynamic damping of the turbine was important for the system dynamics, as has been previously observed [17]. Due to the orientation of the blades (pitched to feather), the effect of aerodynamic damping was more important for the side-side responses than for the fore-aft responses. For example, the standard deviation of the wave-only BMTFA in zero degree waves was approximately equal to BMTSS for 90 degree waves, but aerodynamic damping reduced the responses more in the 90 degree waves.

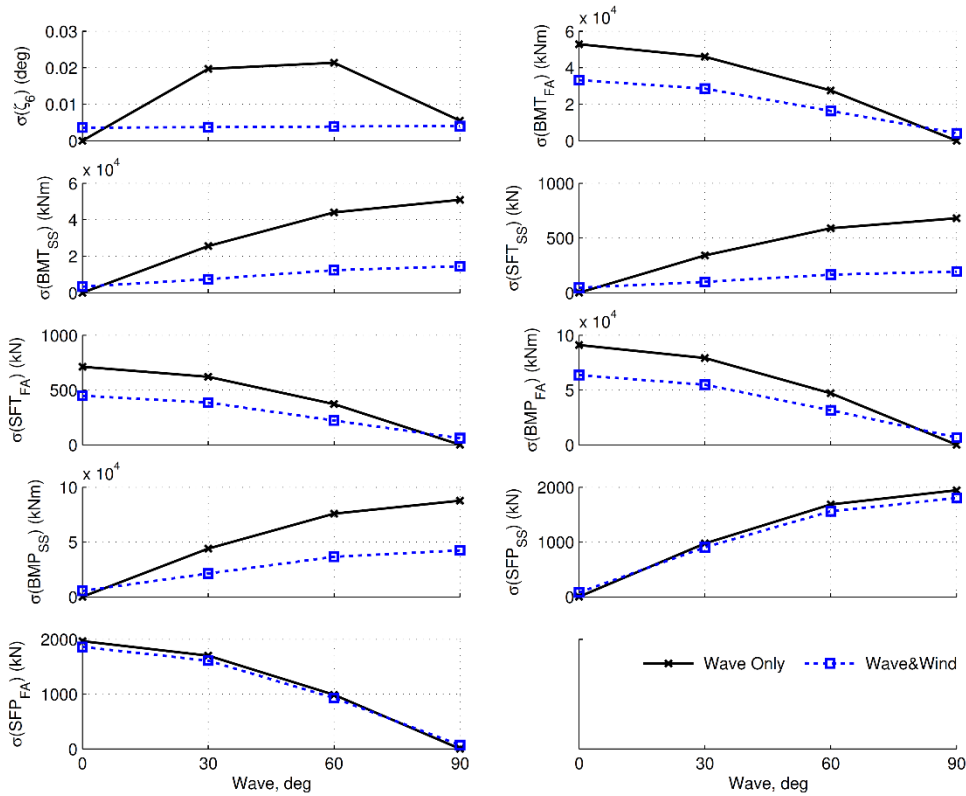


Figure 6: Wave-only and wave-wind-induced responses for the parked turbine, standard deviation of selected responses of the BFWT in storm sea state (EC 4).

6.2. Dynamic torque

The substructure of the turbine experiences the rotational loads on the turbine through the generator torque. In the laboratory, the mean torque could be including using a weight or static mechanism, while the dynamic generator torque would require real-time actuation. When the dynamic generator torque was removed, EC 2 was most affected. For the given control system, which prescribed constant power when the wind speed was above rated, the effects of temporal variation in the generator torque were mainly seen in ECs 1 and 2, and the torque variations were larger in EC 2. From Figure 7, one can see that removing the dynamic generator torque had a significant relative effect on the side-side tower and pile base bending moments, but the effect was only important for waves from zero degrees, such that the absolute magnitude of the effect was small.

6.3. Aerodynamic pitch moment

The local aerodynamic moment on the rotor in pitch - not to be confused with the aerodynamic pitch moment on the platform due to the thrust force – is studied here. The aerodynamic rotor pitch moment depends on the turbine tilt, wind shear, turbulent wind, and the motions of the nacelle. For most of the responses of interest, removing the aerodynamic pitch moment resulted in less than 5% change in the standard deviation. As shown in Figure 8, the side-side tower and pile bending moments in zero-degree wave direction were more significantly affected, but these responses are considered negligible when the wind and waves are acting in the x-direction. The relatively small effect of the aerodynamic pitch moment for the BFWT is in contrast to its importance for the pitch motions of the floating wind turbine studied previously [4]. In the case of the BFWT, however, the low-frequency aerodynamic pitch moment did not excite significant responses, while the motions of the floating wind turbine were sensitive to low-frequency excitation.

