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Real-time hybrid model testing of floating wind turbines: sensitivity to limited actuation

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Abstract

Real-time hybrid model testing (ReaTHM) is a new approach for conducting small-scale experimental campaign [1,2,3]. In the case of a floating wind turbine in a wave basin, the aerodynamic loads on the wind turbine may be applied based on simultaneous simulations (coupled to the experiments), while the wave loads and floater response are physically tested. The objective of this paper is to demonstrate the effects of actuation limitation on the ReaTHM testing setup for a particular platform: numerical simulations are employed to examine the effects of not including some components of the aerodynamic loads (or of inducing error, for example in the direction of the force actuation).

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Keywords: offshore wind energy; floating wind turbines; real-time hybrid testing

1. Introduction

Floating wind turbines (FWTs) are an emerging technology which can be used to generate electricity from the significant wind resource in relatively deep water (>50 m). Model tests are an important part of the qualification process for such novel concepts, but there are challenges related to scaling physical tests including both wind and waves. Hydrodynamic tests generally follow Froude scaling, but a consistent scaling of the wind turbine will then result in low Reynolds number and generally poor aerodynamic performance. Although non-geometrical scaling

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(ie, modifications of the airfoils and chord length) can help improve the turbine performance in a wave basin, it is not currently possible to match the thrust, torque, and slope of the thrust curve adequately [4,5].

In addition to the torque and thrust, accurate modeling of other aerodynamic forces and moments (such as the sway force and yaw moment), including the effects of the wind turbine control system, may be important. When the experimental goal is to qualify the global performance of the system, it may be more accurate to apply a so-called ``hardware-in-the-loop" or ``real-time hybrid testing" approach: in the case of the FWT in the wave basin, this implies that the aerodynamic forces 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 [2,3]. Figure 1 illustrates the concept of real-time hybrid testing for a FWT. The platform motions are measured and passed to the numerical simulator, and actuators apply appropriate aerodynamic/generator forces and moments based on the results of the numerical simulations.

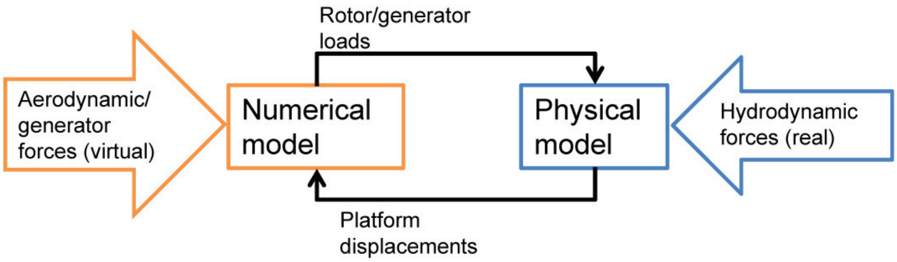

Figure 1: Real-time hybrid testing (ReaTHM) for a FWT in a wave basin

In order to design a real-time hybrid testing campaign of a FWT 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 the 5-MW-CSC (NOWITECH) semi-submersible wind turbine [6] with rigid blades was modeled in the coupled simulation tool SIMO-RIFLEX-AeroDyn [7]. After establishing the baseline behavior of the complete 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. The aerodynamic thrust and generator torque are generally considered to have the most significant effects on floating platforms, but the importance of the other loads has not been established. This study considers the effects of removing:

- Gyroscopic moments,
- non-thrust aerodynamic loads: pitch moment, yaw moment, sway force, heave force,
- dynamic variation of generator torque, and
- thrust directionality.

In the simulations, the blade loads were modified within the aerodynamic module before being applied as distributed loads in the structural module. The modified analysis tool, platform under consideration, and environmental conditions are described in Section 2. Results for the baseline simulations are presented in Section 3.1, and the sensitivity to limited actuation is presented in Section 3.2.

