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A study of the effect of aerodynamic damping on the platform motion of a floating wind turbine using a hybrid hardware-in-the-loop wind tunnel setup

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Abstract. Floating offshore wind turbines show strong coupling between platform motions and rotor aerodynamics, where motion-induced variations in inflow generate aerodynamic forces that can augment or reduce the effective damping of platform degrees of freedom. This paper quantifies the impact of aerodynamic damping on floating wind platform response using a hybrid hardware-in-the-loop wind-tunnel setup that couples a thrust-scaled 1.2m rotor model of a 10MW turbine with a real-time simulation of semi-submersible floater dynamics through force-feedback and motion-actuation. Aerodynamic damping is investigated via single degree of freedom decay tests for all platform motion directions and different wind speeds operating at fixed tip-speed ratio. Results show a pronounced wind-speed dependence, with pitch exhibiting the strongest aerodynamic damping increase. At rated conditions the pitch damping ratio rises by 30% relative to no-wind. In combined wind–wave conditions, a mild reduction of the response at the pitch natural frequency is observed for some wind conditions, while changes in the wave-frequency range are negligible.

1. Introduction

The deployment of floating offshore wind turbines (FOWTs) is widely regarded as key to achieving energy transition targets for regions where bottom-fixed turbines are not an option. In FOWTs, the large motions affect the rotor aerodynamic loads, which in turn influence the dynamics of the floater, in a highly coupled way. The aerodynamic damping phenomenon arises from the two-way interaction of wind-induced forces and platform motions. It can provide stabilizing or destabilizing mechanisms in the system dynamics, and is therefore crucial to floater design and control strategies.

Numerical models are extensively used to investigate FOWT dynamics. Due to the high aero-hydro coupling, it is computationally expensive to run coupled high-fidelity computational fluid dynamics simulations. Mid-fidelity solvers such as OpenFAST, combined with quasi-steady models like BEM, can provide a basis for frequency-velocity dependent aerodynamic damping to be used to better estimate floater motions without modelling the wind turbine [1]. These methods can be used for preliminary design, but lack aerodynamic understanding. The aerodynamic modelling for floating wind turbines is particularly challenging due to the interaction between platform motions and unsteady rotor aerodynamics. At high tip-speed ratios, surge and pitch motions induce complex wake dynamics and motion-dependent aerodynamic damping

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that are not fully captured by quasi-steady or simplified models, leading to noticeable differences in predicted loads and low-frequency platform responses [2].

Experimental testing is needed to increase the fidelity of aerodynamic predictions and serve as validation for numerical models. However, full-scale data are scarce, field demonstrators are costly, and lab-scale model tests are subject to scaling conflicts of the different physics involved. The hybrid testing concept can help overcome the scaling conflicts by physically reproducing one part of the system in scale while numerically emulating the other part in real-time with a hardware-in-the-loop (HIL) approach. In a wave basin, Carmo et al. [3] investigated the aerodynamic damping with an active thrust emulator, where they found measurable pitch aerodynamic damping. Many other studies have investigated hybrid testing approaches in wave basins, with or without hardware-in-the-loop, but their applicability is often constrained by the need to run aerodynamic models in real time. In practice, this requirement typically leads to the use of simplified BEM-based solvers, which may inadequately capture the unsteady and motion-dependent aerodynamic effects that are critical for floating wind turbines [4]. Testing in wind tunnels allows for more accurate aerodynamic results by measuring loads on a scale rotor coupled with simulated motions. Very few such setups have been developed [5][6], and no extensive studies focused on aerodynamic damping have been performed with those.

This work aims at addressing this gap. The study, making use of a hybrid HIL setup in a wind tunnel, investigates the effect of rotor aerodynamics on the motion response of a FOWT. The present study builds upon previous work [7], which provides the development and assessment of the hybrid HIL setup used in this work, including the physical setup and the numerical part (force–feedback motion-control loop with aerodynamic force estimation and modelling of floater dynamics), and whose main features are reported here. The contribution of this paper lies in testing an updated floater and in a systematic investigation of the influence of aerodynamic damping on FOWT dynamics.

