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Uncertainties assessment in real-time hybrid model for ocean basin testing of a floating offshore wind turbine

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Abstract. This work analyses the accuracy of large-scale experimental testing procedure in ocean basin facility involving real-time hybrid model testing (ReaTHM) techniques. The analysis is based on a scaled concept for a 15MW floating offshore wind turbine (FOWT) supported by a concrete semi-submersible platform (*ActiveFloat*) developed within the framework of the project *COREWIND*. The real-time hybrid model considered includes a multi-fan system located at the aero-rotor interface, which permits to generate the aerodynamic loads, reducing the limitations typically given by scaled problems. In order to assess the uncertainties in the hardware in the loop (HIL) implementation, firstly we define the quantities of interest to be evaluated from all the possible sources liable to inaccuracy identified. Then, we quantify the systematic and random discrepancies of the selected mooring, platform and HIL parameters. Finally, we propagate the previously quantified errors, running simulations in *OpenFAST* under extremal and severe environmental load cases in Gran Canaria Island (Spain) site. Comparing the platform response and mooring tensions of these uncertainty propagations with the ones of the unperturbed simulation as a baseline case, we analyse the effect of each representative parameter. Thus, the reliability of the results in ocean basin testing is numerically assessed, depending on the design load case.

1. Introduction

The design of floating offshore wind turbines (FOWTs) to be installed in deep waters, where the greatest potential of wind resource is found, is currently one the most challenging process in offshore engineering. The high complexity of the design process lies in the fact that it is strongly dependent on interconnected, highly non-linear dynamics, such as the hydrodynamic actions on the floater and the aerodynamic response of the turbine. Experimental tests with scale model in an ocean basin facility are a cost-effective tool for assessing second-order hydrodynamic effects and mooring lines dynamics, as well as for validating numerical models to simulate the whole system.

However, as we have just said, FOWTs are complex systems due to a strong coupling between forces coming from several physical phenomena. Their aero-hydro-servo-elastic dynamical behaviour is also influenced by structure flexibility, control system and aerodynamics. The problem of scale modelling is that Froude scaling laws adopted in ocean basin testing to reproduce gravity-influenced phenomena, results in too low Reynolds numbers, and thus in a deviated reproduction of viscous forces. In fact, if $\lambda = D_p/D_m$ is the scale factor with D being a characteristic dimension of the structure, and the Froude number is defined as



$$Fr = \frac{u^2}{gD} \quad (1)$$

with g being the gravitational acceleration and u the fluid velocity, this speed will be scaled with a ratio $\lambda^{1/2} = u_p/u_m$. Therefore, the Reynolds number defined as

$$Re = \frac{uD}{\nu} \quad (2)$$

with ν being the fluid kinematic viscosity, will be improperly scaled [1] with a ratio

$$\lambda^{3/2} = \frac{Re_p}{Re_m} \quad (3)$$

While this deviation may be neglected in water, leads to a consistent change in the associated aerodynamic thrust acting on the rotor [2]. Real-time hybrid model testing (ReaTHM) overcomes this issue by performing scale model testing only on a subpart of the whole structure, the remainder being simulated numerically [3]. In the case of experiments in an ocean basin facility, this approach also termed as hardware in the loop (HIL), calculates the aerodynamic loads acting on the virtual substructure from online-measured motions of the physical substructure and actuates them back on the latter in real-time (Figure 1 on the left). Note that to feed the numerical simulation in full scale, the time steps are upscaled based on the scaling ratio $\lambda^{1/2} = t_p/t_m$, and the aerodynamic forces are then scaled back in model scale based on the scaling ratio $\lambda^3 \cdot \rho_p/\rho_m = F_p/F_m$.

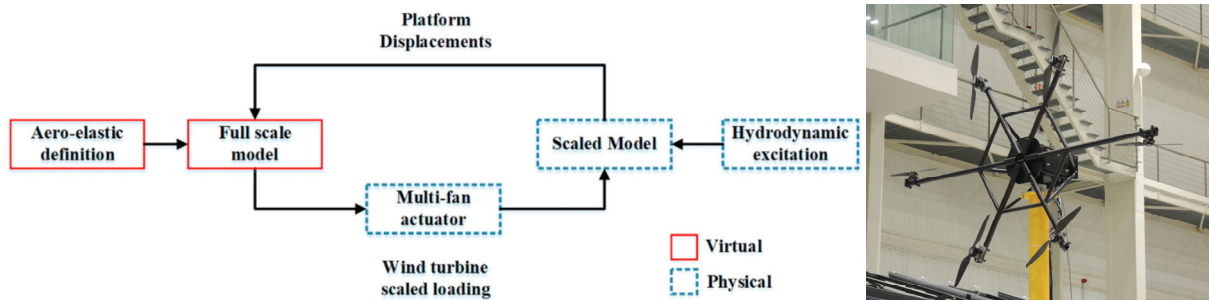


Figure 1. HIL scheme implementation (on the left) [4], and an overview of the multi-fan actuator system (on the right) [5].