2. Methodology

2.1. Modified SIMO-RIFLEX-AeroDyn simulation tool

The aero-hydro-servo-elastic simulation tool SIMO-RIFLEX-AeroDyn has been used to study numerous types of floating wind turbines [7,8,9]. SIMO-RIFLEX-AeroDyn comprises three integrated computer codes: SIMO (from MARINTEK), which models the rigid body hydrodynamics of the hull; RIFLEX (from MARINTEK), which includes the finite element solver, flexible elements for the mooring lines (or tendons), tower, shaft, and blades, and the link to an external controller; and AeroDyn (from NREL), which 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 [10]. The generator torque and blade pitch control system is written in Java.

In order to study the effects of limited actuation, modifications were introduced into the AeroDyn component of SIMO-RIFLEX-AeroDyn, as indicated by the dashed box in Figure 2. Essentially, the differential aerodynamic forces on each element are first expressed in the tower-fixed rotor coordinate system, then modified (for example, by removing the aerodynamic yaw component), then expressed in their local frame before AeroDyn returns the forces to the structural solver (RIFLEX). Mathematical details of the modifications to AeroDyn are not included here.

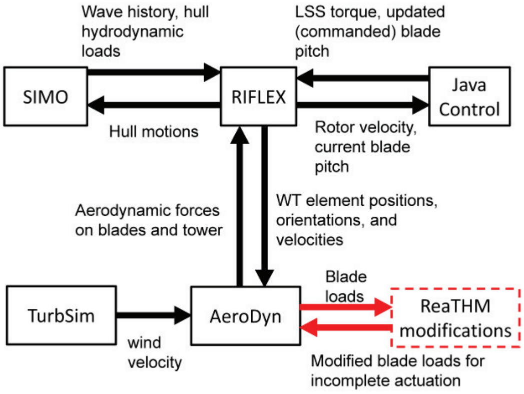

Figure 2: Floating wind turbine simulation using SIMO-RIFLEX-AeroDyn including ReaTHM modifications

2.2. Platform characteristics

The studied platform, referred to as the 5-MW-CSC semi-submersible, is a steel semi-submersible with three offset columns and a central column supporting the wind turbine [6]. Its design has been supported through the NOWITECH program. The main particulars of the platform (excluding the wind turbine) are listed in Table 1.

Figure 3 shows the complete semi-submersible wind turbine as modeled. The natural periods for the rigid body motions of the platform are listed in Table 1. The surge and sway periods are somewhat shorter than those of other well-studied semi-submersible platforms (for example, the generic WindFloat 5MW design [11] and the OC4 design [12]), while the heave period is slightly longer, in order to avoid wave excitation, and the rotational periods are similar.

2.3. Environmental Conditions

Four basic environmental conditions (ECs) were considered for the sensitivity study, as shown in Table 2. These conditions are based on the joint wind-wave distribution for the North Sea proposed by Johannessen et al. [13]. For each condition, the mean wind speed U, significant wave height H_s, peak wave period T_p, and turbulence intensity *I* are shown. Two different turbulence models were considered for each condition: the normal turbulence model (NTM) and extreme turbulence model (ETM) for class C turbines according to the IEC-61400-1 guideline [14]. 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.

Table 1: 5-MW-CSC semi-submersible hull main particulars

Diameter of center and offset columns	6.5 m	Surge natural period	80 s
Pontoon height	6.0 m	Sway natural period	80 s
Pontoon width	9.0 m	Heave natural period	26 s
Distance from center column midpoint to pontoon edge	45.5 m	Roll natural period	31 s
Draft	30.0 m	Pitch natural period	31 s
Freeboard	20.0 m	Yaw natural period	62 s
Water depth	200.0 m		
Anchor point radius	884.3 m		
Mooring line dry mass (total)	258 tonnes		
Hull dry steel mass (excluding turbine and tower)	1686 tonnes		