2. Methodology

2.1. Hybrid setup

The present experimental setup is a hybrid wind-tunnel setup including HIL. The physical setup comprises a wind turbine scale model mounted on a motion system. The wind turbine model is a 1:148 (rotor diameter 1.2m) thrust-scaled model of the DTU 10MW operating with a velocity scale factor of 3. The blades use the SD7032 airfoil, suitable for low-Reynolds applications such as the present one, where the operating Reynolds number is about 30-60k. The blade pitch is fixed, and the rotor is driven by a motor/generator. Previous experiments showed that the rotor can reproduce the static and dynamic thrust. The model is instrumented with a six-component loadcell installed between the tower top and the nacelle, which measures the rotor-integral forces and moments, and with a triaxial MEMS accelerometer, which measures the nacelle accelerations. The motion system is the 6-DOF parallel kinematics hexapod robot platform from Quaser. An overview of the setup is shown in Figure 1.

The HIL architecture is of the type force-feedback-motion-actuation, i.e. the aerodynamic loads are measured on the physical rotor and fed into a floater dynamics simulator, running in a real-time controller, which calculates the next state of the system and transmits it into the hexapod, which actuates the desired motion (scheme in Figure 2).

The aerodynamic loads need to be estimated from the measured rotor loads because the rotor is not inertially scaled. For their estimation, a force correction method based on acceleration measurements is adopted, where the inertial loads are calculated from the acceleration and subtracted from the loads measured by the loadcell.

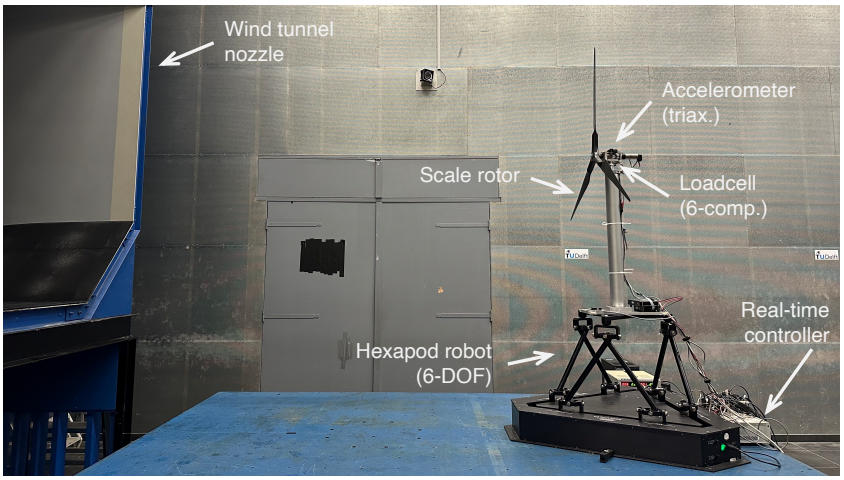


Figure 1. Picture of the experimental setup indicating its components.

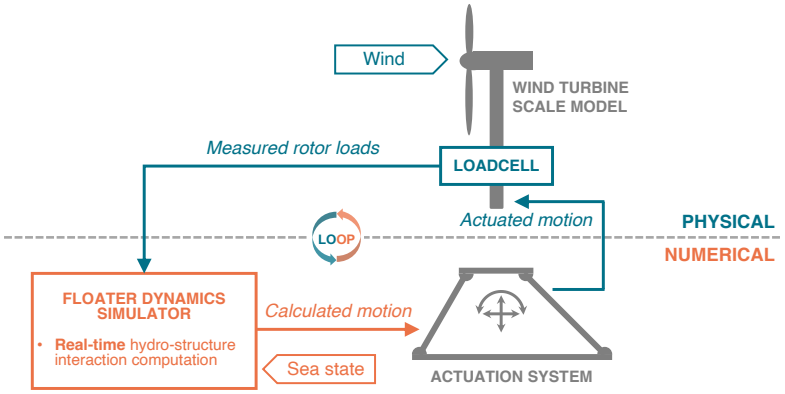


Figure 2. Scheme of the HIL architecture.

The floater simulator solves the dynamics of the floater with a physics-based approach. The floater numerical modelling includes hydrostatics, linear and quadratic viscous damping, radiation forcing (with a state-space formulation), mooring, and wave forcing (first- and second-order diffraction). The floater concept used for this study is the SWE TripleSpar floater, and its OpenFAST model is used as a benchmark.