Meseguer and Guanche [4], Battistella et al. [5] and Battistella et al. [6] described the implementation of the method based on the use of a multi-fan system as the actuator at hub height of the physical model. This system consists of up to six fans in which every rotor can be controlled singularly by electro-servomotors (Figure 1 on the right). Thus, each of the propellers produces its own thrust, what allow the reproduction of aerodynamic torque together with wind turbine thrust force. The numerical calculation of these wind turbine loads is carried out by an unsteady Blade Element Momentum (BEM) model, fed by the relative wind speed seen by the rotor. To process the necessary data, the positions of the platform in subsequent instants are recorded by *Qualysis*, which is a high-definition tracking system able to detect the entity of the six degrees of freedom.

The main bottle neck in hybrid testing using a multi-fan system is generally the reaction speed, requiring a long time to reach the requested load level. This delay provides a limit to track high frequency oscillations of loads by the multi-fan system [7]. Thus, a multi-fan system may act as a low-pass filter (LPF), not posing an issue to deliver wind turbine loads from platform motions dominated by wind excitations at low frequencies but struggling to represent variations of higher frequencies related to either wave motions or the rotational speed of the rotor. By simulating errors in the hybrid coupling system, the sensitivity of the floating wind turbine response to coupling quality can be quantified [8].

Nevertheless, to enhance understanding of how test results are affected by hybrid coupling quality, it would be necessary to take into account also the uncertainties due to both the floating platform and

the mooring system. The objective of the present work is to resume the uncertainties included in scaled model tests of floating wind turbines in wave tank layouts, focusing on the identification, quantification and propagation of the uncertainties related with the implementation and application of the HIL strategies. Therefore, uncertainty bounds on the response metrics of interest will be set, evaluating the accuracy of modelling tools and the levels of the test reliability.

2. Methodology

To assess the uncertainties in this HIL implementation, consisting of a multi-fan system located at the aero-rotor interface, firstly we need to identify all the possible sources liable to inaccuracy. Then, we might assign weightings to these uncertainty sources to optimize the approach neglecting the least important ones, and thus minimizing the number of simulations. Once the quantities of interest (QOI) to be evaluated are defined, next step of an uncertainty analysis is to select representative extremal and severe load cases [9] to propagate the previously quantified errors, running simulations in *OpenFAST* [10].

2.1. Definition of the quantities of interest

In hybrid testing, inaccuracies may arise from either numerical sub-model or physical sub-model or hybrid coupling between them. Although *OpenFAST* simulations in the time domain for the coupled dynamic response of floating wind turbines have certain limitations, we assume the numerical sub-model is ideal in order not to introduce more uncertainty in the propagation of the quantified errors. During wave basin test implementation, we also neglect inaccuracies both in the sea-state characterization and in the *Qualisys Track Manager* (QTM).

We focus our efforts on studying the effect of the tolerances when manufacturing the scale model and the impact of the multi-fan system limitations on the FOWT response. Hall et al. [8] quantified the sensitivity of the FOWT response to coupling quality due to its limitations in terms of measurement and actuation error levels, bandwidths and latency. Since we assume no inaccuracies either in the force actuation of the numerical model or in the motion tracking of the physical model, we will focus on the sensitivity analysis of limited force actuation bandwidth and latency in the overall coupling system's response.

Respecting the fabrication of the scale model, uncertainties may be associated to either the mooring lines or the platform properties. Barrera et al. [11] investigated the effect of the following mooring parameters on the tension at the fairlead: mooring line discretisation, structural damping, drag coefficient, hydrodynamic mass coefficient, stiffness, weight-diameter, friction coefficients and length. The sensitivity study showed a relevant dependence on the length, as well as significant on the weight-diameter. Likewise, platform parameters associated to dimensions and weight properties that define the geometry at the waterplane and the mass distribution, have a direct impact on the displacements and rotations of the floater response. The quantities of interest to be evaluated from all the possible platform parameters liable to uncertainty will be the most significant ones: the metacentric height (GM) and the inertia for pitch tilt rotation about the centre of mass (I_{yy}).

2.2. Uncertainties quantification

The reference offshore wind turbine is an original new concrete-based semi-submersible floater (*ActiveFloat*) supporting a large IEA Wind 15 MW rotor with a turbulence class IEC Class 1B [12]. The wave tank facility at IHCantabria is the *Cantabria Coastal and Ocean Basin* (CCOB) with 30 m length, 44 m width and a maximum water depth of 3 m. An appropriate length scale for ocean basin tests in this facility is 1/40 [13,14].

