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A hardware-in-the-loop wave-basin scale-model experiment for the validation of control strategies for floating offshore wind turbines

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Abstract. This paper presents a new hardware-in-the-loop methodology for wave-basin scale-model experiments about floating offshore wind turbines and its application as a tool for the validation of control strategies. In the hardware-in-the-loop experiments, the physical Froude-scaled wind turbine model used in conventional scale-model tests is replaced by a numerical model, measurements and a multi-fan actuator. As usual, properly-scaled waves are generated in the wave basin and the floating platform is simulated by means of a scale-model. The hardware-in-the-loop methodology was used to recreate the interaction between the collective pitch controller and the platform pitch mode that, often observed in numerical studies. In addition, the blade-root load measurement available in the numerical model of the rotor was used to implement an individual pitch control strategy. Different from in conventional experiments, the hardware-in-the-loop methodology allows to recreate a realistic three-dimensional wind field that was used to demonstrate the effectiveness of the individual pitch control. The improved emulation of the rotor loads and wind field make the hardware-in-the-loop experimental methodology an effective tool for the development and validation of control strategies for floating offshore wind turbines.

1. Introduction

A large portion of wind energy is observed in offshore sites with a water depth greater than 50 meters [1] where bottom-fixed wind turbines are not cost effective. Floating offshore wind turbines (FOWTs) are recognized as a viable solution to exploit the abundant wind resource of deep waters. However, deploying a multi-megawatt wind turbine on a floating foundation poses several engineering challenges which have only been partially addressed. In particular, it is still not clear which is the best way to control the wind turbine. One plausible explanation is that it has not yet been possible to identify a reliable tool for the design and validation of FOWT control strategies.

Most of the studies carried out so far relied on comprehensive simulation codes. However, their



capability to correctly predict the FOWT response is still uncertain and validation tasks, such as OC5 project, has shown the lack of accuracy with respect to the low-frequency hydrodynamic excitation and the fatigue loads for the wind turbine tower and for the mooring system [2]. For this reason, experimental data could play a crucial role in the development of better control strategies.

Full-scale experiments are often limited by economic, time and safety constraints. Difficulties also arise due to the uncontrollable environmental conditions, partially known system parameters and expensive measurements. Few wave-basin scale model experiments were recently carried out to investigate FOWT control strategies [3–5]. The experiments relied on a conventional wave-basin testing methodology and made use of a scale model of the wind turbine and floating platform. The simultaneous emulation of the wind turbine rotor loads, wind environment, platform hydrodynamics, mooring system, and structural flexible dynamics is required to be the scale model experiment representative of the full-scale system, and then for the study of control strategies. However, constraints set by the widely-used Froude-similitude scaling methodology make this hard to be accomplished [6]. An alternative to conventional scale-model wave-basin tests that has been recently proposed by different laboratories [7–10] is represented by hybrid hardware-in-the-loop (HIL) experiments. Part of the FOWT is reproduced by a physical scale model and the rest of the system is modeled by means of a numerical model, measurements, and an actuation system.

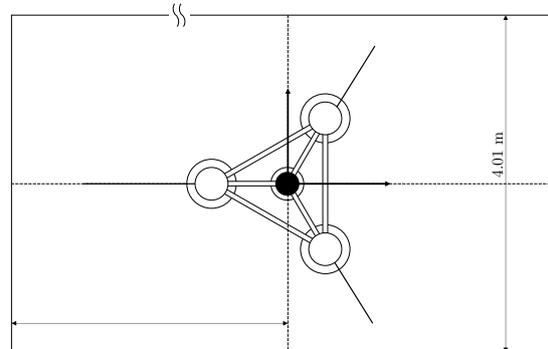
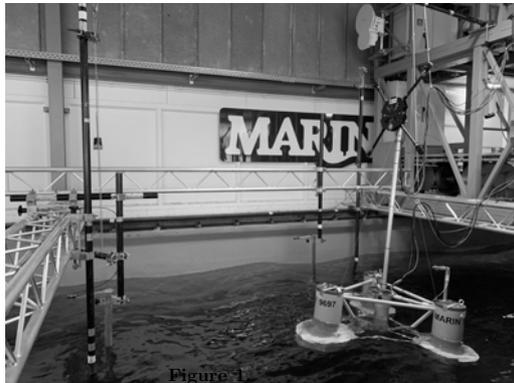
This paper does not introduce a novel control strategy for floating wind turbines but instead it proposes a new scale-model wave-basin HIL methodology and it shows how this can be used for the study of FOWT control strategies. For this purpose, two industry-standard control logics, a generator torque controller combined with a gain-scheduled collective blade pitch controller and an individual blade pitch controller, are implemented in a 5MW semisubmersible FOWT. The results of the HIL tests are compared to those of previous numerical and scale-model studies about the same logics, to highlight the strengths of proposed experimental methodology.