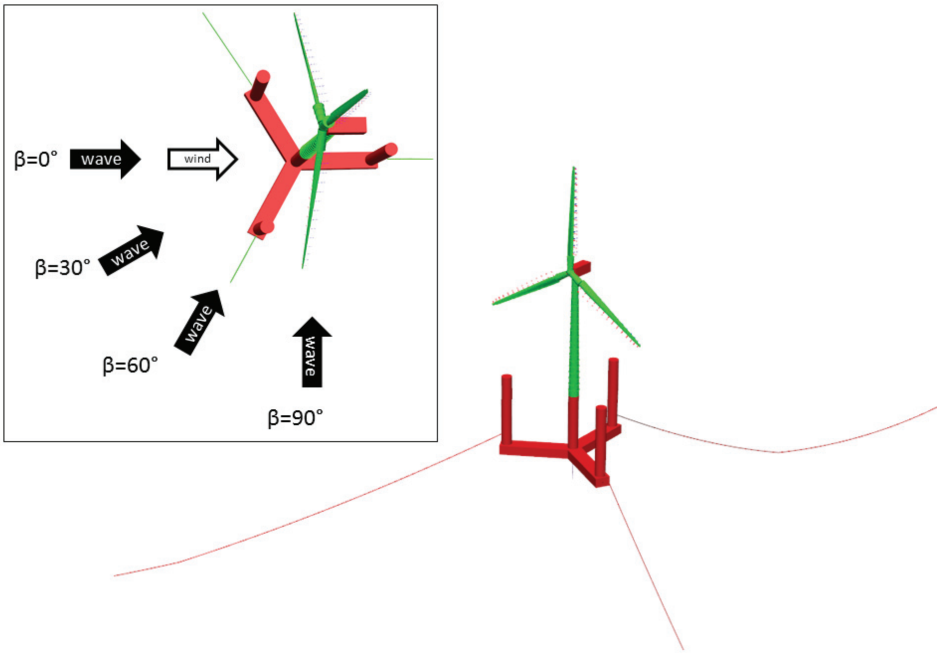

Figure 3: NOWITECH semi-submersible model in SIMA (MARINTEK's workbench for SIMO, RIFLEX, and more) also showing wave directions.

For each of the ECs, four wave directions were considered, as illustrated in Figure 3. The wind direction was always taken to be 0°, and the turbine rotor was always aligned with the wind. The variation of the wave direction shows the effects of incomplete actuation in selected misaligned wind-wave conditions; the probability of encountering such conditions is not evaluated here.

For the dynamic simulations, the long-crested waves were generated according to a two-parameter JONSWAP spectrum, with time step $dt = 0.005$ s and frequency resolution $d\omega = 0.001$ 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 2: Environmental conditions

	EC 1	EC 2	EC 3	EC 4
U, m/s	8.0	11.4	20.0	49.0
H_s, m	2.5	3.0	5.9	14.4
T_p, s	9.8	10.1	11.3	13.3
I, % (NTM)	17.1	14.0	11.5	10.0
I, % (ETM)	28.1	23.2	15.7	10.7

3. Results

3.1. Baseline platform performance

The performance of the NOWITECH semi-submersible as predicted by SIMO-RIFLEX-AeroDyn (without ReaTHM modifications) is summarized in this section. These results are considered the baseline results for further comparison in Section 3.2.

Figure 4 shows the variation of the standard deviation in the selected responses as a function of the wave direction. The surge (ζ_1) and pitch (ζ_5) motions, as well as the standard deviations of the tower fore-aft bending moment (M_{FA}) and downwind mooring line tension (T_1), tend to decrease as the misalignment between the wind and waves increases. The sway, roll, and yaw motions tend to increase, as does the standard deviation of the tower base side-side bending moment (M_{SS}).

As shown in Figure 4, the platform exhibits relatively small motions. The mean surge and pitch angle depend strongly on the thrust, with the maximum values seen at rated speed (7.18 m and 7.51°, respectively).

3.2. Effects of incomplete actuation

3.2.1. Aerodynamic non-thrust, non-torque loads

In addition to the aerodynamic thrust and the generator torque, which are generally considered to be the most important wind turbine effects for a FWT, there are several other aerodynamic loads which affect the platform. The effects of removing the local aerodynamic pitch moment (on the rotor), yaw moment, sway force, and heave force are considered in the follow sections.