Linear mooring is employed for the decay tests to ensure constant stiffness across all wind speeds, thereby preventing wind-dependent changes in restoring behaviour associated with quasi-static mooring formulations, where mean surge and pitch offsets caused by thrust lead to an increase in stiffness in that DOF that is not aerodynamic in origin. The use of linear moorings therefore enables a clearer interpretation of decay responses and allows aerodynamic effects on frequency and damping to be isolated. For the wave cases, the mooring system is instead modelled using a quasi-static formulation, which is newly developed for this work. This choice allows for a more realistic representation of the FOWT dynamics in tests that are meant to reproduce real-world loading conditions. For the same reason, a second-order diffraction wave forces modelling using Newman approximation is also introduced in this work.

The experiments were conducted in the Open Jet Facility at Delft University of Technology, which features a closed-loop open-jet test section with a nozzle exit of 2.85m × 2.85m. The turbulence intensity at hub height upstream of the turbine was approximately 2%, which is lower than typical offshore conditions. However, such low-turbulence inflow is suited for this study as higher turbulence would introduce uncertainty, for example, in the identification of motion-induced aerodynamic damping in decay tests.

2.2. HIL assessment

The HIL setup is first validated under no-wind and non-rotating conditions for all degrees of freedom. This step ensures that the system accurately reproduces the platform dynamics and that the force-feedback and force-correction procedures function correctly before aerodynamic effects are introduced. The HIL setup was already assessed in [7], but an updated floater model is used in this study, therefore requiring an additional assessment.

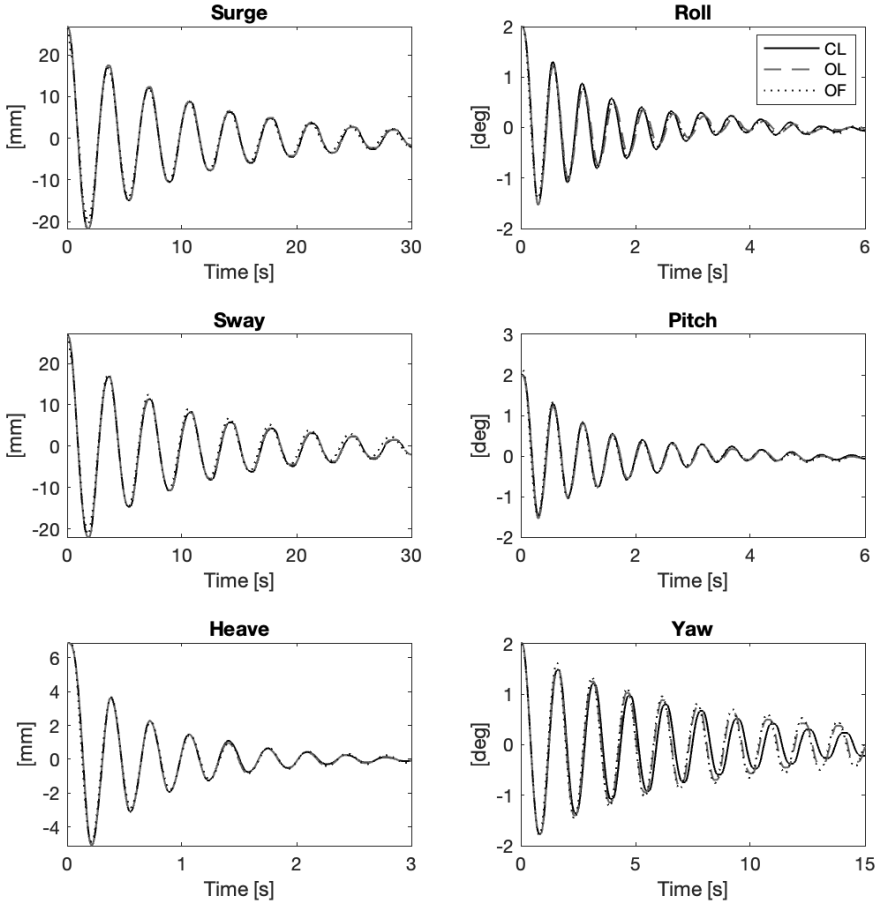


Figure 3. Assessment of the HIL system with decay cases in no wind condition in open-loop (OL) and closed-loop (CL) configurations for all DOFs and benchmarking with OpenFAST (OF).