Robertson et al. [15] used a value of 0.1 m uncertainty in the full-scale geometric dimensions, while Kim and Hermansky [16] suggested a tolerance of $\pm 0.05\%$ of linear dimensions larger than 2 m. In the case of mooring system, as the unstretched lines length is 614 m in prototype scale [17], the latter tolerance would be more restrictive resulting a value of 0.307 m uncertainty. Respecting the weight, Robertson et al. [15] measured a systematic uncertainty of 0.616%, and a random one of

0.028%. Hence, the total standard uncertainty will be the 0.617% of the 561.252 kg/m as the mass per unit length of the line in prototype scale [17], i.e. 3.463 kg/m. Figure 2 shows the Probability Density Functions (PDF) of the Gaussian distributions for the most significant mooring parameters.

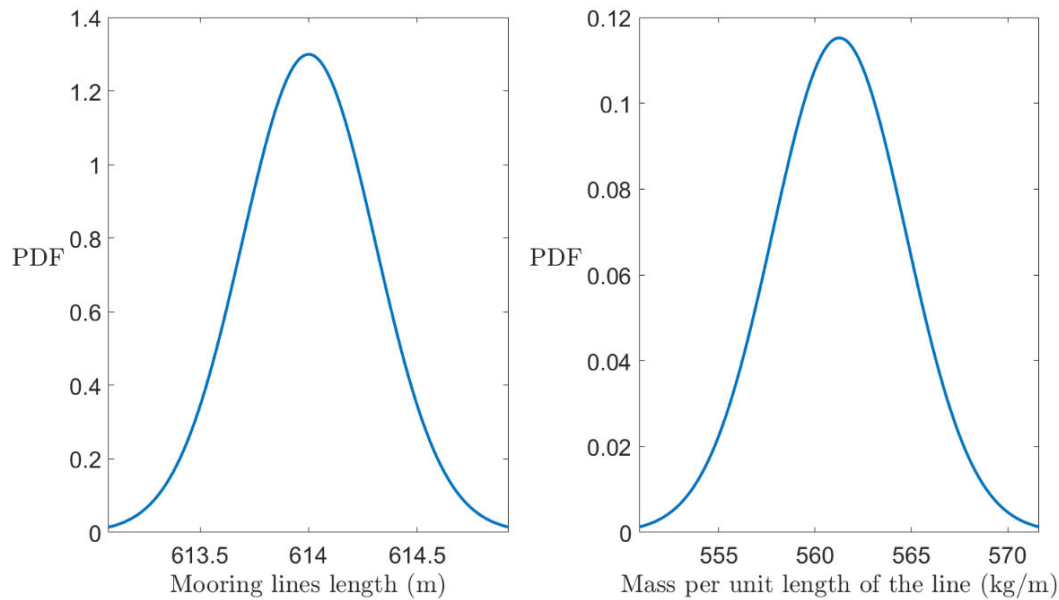


Figure 2. Normal distributions of mooring lines length and mass per unit length.

On the other hand, Robertson et al. [15] used a value of 0.05 m uncertainty in the full-scale geometric dimensions in the vertical distance from the mean sea level (MSL) to the centre of mass (CM), and thus in the metacentric height. The authors also suggested a systematic and a random uncertainty of 1% and 0.008%, respectively, when calculating the I_{yy} . Thus, the total standard uncertainty of the $45.825 \times 10^9 \text{ kg} \cdot \text{m}^2$ as the I_{yy} value in prototype scale, will be $0.458 \times 10^9 \text{ kg} \cdot \text{m}^2$. The Gaussian distributions of the platform parameters are plotted in Figure 3.

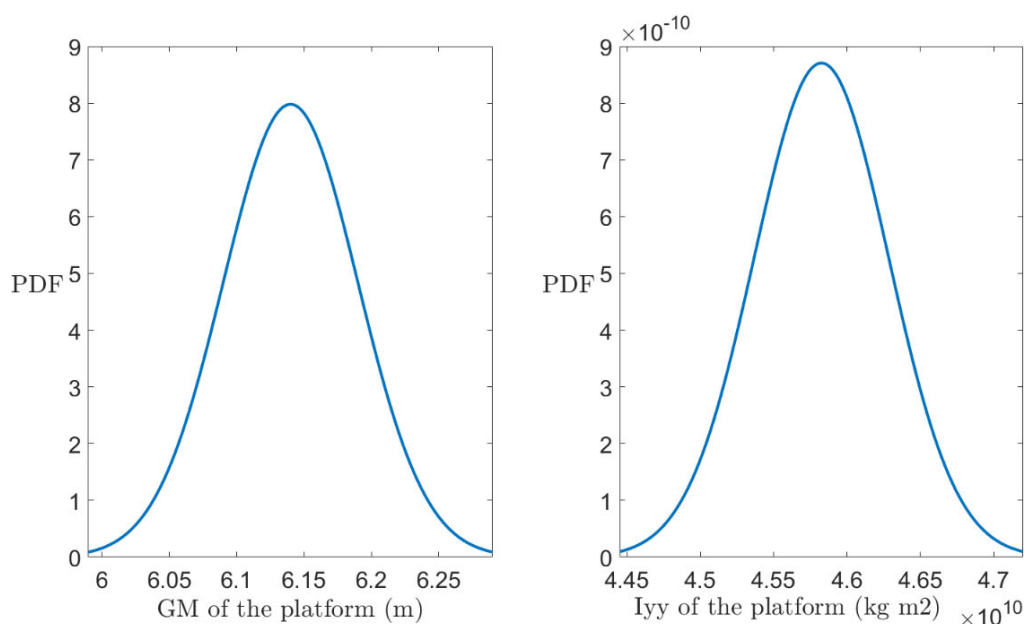


Figure 3. Normal distributions of platform metacentric height and Inertia for pitch tilt rotation.