3.2.1.1. 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 - contributes roughly 1-6 % of the total mean pitch moment on the platform, depending on the wind speed. The aerodynamic rotor pitch moment depends on the turbine tilt, wind shear, turbulent wind, and platform motions. Determining the importance of this moment is crucial in establishing the number of actuators required for ReaTHM testing.

In below-rated wind speeds, the aerodynamic rotor pitch moment was found to have small effects on the sway and roll motions (<5 %) and somewhat larger effects on the tower base fore-aft bending moment (M_{FA}). For the rated and above-rated operational conditions, the most important effects were on the pitch motions and line 1 tension. Changes in the standard deviation of 10-14 % were observed.

Interestingly, the increased pitch moment had little effect on the standard deviation of the tower base fore-aft bending moment (M_{FA}). Platform pitch motions are not the only cause of tower base bending, but one might expect a strong relation between ζ_5 and M_{FA}. The differences in the effects of the aerodynamic pitch moment are related to the different frequency ranges over which these effects are seen. Figure 5 shows the platform pitch motion spectrum (top) and corresponding tower base fore-aft bending moment spectrum (bottom) for different wave directions. As shown, removing the aerodynamic pitch causes an increase in low-frequency platform pitch (and a corresponding increase in the low-frequency M_{FA}) near 0.15 rad/s, while the effect on the wave-frequency (0.5-1.5 rad/s) component of both responses is limited. The wave-frequency component of M_{FA} is relatively important. Furthermore, removing the aerodynamic pitch moment reduces the high-frequency (2.4-4.0 rad/s) variation in M_{FA}, which gives an overall small change in the standard deviation. The difference in the high-frequency variation of M_{FA} is small, but spread over a wide range of frequencies.

Results for the removal of the aerodynamic pitch moment for the parked turbine (EC 4) are difficult to interpret due to the manner by which the tower forces are included. These results are therefore not commented upon here.