Free-decay tests are performed for which aerodynamic loads are negligible, and only inertial forces associated with the platform motion are present. The closed-loop response, with force

feedback activated, is compared to an equivalent open-loop configuration in which the system is driven solely by the simulation, without force input. Figure 3 compares the open-loop and closed-loop configurations, and the OpenFAST benchmark. The time-series responses show an overlap between open-loop and closed-loop, indicating that the activation of force feedback does not alter the system dynamics. This agreement confirms that non-aerodynamic rotor loads measured by the load cell are effectively compensated and assesses the force-correction procedure within the HIL setup. The match with OpenFAST assesses the floater dynamic modelling.

2.3. Test cases

After assessing the HIL setup, the experimental investigation of aerodynamic damping is conducted. The tested cases are reported in Table 1. First, decay tests in all platform rigid-body degrees of freedom are performed. The decay tests are used to isolate the effect of aerodynamic damping on the dynamics of individual degrees of freedom. The tests are performed for wind speeds ranging from 0m/s, corresponding to no-wind and non-rotating rotor conditions seen in the assessment, up to 5m/s, which corresponds to an above-rated condition (the rated velocity is 4m/s). Although 5m/s case is not representative of an operating point because the turbine model has fixed blade pitch and cannot represent above-rated operations, it is used to extend the conditions for the quantification of the damping phenomena towards where it is more prominent.

Then, six cases of combined wind and wave tests representative of realistic metocean conditions are tested to investigate the aerodynamic contribution under operational conditions. These cases have a duration of about 215s, which corresponds to 3h at full-scale. Lastly, to isolate and investigate the effect of the wind speed on the aerodynamic damping also under wave forcing, selected wave cases are tested for wind speeds from 1m/s to 5m/s.

For all operating cases, the turbine is run at a fixed rotational speed corresponding to a tip-speed ratio of 7.5, without control, in order to isolate aerodynamic effects. All results are reported at model scale.

Test		**U (fs)** [m/s]	**U (ms)** [m/s]	**Hs (fs)** [m]	**Tp (fs)** [s]
Decay		0–15	0–5	–	–
Wind–wave	*case* 1	5.0	1.67	1.38	7.0
	case 2	7.1	2.37	1.67	8.0
	case 3	10.3	3.43	2.20	8.0
	case 4	11.4	3.80	3.04	9.5
	case 5	11.4	3.80	4.29	13.0
	case 6	11.4	3.80	6.20	12.5
		3–15	1–5	2.20	8.0

Table 1. Overview of the test cases. Wind speeds (U) are reported at full scale (fs) and model scale (ms), while wave conditions (Hs and Tp) are given at full scale.

3. Results

3.1. DOF dynamics

The decay time histories of individual DOFs are shown in Figure 4. The hexapod actual position signals were first filtered at 10Hz, which is higher than any motion dynamic and, for surge and pitch, the steady-state values of the cases with wind were subtracted to facilitate comparison. The color gradient represents an increase in wind velocity from blue to red. It can be seen that

the effect of wind is pronounced on the damping of the pitch motion, where already in the first peaks, there is a noticeable difference between the no-wind and wind cases, with a clear increase in damping as the wind speed increases. Pitch is expected to be the degree of freedom where aerodynamic damping is the most dominant, which has also been shown in recent studies [3], and it is therefore the DOF of primary interest of this study. The pitch response also shows an increase in frequency for increasing wind speed. Surge shows a similar trend but with a smaller effect, which is due to the higher modal mass of the DOF. Yaw shows a big effect, comparable to that of pitch. However, it has to be noted that the incomplete aerodynamic force estimation in yaw could introduce errors, despite the open-loop and closed-loop responses (Figure 3 match satisfactorily for the first cycles. Roll, sway and heave do not show any trend. This is expected given that the main aerodynamic force, the thrust, acts in a direction perpendicular to them. For the same reason, these DOFs are more subject to the influence of the motor vibrations and variation in torque, which impaired the tests at higher rotational speeds, which are not shown.