2. The floating system

The new HIL methodology is here applied to a floating system consisting of the DeepCWind floating platform [11] and the NREL 5MW wind turbine [12]. The 1/50 scale model of the floating platform and tower is the one already examined in [13,14]. Taut angled lines were used in place of the mooring system of the original DeepCWind concept [11] in order to limit the uncertainty and fit in the tank used for the experiments. In the static equilibrium position, the soft mooring approximates the linear stiffness and vertical angle at the fairlead of the real mooring system. The scale model complete of the multi-fan actuator of the HIL system is shown in figure 1 and the main properties are resumed in table 2.

3. Conventional and hybrid scaling

Froude-number similitude is widely-used in the offshore platform wave-basin test practice because it allows to properly scale all the driving factors of the hydrodynamic problem, as well as the gravity and inertia forces [6]. When Froude scaling is used, the scale factors are a function of the length scale factor λ which is defined as the ratio of any length evaluated at full-scale and at model scale. The mathematical expression of the main scale factors for a wave-basin experiment and the respective value for $\lambda = 50$ are reported in table 1. As shown, the Froude scaling implies a significant reduction of the Reynolds number. For the FOWT case, this means that Froude-scale experiments allow to correctly reproduce most of the parameters influencing the global behavior of the system except for the aerodynamic loads. The specifications for the scale model object of this study were obtained by dividing the corresponding prototype quantity by the appropriate scale factor of table 1 and are reported in table 2.



The floating platform scale model and the multi-fan system inside the wave basin (left) and schematic of the test setup (right).

Table 1. Scale factors for the experiment.

Scale	Expression	Value
Length	λ	50
Density	–	1
Mass	λ^3	1.25E+5
Time	$\sqrt{\lambda}$	7.07
Frequency	$1/\sqrt{\lambda}$	0.14
Velocity	$\sqrt{\lambda}$	7.07
Acceleration	–	1
Force	λ^3	1.25E+5
Power	$\lambda^{3.5}$	8.83E+5
Reynolds number	$\lambda\sqrt{\lambda}$	3.53E+2

Table 2. Main properties of the floating system (RNA is the rotor-nacelle assembly).

Property	Unit	Full-scale value	Model-scale value
Overall system mass	kg	1.420E+7	113.6
Displacement	m ³	1.404E+4	0.112
Tower mass	kg	3.619E+5	2.9
Rotor diameter	m	126	2.52
Rated rotor speed	rpm	12.1	85.56
Rated wind speed	m/s	11.4	1.61
Rated power	W	5E+6	5.66
Hub height	m	90	1.8
Rotor mass	kg	7.003E+4	0.56
RNA overall mass	kg	5.479E+5	4.38

3.1. Traditional wave-basin experiment

If conventional wave basin testing had been used, the physical wind turbine scale model should have been designed to match the values in table 2.

The target rotor speed for the model is high while the rated wind speed is very low. The blade should have been re-designed according to a performance scaling procedure [15,16] and/or the wind speed, rotor speed and pitch angle setting should have been adjusted, disregarding of Froude scaling, to reproduce the aerodynamic forces of the full-scale rotor [6]. With this approach it would have been possible to match better the steady-state thrust force but not the wind turbine power [6] nor the thrust force derivatives with respect to rotor speed and wind speed, that are of major importance for the interaction of the wind turbine controller with the platform motions and so for the global dynamics and stability of the FOWT. The target rotor mass is low and it represents a major constraint for the realization of a scaled blade which mass has to respect the prescribed value in order to correctly model gyroscopic effects.