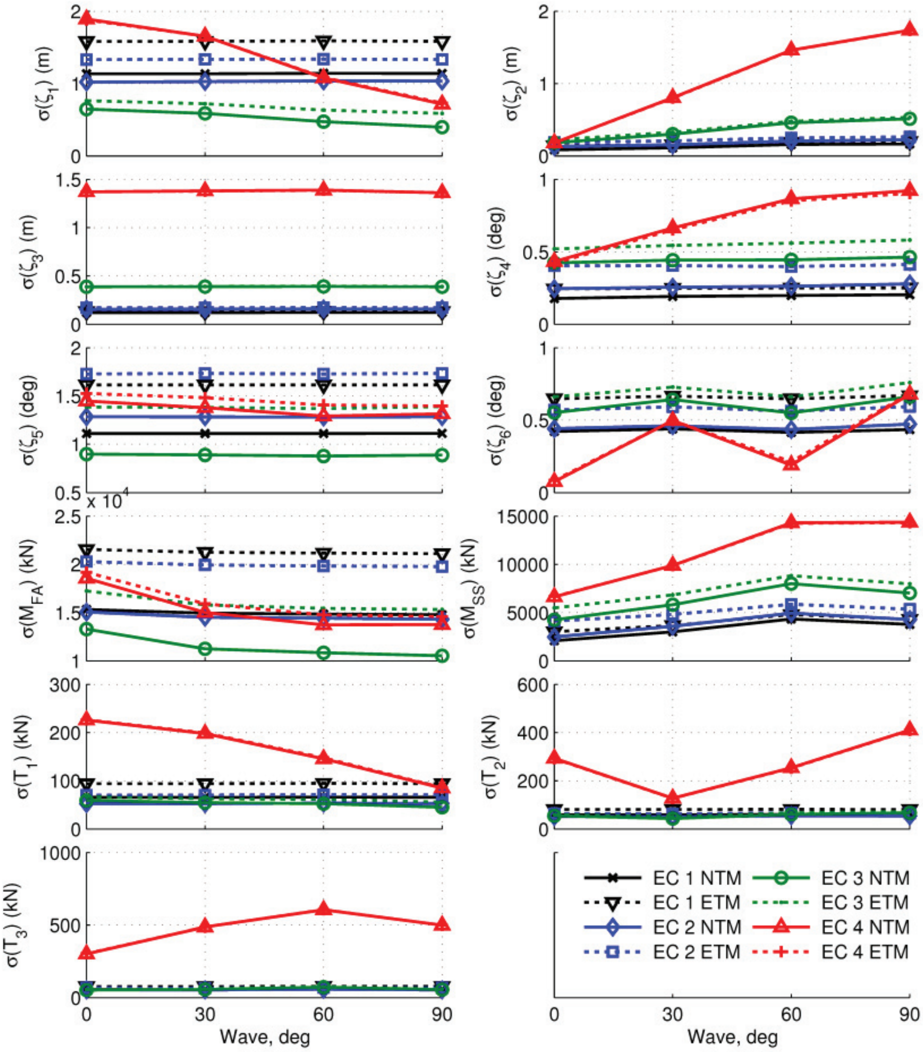

Figure 4: Standard deviation of selected responses of the NOWITECH semi-submersible, baseline case. Note variations in vertical scale.

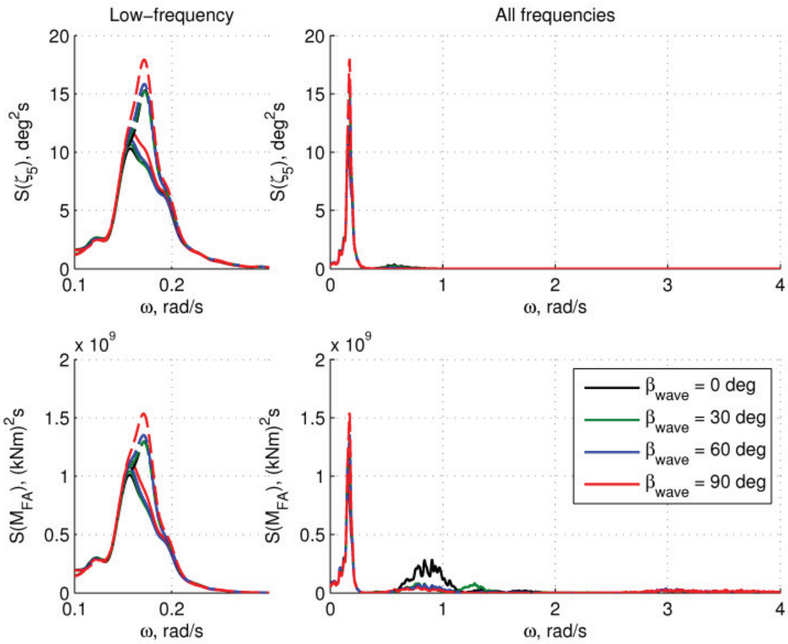

Figure 5: Effect of the aerodynamic pitch moment on the platform pitch motion (top) and tower base fore-aft bending moment (bottom), EC 3 NTM (above rated). Solid lines show the baseline case, while dashed lines show the removal of the aerodynamic pitch moment on the rotor.

3.2.1.2. Aerodynamic yaw moment

The inclusion of the aerodynamic yaw moment also has a large impact on the number of actuators required for ReaTHM testing. For this semi-submersible, the aerodynamic yaw moment was found to primarily affect the platform yaw motions.

In operational conditions, the standard deviation of the yaw moment decreased approximately 80 % when the aerodynamic yaw was not included. The effect of the aerodynamic yaw moment on the platform yaw was 2-10 % in the parked case. As shown in Figure 6, the change in the yaw motion was seen to be particularly important in the cases with the ETM, where the baseline yaw was relatively large. The yaw in the parked cases was seen to depend significantly on the wave direction; the yaw motions are small when the wind and waves are aligned.