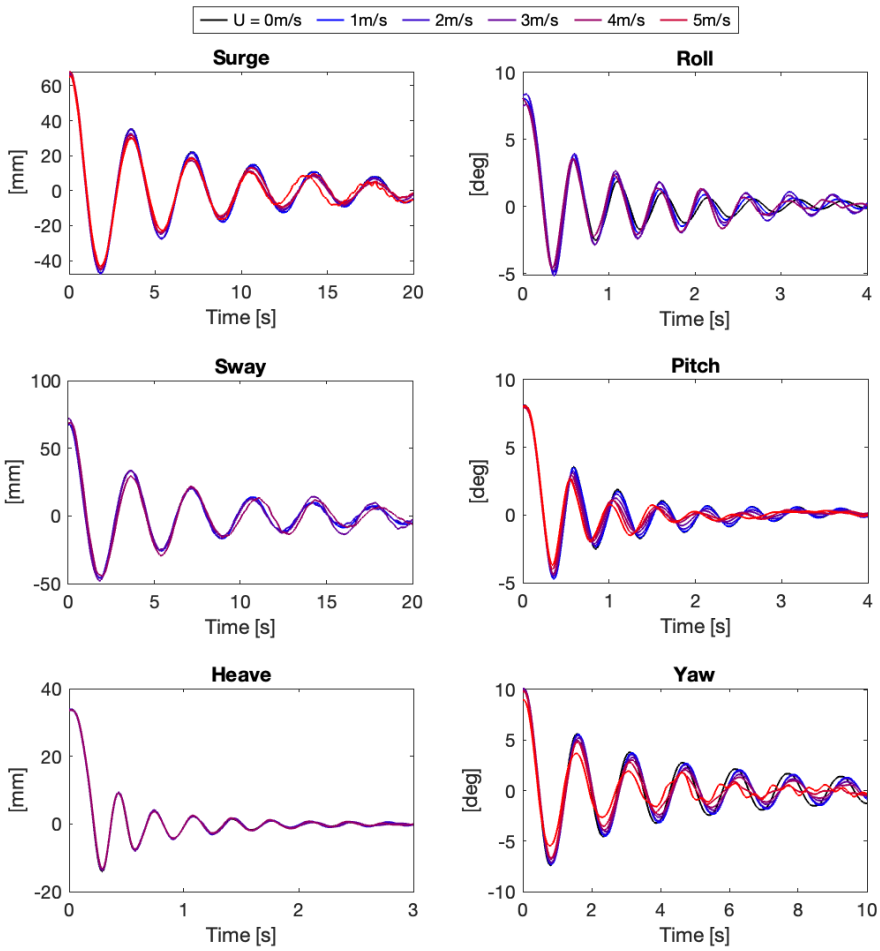


Figure 4. Time histories of decays for all individual DOFs and wind speeds from $0m/s$ to $5m/s$.

To quantify the effects observed in surge, pitch and yaw, the damping ratio and natural frequencies for each DOF are determined and shown in bar graphs in Figure 5. The damping

ratios are calculated with the method of the logarithmic decrement using the first two cycles. Damping ratios show a clear trend for all DOFs, underlining the dependency of aerodynamic damping on wind speed. At 4m/s, which corresponds to the rated wind speed of the full-scale reference, the damping ratio in pitch increases by 30%, from 0.13 to 0.17, with respect to the case with no wind. It is less than what was previously preliminary observed [7] and this can be attributed to the different floater modelling which results in a higher hydrodynamic damping, decreasing the percentage of increase due to the aerodynamics. The natural frequencies exhibit an increasing trend (increase of 11% between no-wind and rated) only for pitch and are instead fairly constant for surge and yaw.