Respecting the hybrid coupling, we must re-write the code of *OpenFAST* to assess the sensitivity either to limited force actuation bandwidth or to latency in the overall coupling system's response. Limited coupling bandwidth is implemented by adding a first-order low-pass filter to the forces calculated by aeroelastic model [8]. To quantify the cut-off frequency, we assume an effectiveness of a hybrid coupling below 2 Hz. Hence, we use in the full-scale geometric dimensions a Normal distribution of $\mu = 2 \text{ Hz}/\sqrt{40} = 0.316 \text{ Hz}$ and $\sigma = 0.01 \text{ Hz}$. Latency in the response of the coupling system is modelled by adding a delay of a discrete number of time steps of 0.01 s in the reaction forces from the aero-rotor coupling. To quantify this delay, we use in the full-scale geometric dimensions a Normal distribution of $\mu = 0.05 \text{ s} \cdot \sqrt{40} = 0.32 \text{ s}$ and $\sigma = 0.01 \text{ s}$. Figure 4 shows the PDF of the Gaussian distributions for these key parameters for the effectiveness of a hybrid coupling.

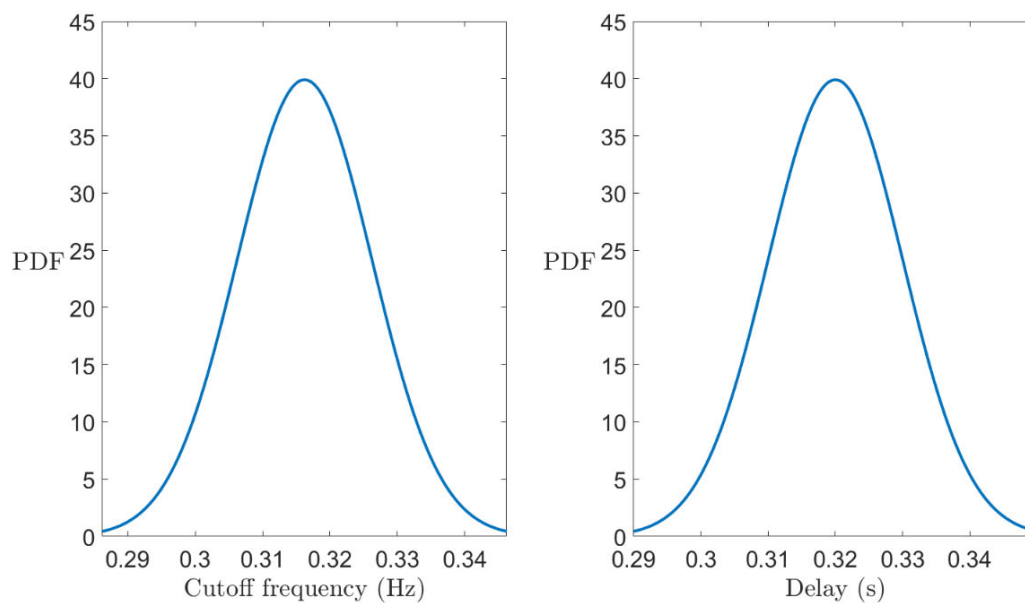


Figure 4. Normal distribution of the cut-off frequency of the first-order low-pass filter and delay in the reaction forces from the aero-rotor coupling.

2.3. Uncertainties propagation

A numerical model of the true system validated in [17] is used to assess the propagation of experimental uncertainty in ocean basin testing of the *ActiveFloat* wind turbine. Each simulation lasts 1 hour (after transient of 1800 s duration), with a temporal resolution of 0.01 s. Table 1 shows the main characteristics of the selected load cases in Gran Canaria Island (Spain) site. The values of different sea states and wind turbulence for this 200 m depth location were taken from [18].

Table 1. Extremal and severe load cases used for the analysis of uncertainties.