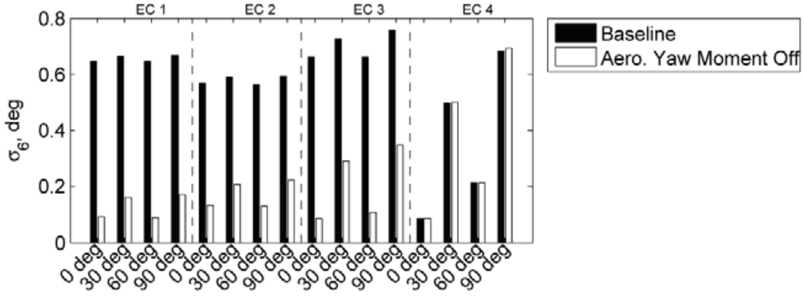

Figure 6: Effect of the aerodynamic yaw moment on the standard deviation of platform yaw motion ($\sigma_6 = \sigma(\zeta_6)$), ETM.

The nature of the effect of the yaw moment on the platform yaw motions in operational and parked cases is illustrated in Figure 7 and Figure 8, respectively. It should be recalled that the yaw moment is relatively small.

In the operational case (Figure 7), the low-frequency yaw motions are most important, and the aerodynamic yaw moment is seen to contribute an excitation. When the aerodynamic yaw moment is removed, the yaw motions decrease in the low-frequency range, while the yaw motions in the wave-frequency range are unchanged.

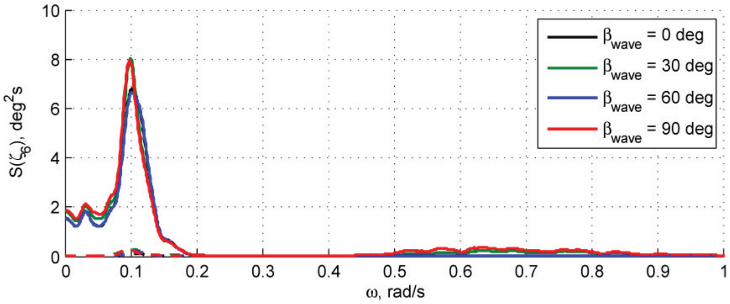

Figure 7: Effect of the aerodynamic yaw moment on ζ_6, EC 3 ETM (above-rated). Solid lines show the baseline case, while dashed lines show the removal of the aerodynamic yaw moment on the rotor.

In the parked case (Figure 8), the wave-frequency yaw motions are seen to be most important (and very dependent on the wave direction). The wave-frequency motions are unaffected by the aerodynamic yaw moment. On the other hand, in the parked condition, the low-frequency yaw motions tend to increase slightly when the aerodynamic yaw moment is removed, but this effect is most noticeable for the condition with 90° misalignment.

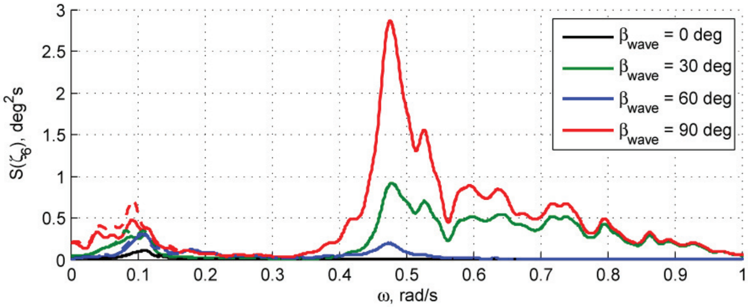

Figure 8: Effect of the aerodynamic yaw moment on ζ_6, EC 4 ETM (storm/parked). Solid lines show the baseline case, while dashed lines show the removal of the aerodynamic yaw moment on the rotor.

3.2.1.3. Aerodynamic sway force

The sway motion, roll motion, and tower side-side bending moment are affected if the aerodynamic sway force is not included. In aligned wind and wave conditions, this effect is seen to be up to 80 % change in standard deviation, with the relative effect tending to decrease with increasing misalignment. In some cases, however, this large relative increase is misleading: the sway motion, roll motion, and tower side-side bending moment are typically smaller than the corresponding surge, pitch, or fore-aft bending. Thus, a large relative change may nonetheless indicate a small absolute change.