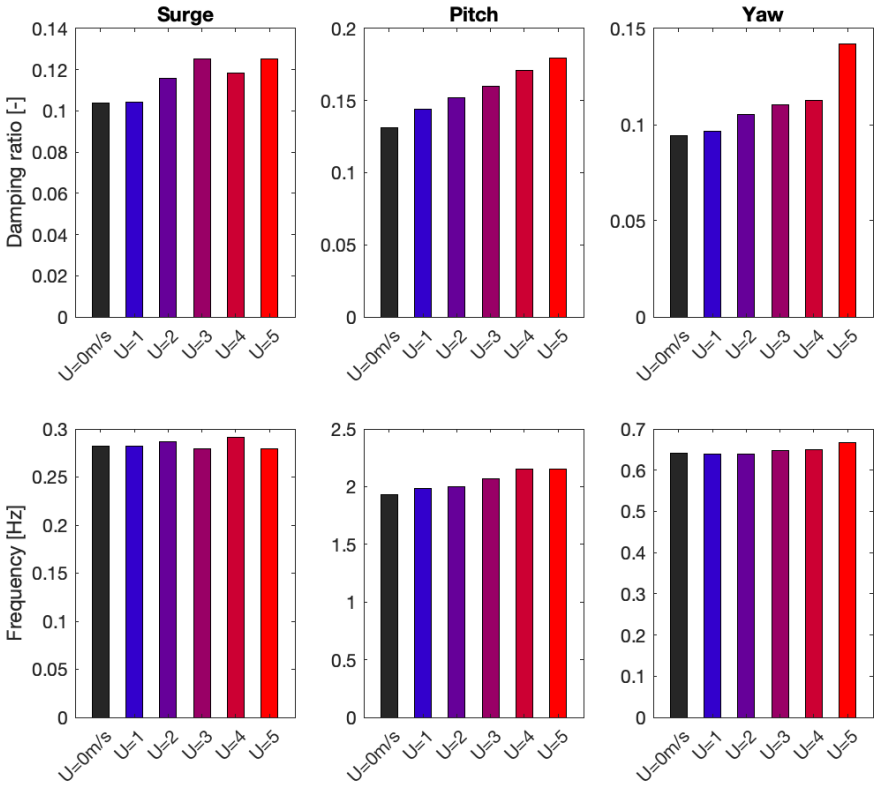


Figure 5. Natural frequencies and damping ratios of surge, pitch and yaw DOFs for wind speeds from $0m/s$ to $5m/s$.

To further investigate the mechanism of the damping increase, the time history of the variation of the aerodynamic thrust for pitch decays is shown in Figure 6. The aerodynamic thrust force is estimated by the HIL system in real-time and here it is reported filtered at 4Hz to visualise the variation at pitch frequency and offset to zero to ease the comparison. The thrust variation happens with a 90deg phase with respect to the motion, therefore confirming itself as the source of damping, and its amplitude increases with the increase of wind speed with a fairly linear trend.

3.2. Combined wind and waves

The motion response to combined wind and waves is shown in Figure 7, where the PSD of surge and pitch DOFs are compared between all the wave cases tested at the corresponding

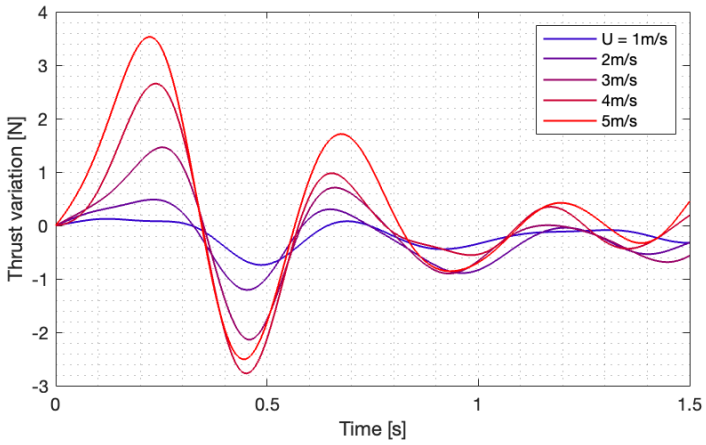


Figure 6. Time history of aerodynamic thrust estimated from measurements in pitch decays with wind speeds from $0m/s$ to $5m/s$.

wind speed. Two areas of activity can be identified: the natural frequencies range, where the peaks in correspondence with surge and pitch frequency are visible, and the motion response is dominated by the natural rigid-body dynamics of the platform DOFs, and the wave frequency range, where the response varies by wave case and is dominated by the wave forcing.