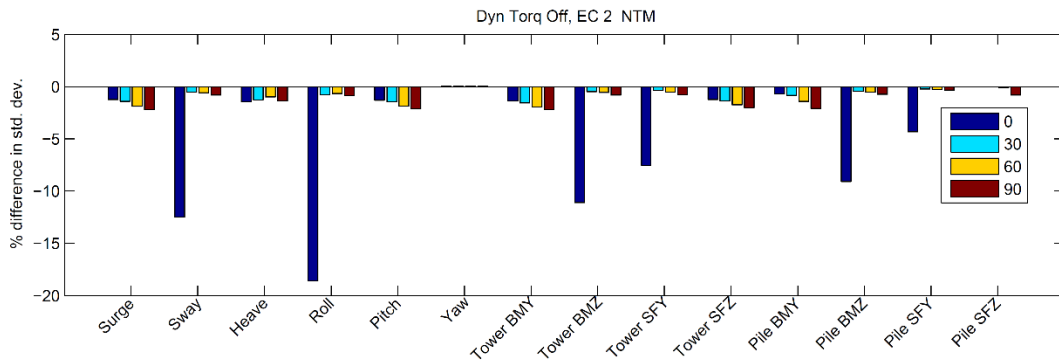


Figure 7: Relative change in the standard deviation of responses in EC2 with dynamic torque removed compared to the base case.

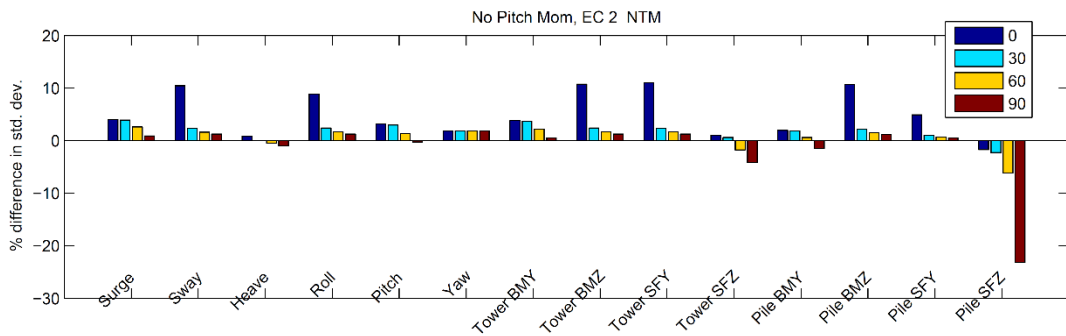


Figure 8: Relative change in the standard deviation of responses in EC2 with aerodynamic pitch moment removed compared to the base case.

6.4. Aerodynamic sway force

In operational conditions, the aerodynamic sway force – the horizontal force which is perpendicular to the wind direction – was seen to have little effect (less than 5%) on the dynamic responses of the monopile wind turbine. The most significant effect of limiting the actuation of the sway force appeared in EC 4 when the turbine was parked with feathered blades. The standard deviation of the fore-aft bending moment at the bottom of the turbine and at the seabed increased by about 7% compared to the baseline results, as shown in Figure 9.