Name	Duration [s]	Waves	Wind [m/s]	Turbine
DLC1.3	5400	Irregular; Hs=2m, Tp=6s	Turbulent ETM; 10.5 m/s	Operational Active control
	5400	-	Turbulent ETM; 10.5 m/s	Operational Active control
DLC1.6	5400	Irregular; Hs=5.11m, Tp=9s	Turbulent NTM; 10.5 m/s	Operational Active control
	5400	Irregular; Hs=5.11m, Tp=9s	-	Operational Active control
DLC6.1	5400	Irregular; Hs=5.11m, Tp=9s	Turbulent EWM50; 41.2 m/s	Idling Active control

	5400	-	Turbulent EWM50; 41.2 m/s	Idling Active control
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For each extremal load case and each type of error to be examined, simulations for several amounts of introduced noise related to the Normal distribution of each QOI measurement are run and compared with the unperturbed simulation as a baseline case. We quantify discrepancies by taking the absolute difference between the mean of the time-series output of the perturbed simulation and that one of the baseline case

$$\text{Mean discrepancy} = \left| \frac{\sum_{i=1}^n x'_i}{n} - \frac{\sum_{i=1}^n x_i}{n} \right| \quad (4)$$

where x is the time-series of the quantity of interest in the baseline simulation, x' is the same QOI in the perturbed simulation, and n the number of recorded samples. Finally, we assess the Gumbel distributions of the resulting mean discrepancies for each QOI. The time-series output analysed in this study will be the surge displacements and the pitch rotations of the platform response, as well as the tensions on the windward mooring line.

3. Results

3.1. Uncertainty of mooring parameters

We simulate 31 amounts of introduced noise both in the mooring lines length and in the mooring lines mass per unit length, separately. The 31 resulting mean discrepancies for the outputs analysed in the former parameter, are fitted by a Gumbel distribution for each load case and plotted in Figure 5. Wind loads seem to be dominant in platform response uncertainty as the only load case without wind presents lower mean discrepancies, above all in surge displacements. Besides, DLCs with extremal (and severe) sea states exhibit higher uncertainty values in pitch rotations of the platform. However, mean discrepancies in tensions of the windward mooring fairlead do not seem to vary too much between the different load cases.

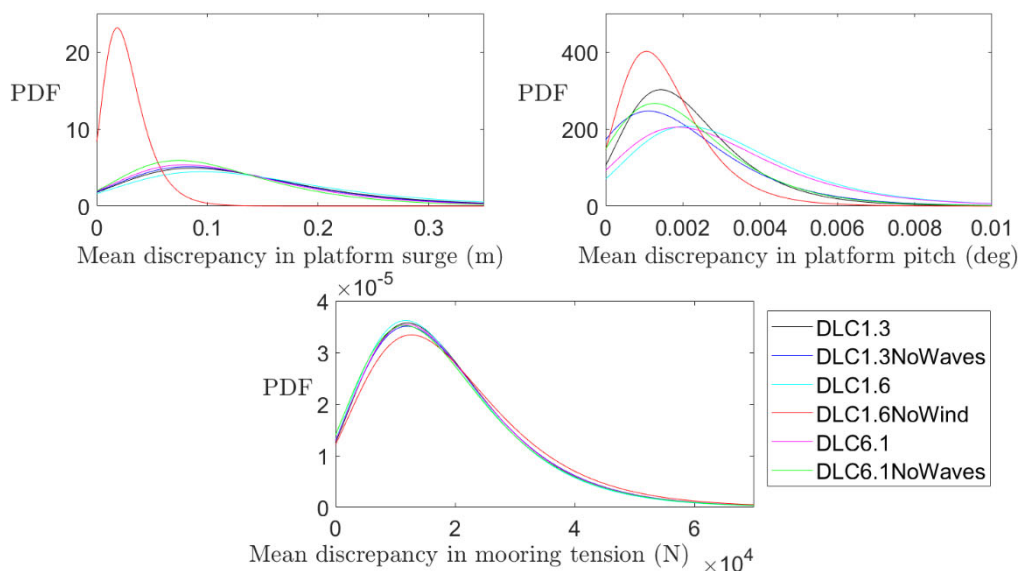


Figure 5. Gumbel distributions of mean discrepancies due to mooring length in platform surge and pitch, and windward mooring fairlead tension.

On the other hand, Gumbel distributions of mean discrepancy in surge displacements and pitch rotations of the platform response, as well as in tensions on the windward mooring line, fitted with 31 amounts of introduced noise in the mooring lines mass per unit length are plotted in Figure 6.

Although tendencies are similar in platform surge and mooring tension, the propagation of the mooring weight uncertainty is not as relevant as the mooring length one, as Barrera et al. [11] had already concluded. Respecting platform pitch, this time DLCs with extremal (and severe) sea states exhibit lower uncertainty values.