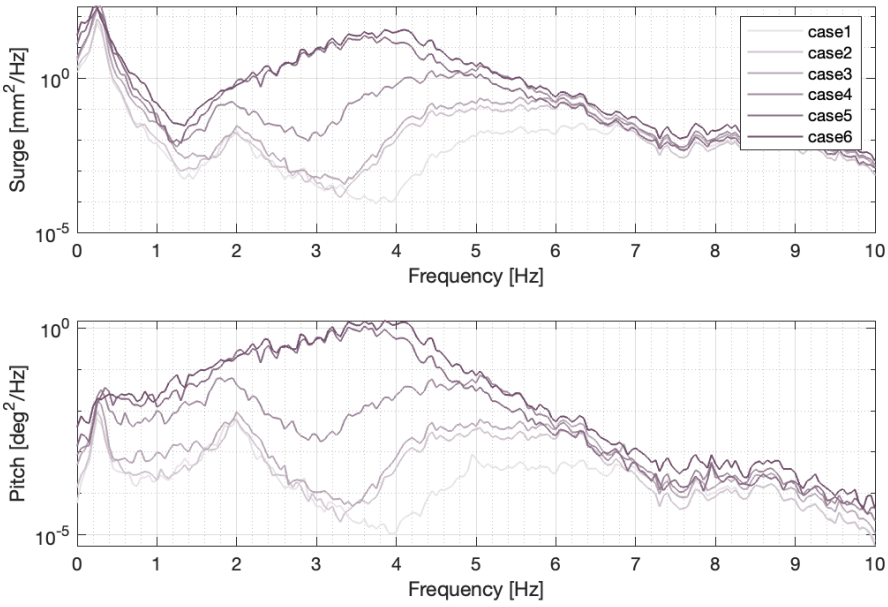


Figure 7. PSD of surge and pitch motion for wave cases 1 to 6.

The PSDs of one wave (case 3) for different wind speeds are reported in Figure 8. In both surge and pitch motion responses, the peak in correspondence with surge natural frequency (0.25Hz at model scale) remains invariant, with the only exception of the case of 5m/s. A

decrease of the peaks in correspondence with the pitch natural frequency (2Hz at model scale) for increasing wind speeds is observed in both the surge and the pitch response, except for the cases of 5m/s, whose peaks are the highest, and 4m/s, which has peaks lower if compared to the lowest wind (1m/s), but higher than $2-3$m/s. However, in the neighbourhood of the peak locations, the responses are observed to be higher for higher winds. The observed reduction in surge response at the pitch frequency is attributed to surge–pitch coupling, whereby increased pitch damping indirectly damps surge components coupled into the pitch-dominated band. As a limitation, it was noted that the tests at high rotational speed introduce additional low-frequency noise, possibly impairing the response in that area. At wave frequency, there is no visible effect of rotor aerodynamics on the motion response, which is only driven by the wave forcing in that range and does not seem to benefit from any aerodynamic damping.

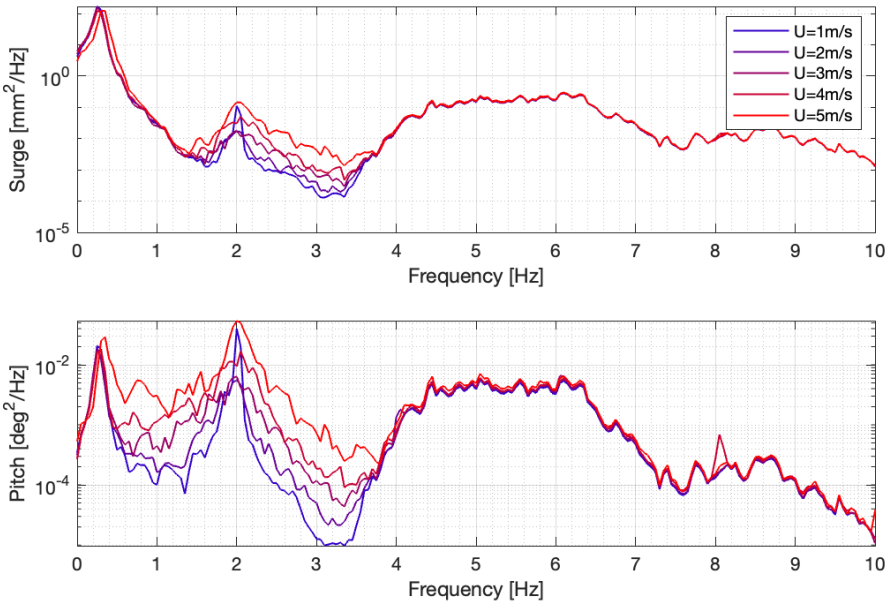


Figure 8. PSD of pitch and surge motion for wave case 3 and wind speeds from 1 to 5m/s