The effects of the aerodynamic sway force are similar to the effects of the horizontal thrust directionality, as discussed in Section 3.2.3.1.

3.2.1.4. Aerodynamic heave force

The effect of the aerodynamic heave force on the platform motions, tower base bending moments, and mooring line tensions is small (<3 %) for operational conditions. The maximum relative effect for operational conditions is on the heave motion in EC 1 ETM.

The nature of the loads in the parked condition differs significantly from the loads in the operational condition. Two effects can lead to vertical aerodynamic loads: 1) the lift forces on the parked, feathered blades and 2) the drag forces on the slightly inclined tower. Removing these force components can affect the standard deviation of the surge, pitch, and yaw motions, as well as the tower fore-aft bending moment, by up to 15 % in EC 4. The effect on surge is most pronounced for 90° misalignment (where the surge is small), and the effect on yaw is most pronounced for 0° and 60° misalignment (where the yaw is smaller). The effect of the vertical force component on the pitch motions is consistent across different wind directions, and has more effect on the motions at the natural frequency than the wave-induced motions.

3.2.2. Dynamic generator torque

For the given control system, which prescribes constant torque when the wind speed is above rated, the effects of temporal variation in the generator torque are limited to ECs 1 and 2, where the wind speed is (at least at times) below rated. The primary effect of dynamic generator torque is seen on roll motions and on the side-side tower base bending moment. For ECs 1 and 2, the effect of ignoring the dynamic generator torque is seen to be a 4-9 % decrease in the roll standard deviation ($\sigma_4 = \sigma(\zeta_4)$), without a strong dependence on the wave direction. It should be noted, however, that σ_4 in these conditions is roughly 15 % of the value of the pitch standard deviation ($\sigma_5 = \sigma(\zeta_5)$), such that the absolute effect is relatively small.

3.2.3. Thrust directionality

In the ReaTHM testing in the ocean basin, the thrust force is expected to be actuated via a wire from an actuator which is external to the platform model. As such, the thrust force must act along the wire. The actuator may or may not be free to move horizontally and/or vertically; the two cases are considered separately here in Sections 3.2.3.1 and 3.2.3.2. In EC 4, the drag force on the tower is considered as part of the thrust force.

3.2.3.1. Horizontal thrust directionality

The sway motion, roll motion, and tower side-side bending moment are affected if the thrust actuator does not follow the motions of the hub in the horizontal plane. In aligned wind and wave conditions, the effect on the standard deviation is seen to be up to 80 %, with the relative effect tending to decrease with increasing misalignment. This result is approximately equivalent to removing the aerodynamic sway force (see Section 3.2.1.3).

In the cases where roll is non-negligible compared to pitch, such as EC 3, the removal of the thrust directionality can explain a 50 % change in the standard deviation of the roll motion. Figure 9 illustrates the importance of the horizontal directionality of the thrust for the roll motion.

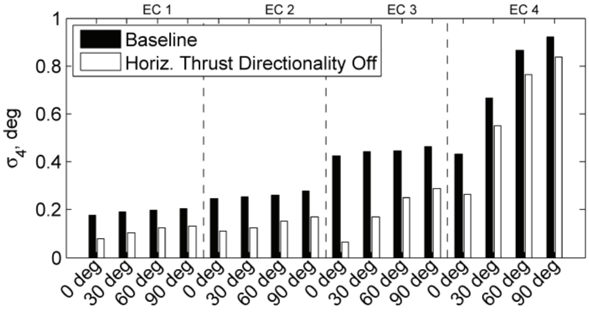

Figure 9: Effect of the horizontal thrust directionality on the standard deviation of platform roll motion, NTM.

The corresponding effect on the mooring line tension is limited to 10 % change in the standard deviation. Lines 2 and 3 are most affected, and the impact is largest in EC 3 with the ETM.

3.2.3.2. Vertical thrust directionality

The effect of vertical thrust directionality on the platform motions, tower base bending moments, and mooring line tensions was small (<5 %) for operational conditions. The maximum relative effect for operational conditions was on the heave motion in EC 2 ETM.