The target mass of the rotor-nacelle assembly is low, which will limit the installation of actuators and sensors needed to implement the advanced control strategies. Errors in the reproduction of the wind turbine mass and mass distribution also affect the tower flexible dynamics and the rigid-body motion of the floating structure. Wind had to be generated by a wind machine installed in the wave-basin. This setup has some limitations, namely fan-generated swirl [6], turbulence and small cross section, that make it difficult to simulate a realistic three-dimensional turbulent wind.

3.2. The hardware-in-the-loop methodology

The HIL methodology avoids the limitations imposed by Froude-scaling by emulating the rotor in a non-scaled environment and applying scaled loads to the model as shown in figure 2. The FOWT is divided into two complementary domains. The floating platform, mooring system and hydrodynamic loads are reproduced by a physical scale model designed from the scaled properties of table 2. The model is operated in the wave basin where Froude-scaled waves are generated. The wind turbine loads and the turbulent wind field are instead emulated by a numerical model of the full-scale wind turbine that is implemented in FAST run in parallel to the experiment. The wind turbine control and actuators are simulated in the numerical model and do not suffer of the physical constraints (e.g. space, weight) that are common for physical scale models [17]. A realistic three-dimensional turbulent wind field can be recreated. To interface the two sub-domains, the rigid-body motions of the platform scale-model are measured, upscaled and used as input for the numerical simulation. Tower-top forces resulting from the real-time numerical tool are downscaled and applied to the tower-top by means of a force actuator.

In recent years, CENER (Centro Nacional de Energias Renovables) developed a HIL setup for wave-basin scale-model testing that used a ducted fan to reproduce the rotor thrust force only [10]. The main limitation of the system was the lack of the rotor out-of-plane moments caused by aerodynamic effects such as imbalances, wind shear, pitch failures, misalignments, or gyroscopic effects that were not captured by the punctual thrust force. In the present test campaign, the above-mentioned HIL system has been improved to allow the reproduction of more realistic rotor forces. The original ducted fan has been replaced by a multi-fan system made of four propellers mounted on a frame and operated in still-air. With this setup it is now possible to generate the thrust force, pitch and yaw moments. The enhanced capabilities of the new HIL methodology were used to implement and study two industry-standard control strategies, namely a generator-torque/collective-blade-pitch controller and an individual pitch controller for blade loads alleviation. Experiments were carried out at the MARIN (Maritime Research Institute Netherlands) concept basin (220 m length, 4 m width and 3.6 m depth).

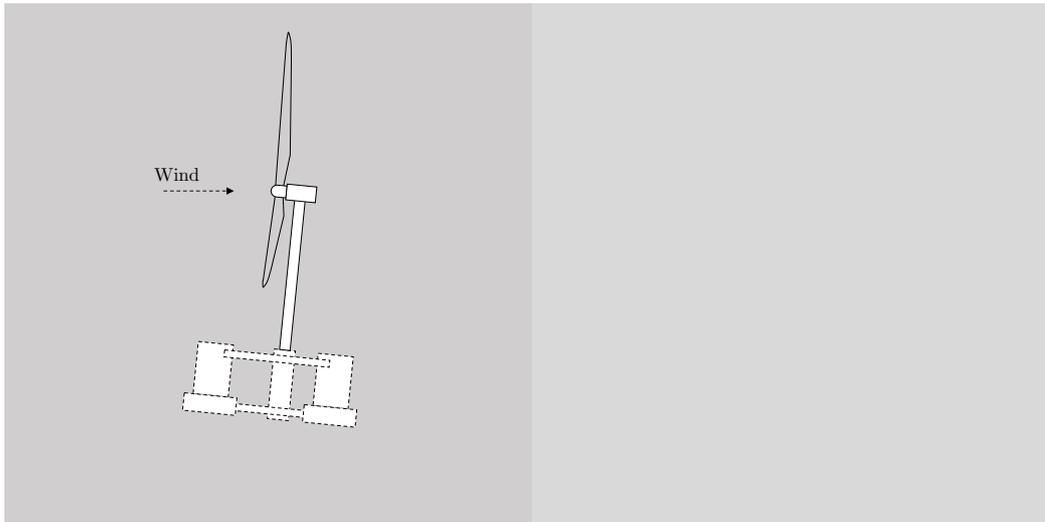


Figure 2. Schematic of the hardware-in-the-loop methodology for wave-basin experiments.