4. Conclusions

This study shows that a hybrid HIL wind-tunnel methodology can capture the coupling between rotor aerodynamics and floater dynamics with experimentally measured aerodynamic loads, enabling a direct assessment of aerodynamic damping effects on floating wind turbine motion response. The presented setup couples a thrust-scaled 10MW rotor model mounted on a 6-DOF hexapod with a real-time floater dynamics simulator representing a semi-submersible concept. A key enabler is the HIL architecture and force correction, which has been validated in a previous study [7], upon which this study builds. An updated model of the system is validated through no-wind, non-rotating free-decay tests across all DOFs, where open-loop and closed-loop responses overlap closely, indicating that the force-feedback loop does not distort platform dynamics and that non-aerodynamic load components are effectively compensated.

Decay tests under increasing wind speeds reveal that aerodynamic damping is strongly dependent on operating condition and DOF. Pitch is the most affected motion, and exhibits a

marked increase in estimated damping ratio with wind speed. The pitch damping ratio increases by approximately 30% at rated conditions relative to the no-wind case, while the pitch natural frequency shows a small upward shift with wind speed. This is confirmed by the increase in estimated thrust variation amplitude with increasing winds. Yaw and surge DOFs show similar trends for the damping ratio, but their natural frequencies remain constant.

Under combined wind–wave excitation representative of realistic metocean conditions, the influence of aerodynamics remains observable but becomes more selective in frequency: in most cases, power spectral densities show a reduction of response at the pitch natural frequency for increasing wind, whereas the surge natural-frequency peak is largely unchanged, and the wave-frequency range shows no effect. Overall, the results confirm that aerodynamic damping can alter the low-frequency motion response of floating systems, particularly pitch, yet its signature may be weak in wave-dominated frequency bands for the tested conditions.

References

[1] Deng Y, Zhang S Y, Yang Y, Zhang B, Wang Y, Chen J and Hou W 2025 Aerodynamic damping in decoupled dynamic modeling of floating offshore wind turbines *Ocean Engineering* **340** 122327 URL https://doi.org/10.1016/j.oceaneng.2025.122327

[2] Leroy V, Gilloteaux J, Lynch M, Babarit A and Ferrant P 2019 Impact of aerodynamic modeling on seakeeping performance of a floating horizontal axis wind turbine *Wind Energy* **22** 1019–1033 ISSN 1095-4244, 1099-1824 URL https://onlinelibrary.wiley.com/doi/10.1002/we.2337

[3] Carmo L, de Mello P C, Monaro R M, Mas-Soler J, Simos A N and de Carvalho e Silva D F 2024 Numerical modeling of wave basin experiments of a floating wind turbine with active thrust emulation: A discussion of important aspects *Ocean Engineering* **309** 118379 URL https://doi.org/10.1016/j.oceaneng.2024.118379

[4] Bonnefoy F, Leroy V, Mojallizadeh M R, Delacroix S, Arnal V and Gilloteaux J C 2024 Multidimensional hybrid software-in-the-loop modeling approach for experimental analysis of a floating offshore wind turbine in wave tank experiments *Ocean Engineering* **309** 118390 ISSN 0029-8018 URL https://www.sciencedirect.com/science/article/pii/S0029801824017281

[5] Belloli M, Bayati I, Facchinetti A, Fontanella A, Giberti H, La Mura F, Taruffi F and Zasso A 2020 A hybrid methodology for wind tunnel testing of floating offshore wind turbines *Ocean Engineering* **210** 107592 URL https://doi.org/10.1016/j.oceaneng.2020.107592

[6] Jiang Z, Wen B, Chen G, Tian X, Li J, Ouyang D, Peng Z, Dong Y and Zhou G 2025 Real-time hybrid test method for floating wind turbines: Focusing on the aerodynamic load identification *Journal of Ocean Engineering and Science* **10** 449–461 URL https://doi.org/10.1016/j.joes.2024.06.002

[7] Taruffi F, Thinakaran S and Viré A 2025 On the development of a hardware-in-the-loop wind tunnel setup to study the aerodynamic response of floating offshore wind turbines *Wind Energy Science Discussions* **2025** 1–28 URL https://doi.org/10.5194/wes-2025-100