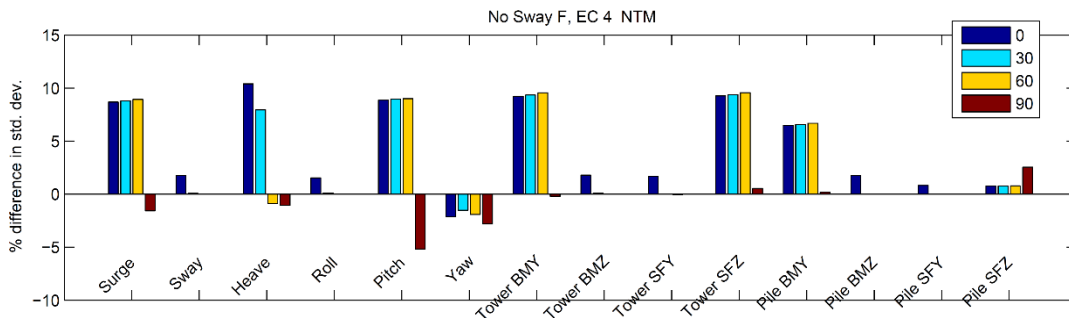


Figure 9: Relative change in the standard deviation of responses in EC4 with aerodynamic sway force removed compared to the base case.

6.5. Aerodynamic yaw moment

Limited actuation of the aerodynamic yaw moment was seen to primarily affect the yaw (and torsional moment) responses of the wind turbine, while other responses of interest were generally not significantly affected. For the above-rated wind speed load case (EC 3) shown in Figure 10, the yaw response is reduced by almost 80% when the aerodynamic yaw moment is removed. Although the yaw response is generally small, and the yaw excitation is primarily at low frequencies, if the objective of the tests is to study the torsional responses, actuation of the yaw moment is needed.

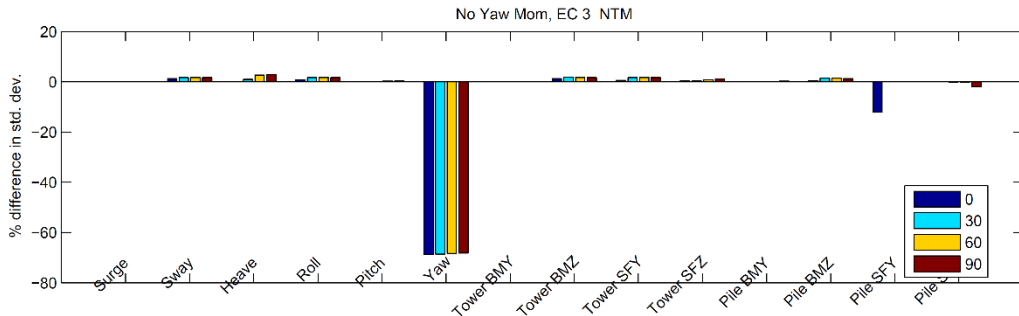


Figure 10: Relative change in the standard deviation of responses in EC3 with aerodynamic yaw moment removed compared to the base case.

7. Baseline platform performance under fault conditions

Before examining the effects of limited actuation on the response of the BFWT under fault conditions, the baseline responses to fault are summarized in this section. Figure 11 compares different fault conditions versus the operational case without any fault.

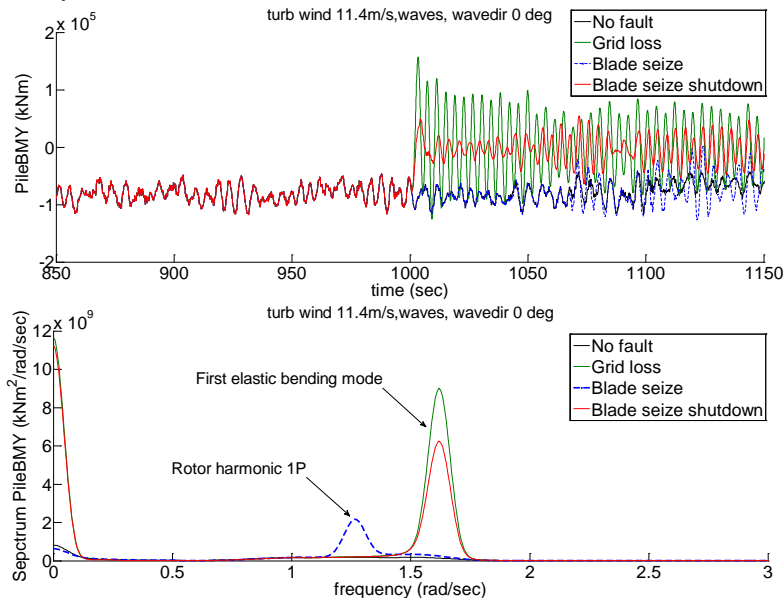


Figure 11: Time series (up) and spectra (down) of the fore-aft bending moment of the pile at the seabed. Different fault cases (grid loss, blade seize and blade seize with shutdown) are compared versus the operational case without any fault at rated wind speed (EC 2).