4. Experiments about the baseline control

The baseline control strategy regulates power by means of a generator torque controller combined with a gain-scheduled proportional-integral collective blade pitch controller (CPC). In below-rated winds the controller maximizes the extracted power by keeping the blade pitch angle at zero degree θ and varying the generator torque Q_G as a function of generator speed ω_G squared:

$$Q_G = k_G \omega_G^2, \quad (1)$$

with $k_G = \frac{1}{2} \rho \pi R^3 (C_{p,max} / \lambda_{opt}^3)$, where ρ is the air density, R the rotor radius, $C_{p,max}$ the maximum power coefficient that is achieved for zero pitch angle and the optimal tip-speed-ratio λ_{opt} . In above-rated winds, the controller limits the extracted power to its rated value P_{rated} by setting the generator torque equal to:

$$Q_G = \frac{P_{rated}}{\omega_{rated}}, \quad (2)$$

where ω_{rated} is the rated generator speed. The rotor speed is regulated to its rated value by the CPC that reacts to the generator speed feedback. Gains were chosen as in [11]. These are lower than those of the baseline 5MW NREL were chosen so that the blade pitch controller bandwidth is lower than the platform pitch natural frequency, assumed to be equal to 0.037 Hz.

4.1. Steady-state rotor performance

Reproducing the rotor performance of the full-scale wind turbine is often difficult in conventional wave-basin scale model tests, since the mandatory Froude-scaling results into a considerable reduction of the Reynolds number [6] (see table 1). This issue is solved by the HIL because the rotor aerodynamic loads are simulated by the numerical model at full-scale and subsequently scaled down before being applied to the physical scale model. The steady-state thrust force F_x and rotor power that were measured in the wave-basin are reported in figure 3. As visible, values are very close to those of the full-scale 5MW NREL.

4.2. Free-decay tests

Free-decay tests in a steady wind of 9 m/s (below-rated), 11.4 m/s (rated) and 16 m/s (above-rated) were carried out to assess the influence of the baseline controller on the platform pitch motion. The natural period and damping ratio of the platform pitch mode for the three wind

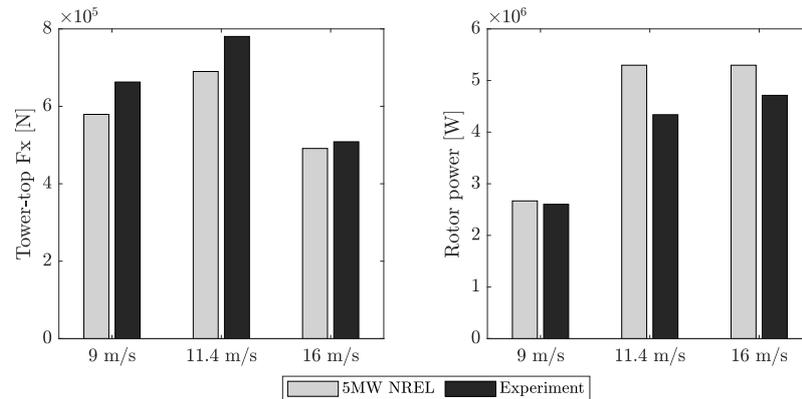


Figure 3. Comparison of the steady-state tower-top Fx force (left) and rotor power (right) for the 5MW NREL reference wind turbine and the scale-model.

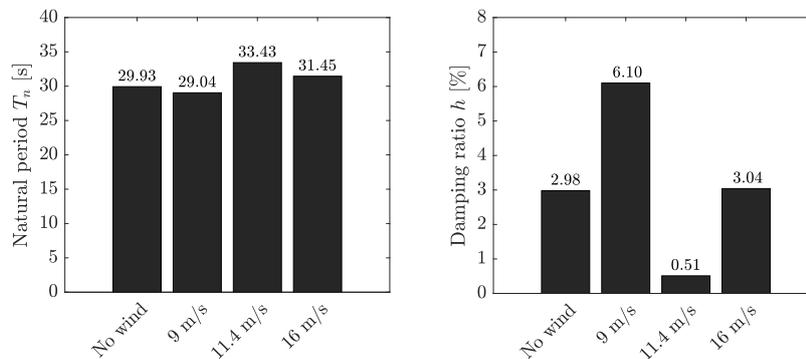


Figure 4. Platform pitch natural period (left) and damping ratio (right) for different wind conditions as obtained in free-decay experiments.

conditions and still-air are shown in figure 4. As it has been shown either by numerical studies [18–20] and scale model experiments [3], in above-rated winds the CPC has a strong interaction with the platform pitch mode that results in a low-damping. As expected, the damping of the platform pitch mode is minimum in slightly above-rated winds and increases in higher winds.