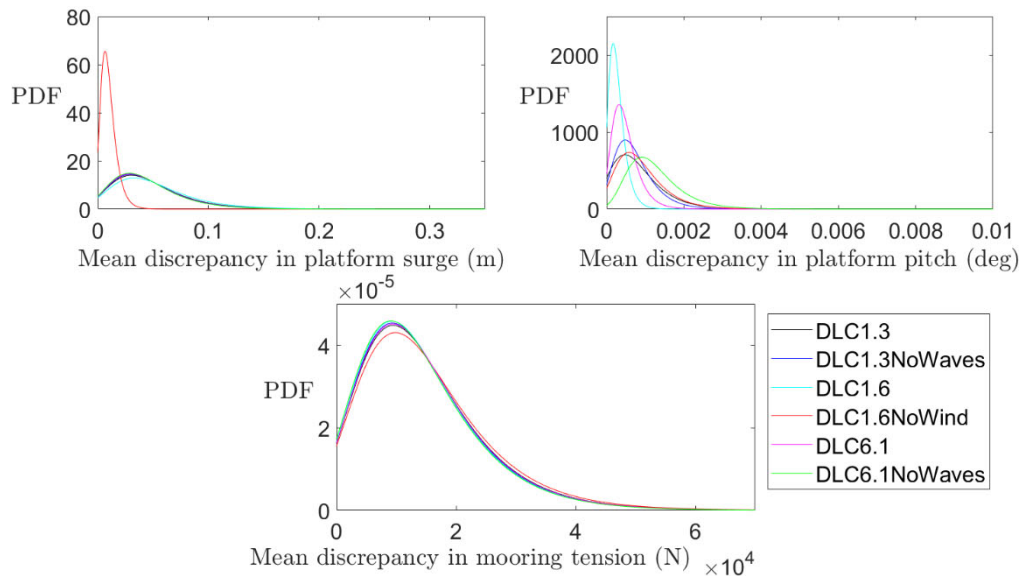


Figure 6. Gumbel distributions of mean discrepancies due to mooring weight in platform surge and pitch, and windward mooring fairlead tension.

3.2. Uncertainty of platform parameters

Changing the geometric measurements related to the platform implies a modification on the hydrodynamic parameters of the floating structure. For the sake of computational manageability, we simulate 8 amounts of noise in the platform parameters. Figure 7 shows the resulting mean discrepancies due to the metacentric height, fitted by a Gumbel distribution for each load case. Coupling loads of wind and waves are found relevant in the outputs of the platform response analysed. The DLC 6.1 and the DLC 6.1 without waves present lower and higher uncertainties, respectively, in surge displacements of the platform. Respecting platform pitch rotations, the DLC 1.6 and the DLC 1.6 without wind exhibit a lower and a higher mean discrepancy, respectively. Besides, DLCs with extremal (and severe) sea states show lower tensions of the windward mooring fairlead.

For each load case, Gumbel distributions of the outputs analysed are fitted with 8 values of mean discrepancy due to introduced noises in the inertia for pitch tilt rotation about the centre of mass. In the resulting Figure 8, the three cases DLC1.3, DLC1.6 and DLC6.1 with coupled loads of wind and waves, present higher uncertainties in platform surge displacements. In comparison to inaccuracies of Figure 7 due to platform GM, the propagation of I_{yy} uncertainties is negligible in pitch rotations and exhibits significantly lower values for every load case in mooring tension. Moreover, in the latter output analysed wind loads seem to be dominant, as the only load case without wind presents lower mean discrepancies.

3.3. Uncertainty of HIL parameters

For the multi-fan parameters, we analyse the outputs for the four load cases in which the turbine is operational. As for the mooring parameters, Gumbel distributions are fitted with resulting mean discrepancies from 31 amounts of introduced noise in the limited force actuation bandwidth. In Figure 9, DLCs 1.3 with and without waves show higher mean discrepancies in surge displacements and in pitch rotations of the platform response, as well as in tensions of the windward mooring fairlead.

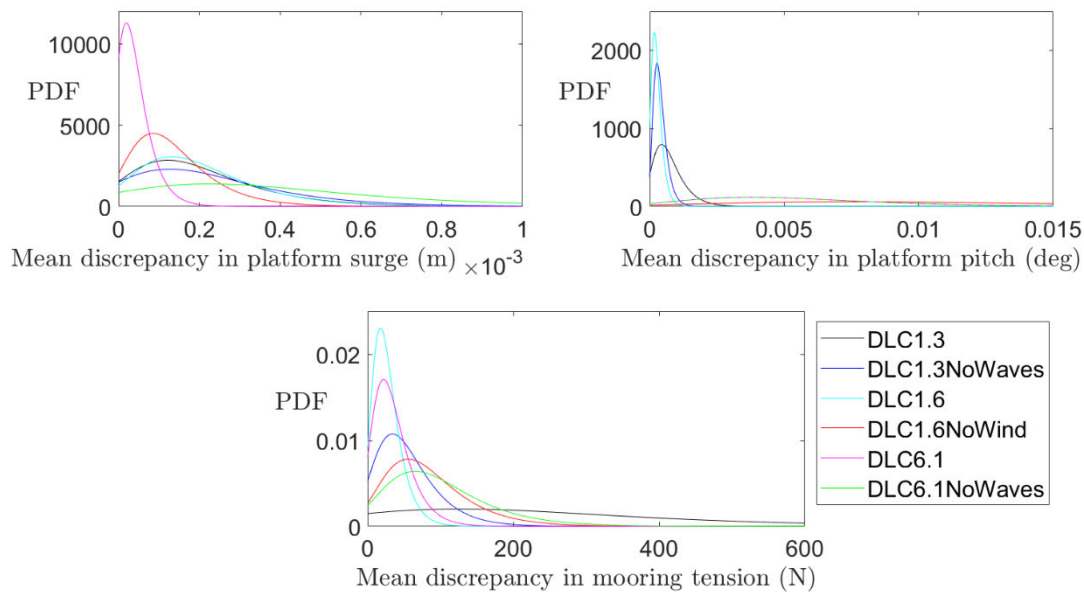


Figure 7. Gumbel distributions of mean discrepancies due to metacentric height in platform surge and pitch, and windward mooring fairlead tension.

