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Active control of yaw drift of single-point moored wind turbines

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Abstract. Single-point moored floating wind turbines can benefit from the self-alignment of the structure with the prevailing wind direction. However, to be successful, the effects of yaw-drift must be mitigated using effective control strategies during power production. In this work, we investigate sources contributing to yaw drift and propose active control solutions to the problem. The analyses utilize the IEA 15 MW wind turbine mounted on a single-point moored floating foundation. Aero-hydro-servo-elastic simulations using the software 3DFloat are performed under various conditions of wind, waves and current. The results indicate that yaw drift can be actively controlled using nacelle-yaw actuation techniques and individual pitch control of the blades. These approaches effectively align the rotor with the wind direction, increasing the robustness of single-point wind turbines by ensuring increased power production, and maintaining the structural life.

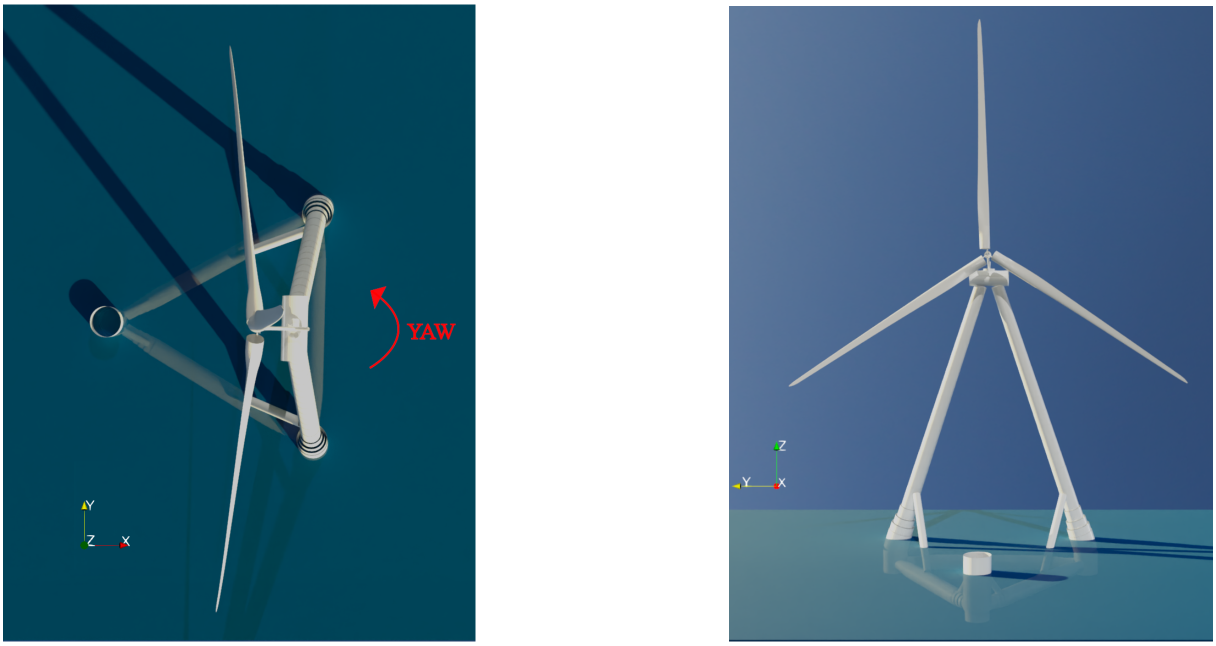
1. Introduction

To reduce the levelized cost of energy in floating wind systems, innovative substructures and foundations have been proposed in recent years. Among the solutions, single-point mooring (SPM) systems offer unique capabilities that can reduce the cost of offshore energy production [1].

SPM systems were first used in the oil and gas industry on floating production, storage, and offloading units (FPSOs). The SPM allows vessels to rotate freely around the mooring point, thereby aligning with the main direction of waves and currents. This behavior reduces loads due to environmental conditions [2].