4.3. Turbulent wind and irregular wave tests

Three power-production cases with realistic wind and wave conditions were simulated with the baseline controller. The irregular waves were generated according to the JONSWAP spectrum with a significant height H_s of 7.1 m and peak period T_p of 12.1 s. The turbulent wind field was simulated at full-scale in the numerical model (Isee figure 2). The three-dimensional stochastic wind field was created prior to simulation using TurbSim [21], considering a power-law profile (exponent 0.14), a surface roughness-length of 0.03, a Kaimal spectrum with normal turbulence model (NTM) and a turbulence intensity of 22%, 19.89% and 17.63%.

The power-spectral density (PSD) of the platform surge, heave and pitch motions recorded in the three load cases is shown in figure 5. The motion amplitude at the platform pitch natural frequency varies with the wind turbine operating condition in agreement with the damping variation seen in free-decay experiments.

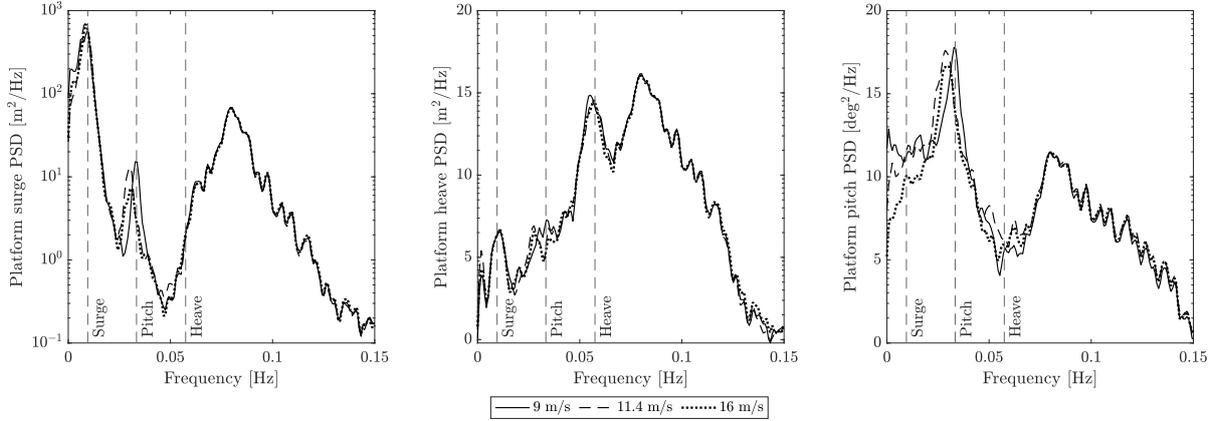


Figure 5. PSD of the platform surge (left), heave (middle) and pitch (right) motion for irregular waves, three turbulent winds and baseline control. The natural frequencies of the platform motion modes in still-air are marked by vertical dashed lines.

5. Experiments about IPC

The second control strategy is an IPC, often used to alleviate periodic loads on the blades caused by the uneven wind field [22]. The purpose of implementing an IPC strategy in the HIL experiment was threefold. First, it shows that the HIL methodology can be used to test control logics that require multiple feedbacks and the individual actuation of the blades pitch angle that are hard to implement in a conventional wind turbine scale model. Second, IPC requires a realistic three-dimensional wind field to show its benefits and this can be recreated with the HIL methodology. Finally, as it will be briefly recalled below, IPC acts by creating a yaw and tilt moment in the non-rotating reference frame that are effectively recreated by the multi-fan system.