In the parked condition with extreme wind and waves, the vertical thrust directionality appeared to have greater importance. This is in agreement with the remarks in Section 3.2.1.4. The vertical directionality affected the standard deviation of the surge, pitch, and yaw motions, as well as the tower fore-aft bending moment, by up to 15% in EC 4.

3.2.4. Gyroscopic moments

The gyroscopic moment and centrifugal forces due to the rotation of the wind turbine rotor can be included in a hybrid model test using a spinning rotor with the correct mass distribution (without airfoils). These inertial couplings primarily affect the sway, roll, and yaw motions, and are only relevant for the operational conditions. As shown in Figure 10, when the gyroscopic effects were not included, there was up to a 5 % change in the standard deviation of the yaw motion. The effect was largest for EC 2 ETM.

The gyroscopic moment effect is seen at low frequencies, that is, near the yaw and pitch natural frequencies of the platform. Figure 11 shows the spectrum of the yaw motion with and without the gyroscopic moment.

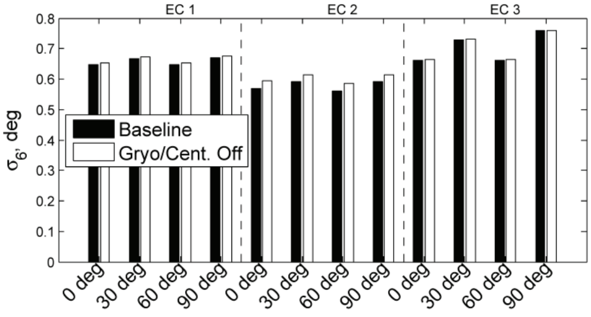

Figure 10: Effect of the gyroscopic moment on the standard deviation of platform yaw motion, ETM.

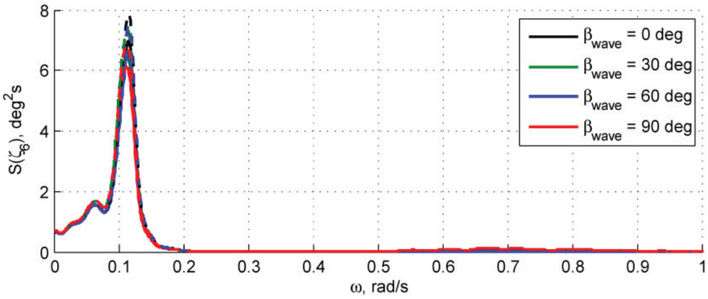

Figure 11: Effect of the gyroscopic moment on ζ_6, EC 2 ETM. Solid lines show the baseline case, while dashed lines show the removal of the gyroscopic moment

4. Conclusions

A methodology for investigating the sensitivity of ReaTHM testing of FWTs to limited actuation of aerodynamic forces was developed and employed. The studied FWT presented a challenge: the platform's small motions meant that the sensitivity of the responses to the non-thrust, non-torque loads was relatively large.

For the given platform, the non-thrust aerodynamic loads had varied effects on the responses. The aerodynamic pitch moment was important for both the pitch motions and mooring line tension (10-15 % changes in standard deviation), while the aerodynamic yaw moment primarily affected the yaw motions. The effect of the aerodynamic yaw moment was up to 80 % change in the standard deviation. Similarly, the aerodynamic sway force and the horizontal thrust directionality were very important for the sway and roll motions, but these motions were relatively small. The vertical directionality of the thrust was only important for EC 4 (storm/parked condition). The gyroscopic moment was found to have limited effects on the low-frequency yaw response, near the yaw and pitch natural frequencies of the platform, in operational conditions.

The present study illustrates the complexity of floating wind turbines: significant couplings were observed between aerodynamic loads and the platform responses. In part due to the large mass and small motions of the system, the relative effects of limited actuation on motions were large. In order to design the model tests, one must also consider which responses are of interest and the measurement accuracy. The observations from the sensitivity study, carried out using the presented methodology, will allow model test designers to make informed trade-offs between complexity and fidelity.

Acknowledgements

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