To achieve a similar self-aligning behavior, some floating platforms for offshore wind turbines employ SPM technology. One of the current designs that exploit this ability is the BRUNEL floating foundation developed by Fred. Olsen 1848. Figure 1 gives an overview of the BRUNEL design with three columns interconnected by horizontal pontoons and two inclined towers to support the rotor-nacelle assembly (RNA).

However, differently from ships, SPM floating wind turbines are subject to significant aerodynamic loads and their self-alignment behavior is non-trivial [3]. Indeed, power production in SPM floating wind systems can benefit from the use of control systems to mitigate yaw drift [4, 1].



(a) Top view. (b) Front view.

Figure 1: 3DFloat model of the BRUNEL design.

Liu et al. [2] discussed several causes for this drift, such as wind shear, shaft tilt and coning angle. The resulting yaw misalignments reduce the energy yield and increase structural loads. Therefore, in all floating wind turbines, active control is already necessary to maintain performance and limit motions. Additionally, within SPM systems, active control plays a crucial role in stabilizing yaw behavior.

Among the active solutions to control the yaw drift of SPM floating wind turbines, individual pitch control (IPC) is suggested in [4] and [5]. By doing so, a periodic pitch of the blades during each rotation corrects for the occurrence of the aerodynamic moment that tends to yaw the system.

The work below builds upon previous studies on SPM applied to floating offshore wind turbines. While previous efforts suggested different sources for yaw drift and the use of IPC to solve it, the present effort shows that the source of yaw drift in the BRUNEL design with a 15 MW wind turbine is an aerodynamic effect, and we compare a strategy to control the drift based on the yaw bearing control of wind turbines with the IPC strategy.

2. Sources of yaw drift in SPM floating wind turbines

The results in this study suggest that the yaw drift in SPM floating wind turbines occur primarily due to aerodynamic effects. A wind turbine will experience a difference in the relative wind speed at each side of the rotor. Figure 2 shows the variation in the local wind speed at relative radius $r/R = 0.78$ as a function of the azimuth angle, Ψ, considering two tilt angles, θ, of the rotor shaft: $\theta = 6°$ (used by the IEA 15 MW rotor) and $\theta = 0°$. The results in Figures 2 and 3 reflect purely aerodynamic simulations of the rotor, thereby neglecting platform oscillations, gravitational or gyroscopic effects. Collective pitch of the blades is computed through the ROSCO controller [6]. The wind speed, V, is constant and uniform at 20 m/s, but the tilt of the rotor leads to a higher local wind speed when the azimuth angle is close to $\pi/2$ (90°) and a lower wind speed when the azimuth angle is close to $3\pi/2$ (270°).

The difference in the local wind speed leads to higher aerodynamic loads at one side of the

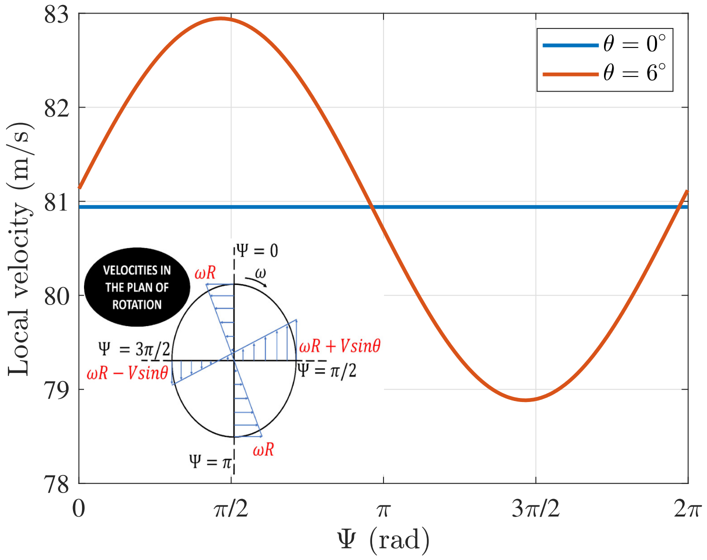


Figure 2: Relative wind speed variation during a rotor rotation in steady state without gravity.

rotor, which causes an aerodynamic moment, M_z, that tends to yaw the turbine. Figure 3 shows how this moment varies as a function of the wind speed and of the tilt angle of the rotor, θ, which was found to be the main source of yawing moment in the IEA 15 MW.