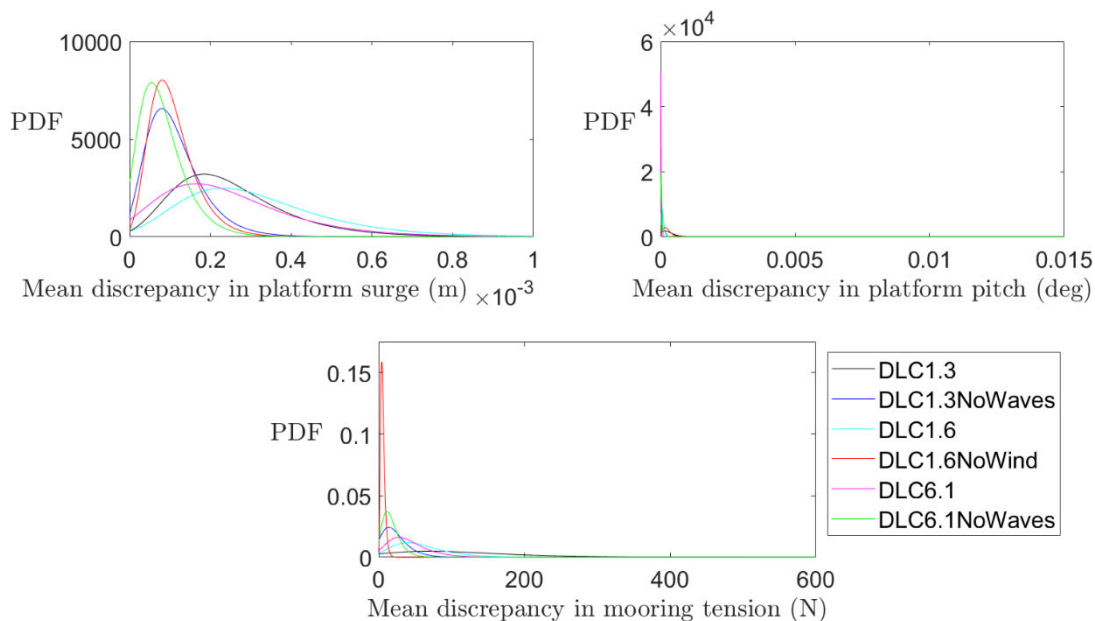


Figure 8. Gumbel distributions of mean discrepancies due to Inertia for pitch tilt rotation in platform surge and pitch, and windward mooring fairlead tension.

On the other hand, we simulate 5 amounts of introduced noise in the latency in the multi-fan system response, due to the limitation of the time step to 0.01 s. In this case, the elasticity of the turbine is not considered in *OpenFAST*, and thus the outputs obtained do not contain aero-elastic effects. Although tendencies are similar in the resulting Gumbel distributions for the outputs analysed in Figure 10, the propagation of the multi-fan latency uncertainties is notably higher than the actuation bandwidth one.