The bending moment of the pile at the seabed was sensitive to the fault cases. In particular, grid loss and blade seize with shutdown resulted in very large responses. Following grid loss, the turbine shut down quickly (using all three blades) and the subsequent rapid change in thrust excited the first mode of the structure. Shutdown following blade seize (with only two active blades) was somewhat slower and gave a smaller transient response. When blade

seize is not followed by shutdown, the 1P excitation from the imbalanced rotor can be seen in the spectrum of the fore-aft bending moment. Figure 12 shows the variation of the absolute maximum in the selected responses as a function of the wave direction. The responses are shown for different fault cases, grid loss, blade seize and blade seize with shutdown.

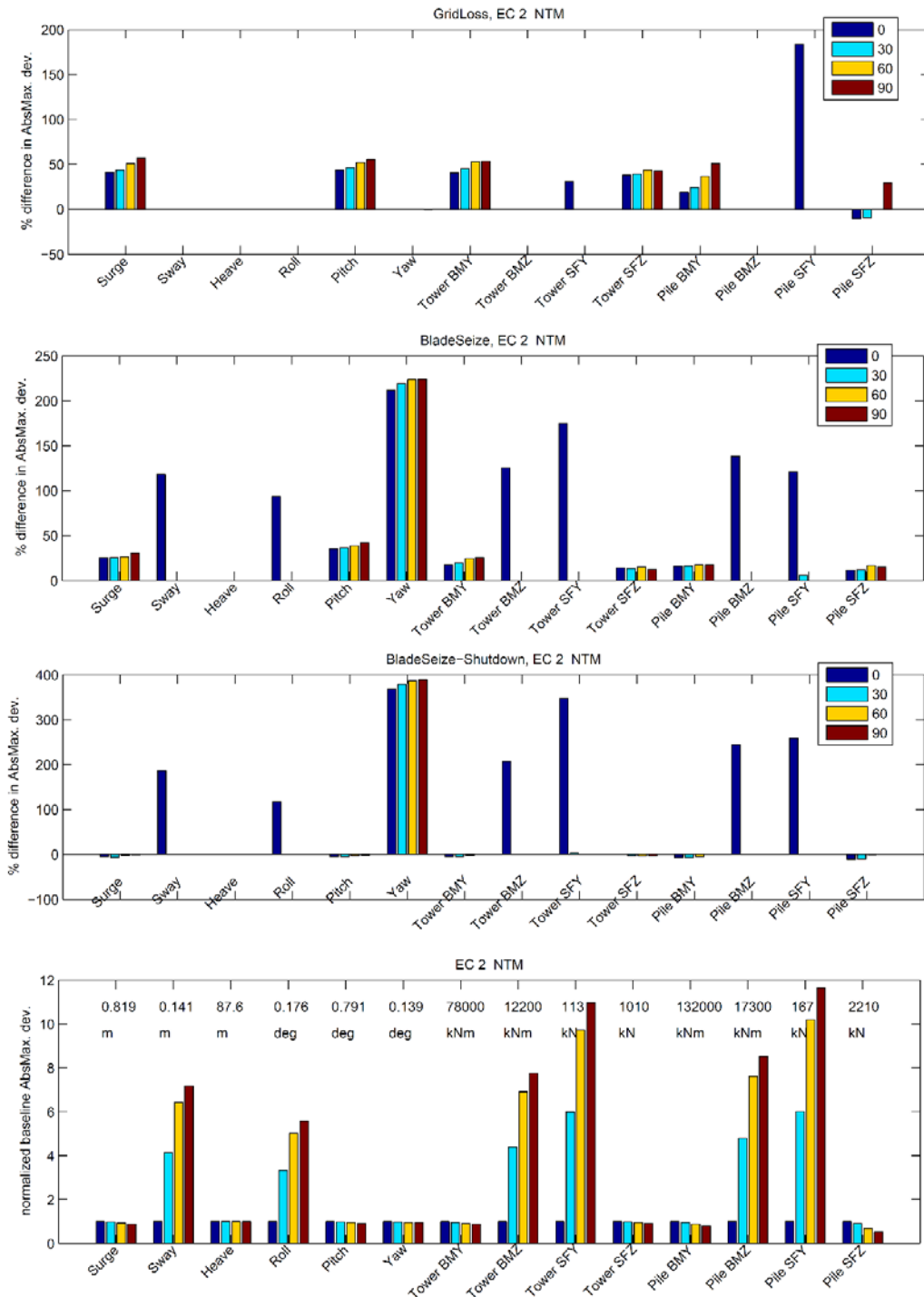


Figure 12: Absolute maximum of selected responses of the BFWT, baseline case with and without faults (note variations in vertical scale).

The last subplot in Figure 12 corresponds to the base case with normal operational condition without any fault included (the values of the responses are shown as well at the top of this subplot). As with the standard deviation, the maximum values of side-side motion and loads such as roll, sway, BMT_{SS} , BMP_{SS} , SFT_{SS} and SFP_{SS} increased when increasing the wave angle while the fore-aft motions and responses decreased. The magnitude of the structural responses was highly affected by fault cases compared to normal operational cases, which explains why these cases should be included in laboratory testing. The effects of limited actuation for the fault cases is described in the next section.

8. Effects of incomplete actuation for fault cases

For most of the responses of interest, the effects of limited actuation on the maximum responses due to fault are limited (less than 5%). Two exceptions are found: the aerodynamic pitch moment was important for blade seize, and the aerodynamic yaw moment was important for yaw/torsional responses. The aerodynamic pitch moment could affect the maximum pile and tower bending moments by about 20%, as illustrated in Figure 13. Removing the aerodynamic yaw moment gave errors up to a factor of two, but only on the yaw/torsional moment.