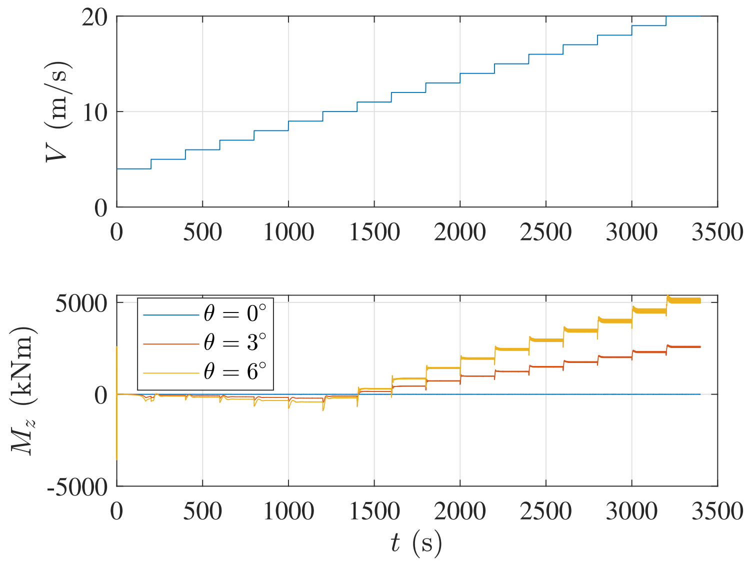


Figure 3: Upper plot: wind step variation; lower plot: corresponding yawing moment for different tilt angles of the rotor.

The aerodynamic moment observed in Figure 3 is present in all wind turbines that have some source of difference in the local wind speeds between opposite sides of the rotor. Wind shear, shaft tilt and coning angle have all been suggested in previous work [2] as possible reasons for the yaw drift of SPM floating wind turbines. In fact, the platform pitch also induces a relative angle between the rotor plane and the incident wind that leads to an aerodynamic yaw moment.

Other effects such as turbulence, controller settings and aeroelastic response of the blades can also contribute to the yaw moment. However, the resulting aerodynamic moment is commonly counterbalanced by the mooring system (in the case of floating wind turbines with mooring lines in multiple points) or the attachment to the ground (in the case of bottom-fixed or onshore wind turbines). Floating wind turbines with SPM lack these countermeasures and will hence rotate freely under such aerodynamic moments from the rotor. Therefore, a yaw offset can be observed between the wind direction and the steady-state rotor axis orientation, as shown in Figure 4 for cases with uniform wind without waves or current.

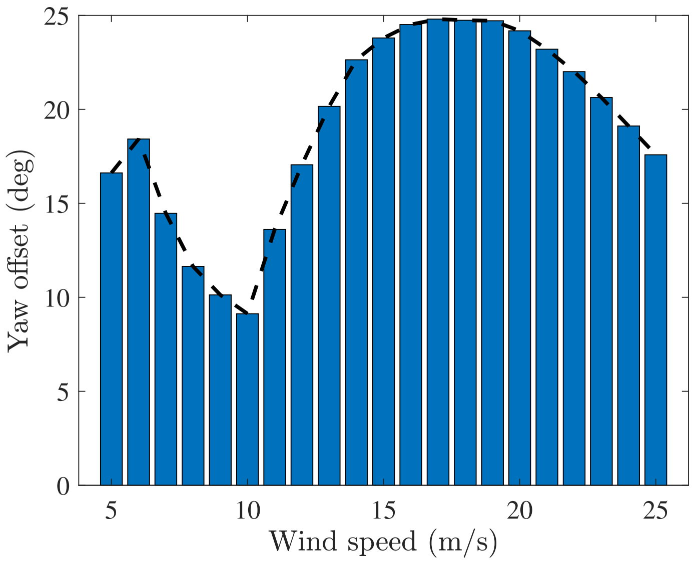


Figure 4: Yaw offset in steady-state regime for uniform wind without waves or current.