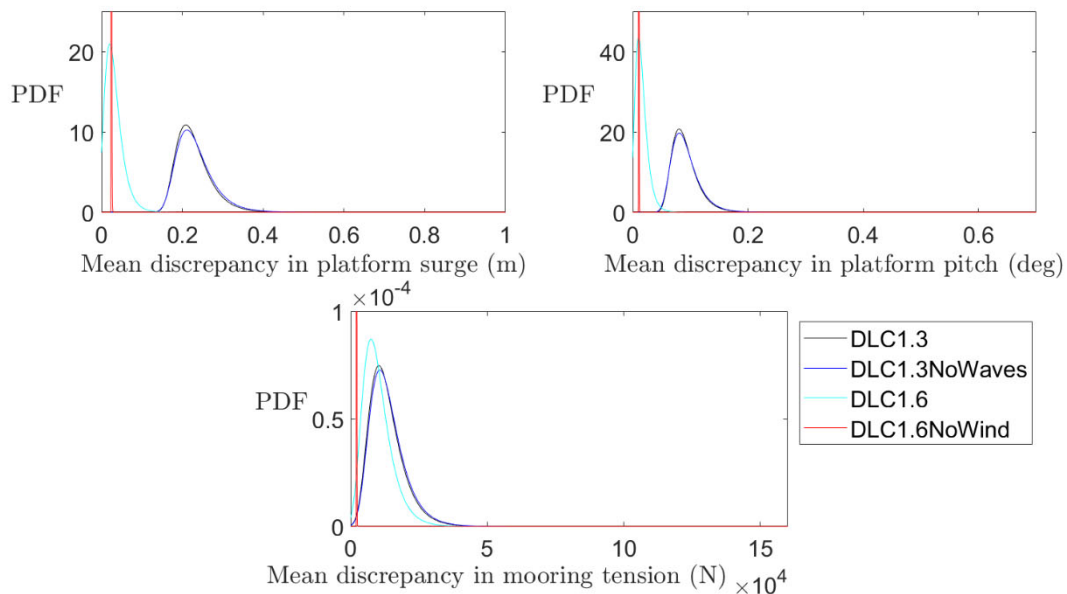


Figure 9. Gumbel distributions of mean discrepancies due to limited force actuation bandwidth in platform surge and pitch, and windward mooring fairlead tension.

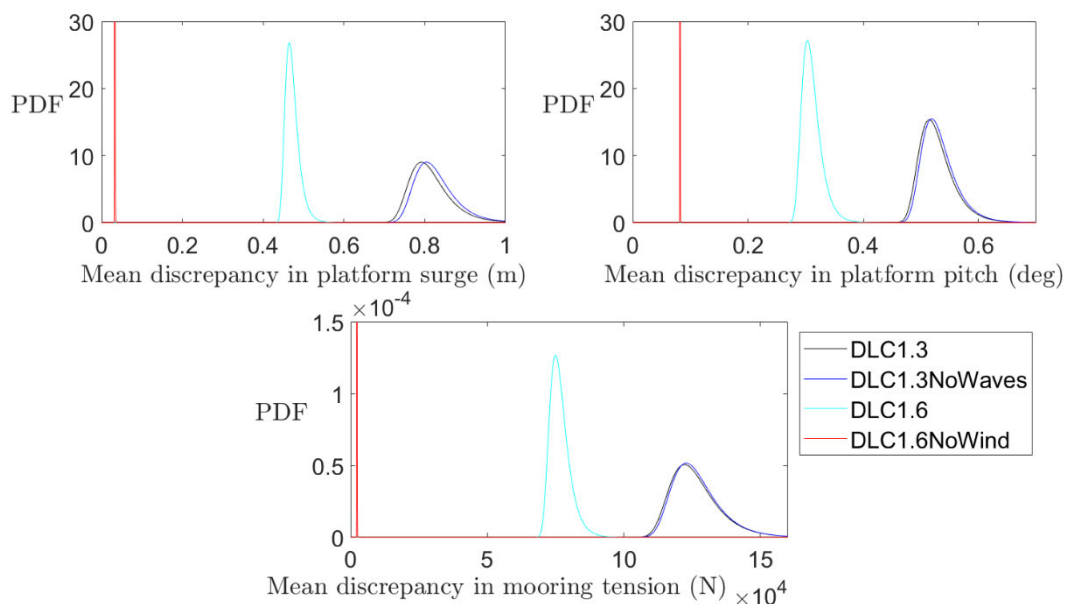


Figure 10. Gumbel distributions of mean discrepancies due to latency in the multi-fan system response in platform surge and pitch, and windward mooring fairlead tension.

4. Conclusions and future work

We assess the uncertainties in a real-time hybrid model for ocean basin testing of a 15MW floating offshore wind turbine supported by a concrete-based semi-submersible substructure (*ActiveFloat*). The reliability of the outputs is numerically quantified by running 1-hour duration simulations in *OpenFAST* with introduced errors in mooring, platform and HIL parameters, and comparing them with

the unperturbed simulation as a baseline case. Values of sea states and wind turbulence are taken from extremal and severe design load cases in Gran Canaria Island (Spain) site.

Analysing the uncertainty propagation of the mooring parameters, we may corroborate that inaccuracy in the length of the mooring lines are more relevant than in their mass per unit length. On the other hand, the propagation of uncertainty in the platform metacentric height presents significantly higher values in the outputs analysed than those ones due to discrepancies in the inertia for pitch tilt rotation. Respecting the quantities of interest of the multi-fan system located at the aero-rotor interface, the latency in the reaction forces of the coupling system has a larger effect on the platform response and mooring tensions than the limited coupling bandwidth.

As future work, we will improve the implementation of limited coupling bandwidth by adding a second-order low-pass filter to the forces calculated by aeroelastic model. Moreover, we will use the Monte Carlo method to figure out the effect of combined discrepancies which take place simultaneously in a real case. For the sake of computational manageability, we will introduce amounts of noise only in three parameters: one of each type analysed. From the mooring and platform parameters, we will choose the mooring length and the metacentric height, respectively, because they are more relevant. From the HIL parameters, we will pick up the force actuation bandwidth not to be limited by the time step.

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