The IPC strategy is based on the multi-blade coordinate (MBC) transformation. The yaw and tilt moments exerted by blades on the rotor hub (non-rotating coordinate system loads) are computed from the out-of-plane root bending moment of each blade (rotating coordinate system loads) by means of the inverse MBC transformation as in Eq. 3.

$$\begin{bmatrix} M_t(t) \\ M_y(t) \end{bmatrix} = \begin{bmatrix} \frac{2}{3} \cos(\phi(t)) & \frac{2}{3} \cos(\phi(t) + \frac{2\pi}{3}) & \frac{2}{3} \cos(\phi(t) + \frac{4\pi}{3}) \\ \frac{2}{3} \sin(\phi(t)) & \frac{2}{3} \sin(\phi(t) + \frac{2\pi}{3}) & \frac{2}{3} \sin(\phi(t) + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} M_1(t) \\ M_2(t) \\ M_3(t) \end{bmatrix} \quad (3)$$

where $\phi(t)$ is the rotor azimuth. Two independent integral controllers minimize $M_t(t)$ and $M_y(t)$ computing a tilt $\theta_t(t)$ and yaw $\theta_y(t)$ commands in non-rotating coordinates that are transformed into rotating coordinates according to the MBC transformation of Eq. 4. The gain of the two controllers was tuned by means of FAST simulations of the full-scale DeepCWind floating wind turbine [11]. The rotor of the wind turbine considered in the tuning process is exactly the one that was simulated in the HIL experiment. The zero-mean individual pitch set-points are summed to the collective pitch command of the baseline controller.

$$\begin{bmatrix} \theta_1(t) \\ \theta_2(t) \\ \theta_3(t) \end{bmatrix} = \begin{bmatrix} \cos(\phi(t)) & \sin(\phi(t)) \\ \cos(\phi(t) + \frac{2\pi}{3}) & \sin(\phi(t) + \frac{2\pi}{3}) \\ \cos(\phi(t) + \frac{4\pi}{3}) & \sin(\phi(t) + \frac{4\pi}{3}) \end{bmatrix} \begin{bmatrix} \theta_t(t) \\ \theta_y(t) \end{bmatrix} \quad (4)$$

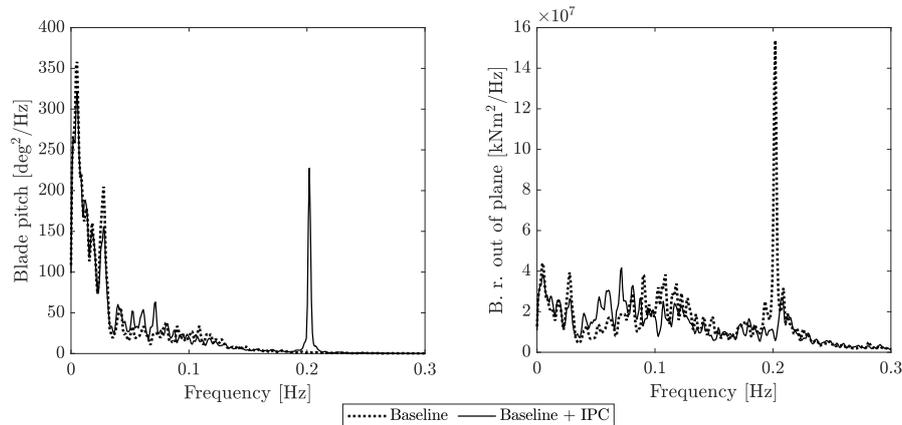


Figure 6. PSD of the blade 1 pitch angle command (left) and of the blade 1 out-of-plane root bending moment (left) for irregular waves and a 16 m/s turbulent wind with baseline control and baseline + IPC.

5.1. Turbulent wind and irregular wave tests

The FOWT with the IPC added to the baseline controller is studied for combined irregular waves and a 16 m/s turbulent wind (power-law profile, exponent 0.14, surface roughness-length 0.03, Kaimal spectrum with normal turbulence model (NTM), turbulence intensity 17.63%). Results obtained with IPC + baseline are compared to those of the baseline control considering the power spectral density (PSD) of the quantities of interest. A direct comparison of time histories is not possible in reason of the random seed used for wind and wave generation.