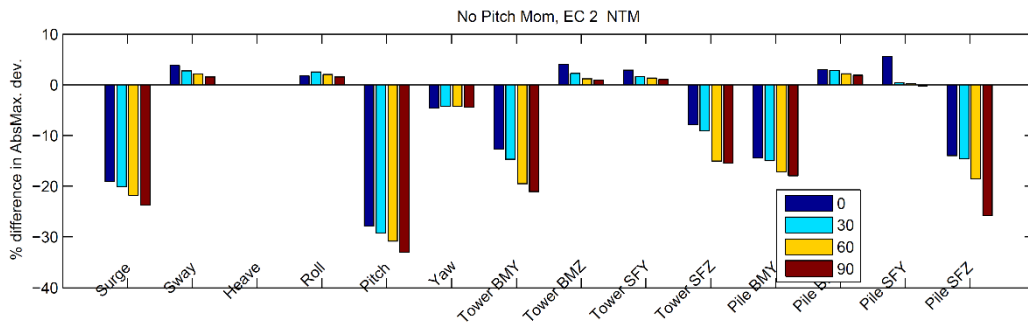


Figure 13: Effect of no pitch moment for different responses (up), the difference of responses respect to response for the base case with blade seize fault (at the same direction of the wave) are shown in percentage.

9. Conclusions

Sensitivity analyses were performed to investigate the importance of limited actuation of aerodynamic and generator loads for the responses of a 5MW bottom-fixed turbine. In normal operational cases, the dynamic torque, and aerodynamic sway force and pitch moment were not significant for the selected motion and structural responses. The aerodynamic yaw moment was only important for the yaw/torsional responses, but the sensitivity was quite high (up to 80% changes in the dynamic responses). In contrast to the floating offshore wind turbine, these results suggest that much more limited actuation may be acceptable for the BFWT.

The aerodynamic forces cannot, however, be completely ignored. Even in severe conditions with a parked turbine, aerodynamic damping had a significant effect on the responses. The inclusion of the thrust force and aerodynamic sway force should therefore be considered for the parked conditions.

This study also included the effects of limited actuation for blade pitch and grid loss faults, where the maximum transient responses are of interest. As in the operational cases, the yaw moment was seen to have important effects on the yaw/torsional responses. Unlike the operational cases, the aerodynamic pitch moment was found to be important for fault conditions. Removing the aerodynamic pitch moment induced errors up to 20% for some important load actions, i.e. pile and tower fore-aft bending moments.

10. Acknowledgement

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