In figure 6, the IPC + baseline control is compared to the baseline control in terms of the blade pitch angle command and the blade-root out-of-plane bending moment. IPC achieves the expected reduction of the 1P component of the blade-root bending moment at the expense of an increased pitch activity at the same frequency [22]. The 1P component of the blade-root out-of-plane bending moment is mostly caused by wind shear, tower shadow and rotational sampling of the turbulence and the results show that these phenomena are correctly captured by HIL experiment.

Figure 7 shows the PSD of the tilt moment M_y and yaw moment M_z applied at tower-top by the multi-fan. The action of the IPC on the load components in the non-rotating reference frame is visible in the low-frequency range [22] and it is highlighted in the figure by the dashed box.

6. Conclusions

FOWTs are a promising technology for exploiting the vast wind energy resource of coastal areas characterized by a water depth greater than 50 meters where conventional support structures are not a viable solution. Control is even more critical than in bottom-fixed wind turbines and experimental data play a crucial role in the development of new and more advanced control strategies. However, conventional wave basin scale model experiments suffer of some limitations inherent to the Froude-similitude scaling approach that is mandatory to correctly emulate hydrodynamic, gravity and inertia loads. In this paper, a novel HIL wave-basin experimental methodology is proposed to overcome the limitations of traditional tests. The same, is used to carry out scale model tests about a floating system formed by the 5MW NREL wind turbine and the DeepCWind semisubmersible.

In particular, it is shown how the HIL methodology can be exploited in the development and validation of control strategies. Two industry-standard controls are considered. The first one is

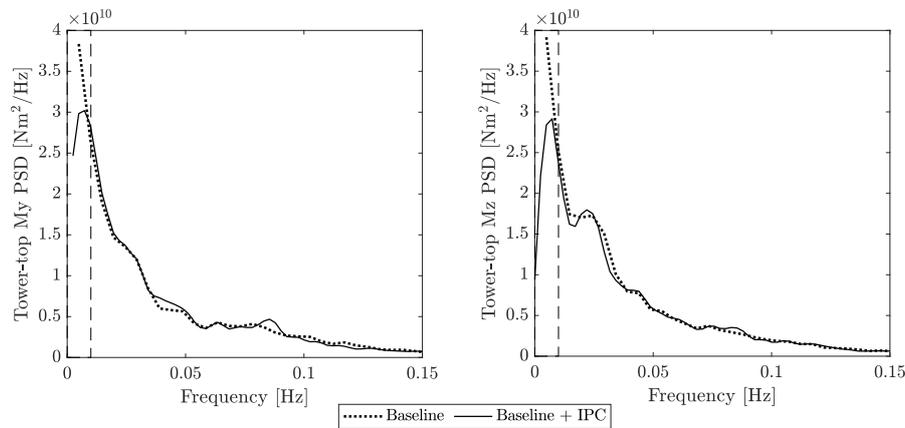


Figure 7. PSD of the tilt moment M_y and yaw moment M_z applied at tower-top by the multi-fan for irregular waves and a 16 m/s turbulent wind with baseline control and baseline + IPC.

a generator-torque collective-pitch-control that represents the most common way of regulating power in modern wind turbines. The steady-state thrust force and power developed by the wind turbine in the experiment match the full-scale values, which is a result hardly achieved in conventional wave-basin tests. The interaction between the collective-pitch-controller and the platform pitch mode, which is of major importance for the control of FOWTs, is effectively recreated. The second control strategy is an IPC-MBC designed to reduce the blade-root fatigue loads that is added to the baseline controller. This has been possible because the feedback of the blade-root loads and the individual control of the blades pitch angle are readily available in the numerical model of the wind turbine rotor part of the HIL system. To recreate a realistic wind environment is hard in conventional wave-basin experiments where a wind machine is used. As shown, with the HIL methodology it has been possible to emulate the three-dimensional turbulent wind field with prescribed features that was required to validate the IPC control strategy.

As was mentioned many times in this paper, the tested control strategies are an industry standard and served the purpose to prove the potentialities of the HIL methodology as a tool for the design and validation of wind turbine controls. With the same methodology, advanced FOWT control strategies could be tested in future, making full use of the accurate wave environment of the wave-basin and the high-fidelity aerodynamic loads emulated by the HIL system.

7. Acknowledgements

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