3. Aero-hydro-servo-elastic simulations

The BRUNEL floating platform developed by Fred. Olsen 1848, which serves as the basis for this study, was modeled using the software 3DFloat [7]. Gravitational and gyroscopic effects are taken in account during the simulations. The model was validated against experimental decay tests. Figure 1 shows the finite element model representation of the system. The IEA 15 MW wind turbine [8] is mounted on top of the platform. The blades are modelled as flexible elements and hydrodynamic loads are computed from the Morison equation [9].

4. Yaw-drift control

Previous studies [4] have successfully employed individual pitch control (IPC) to reduce the drift between the rotor and the wind direction in SPM wind turbines. Here, the classical nacelle yaw actuation will be considered as an alternative to mitigate yaw misalignments in SPM floating wind turbines.

4.1. Individual pitch control

Sandua-Fernández et al. [5] suggests the use of IPC with a classical proportional-integral controller along with the inverse multi-blade coordinate transformation [10]. Figure 5 offers a comprehensive schematic of IPC applied to SPM floating wind turbines, where $\Delta\psi$ is an error signal defined as the difference between the signals from the sensors measuring the main wind direction and rotor hub axis direction and subjected to low-pass filtering. ψ_{wind} is the main wind direction, β_A is the amplitude of the individual pitch actuation, k_P and k_I are the proportional and integral gains of the controller, respectively, β_C is the collective pitch, ϵ is an offset in the azimuth angle and β_1, β_2 and β_3 are the individual pitch angles of the three blades, respectively. ψ_p is the platform yaw, which is adjusted by means of IPC.

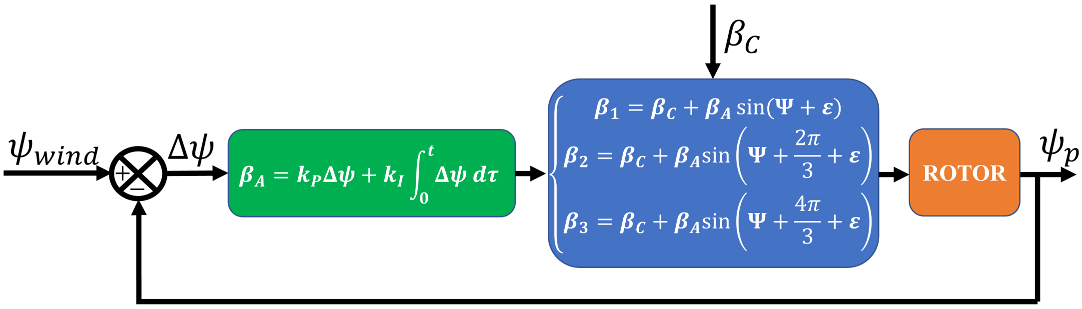


Figure 5: Schematic of IPC applied to SPM floating wind turbines.

4.2. Nacelle yaw actuation

The control design based on the yaw bearing actuation uses a logical architecture. The following signal is input to the controller:

$$\dot{\psi}_{actuator} = \dot{\psi}_{motor} sign(\Delta\psi) \ , \tag{1}$$

where $\dot{\psi}_{actuator}$ is the output yaw rate, and $\dot{\psi}_{motor}$ is the nominal yaw rate of the motor.

Yaw actuation is not continuously active. The error signal is measured at time intervals ΔT and yaw actuation occurs according to Equation (1) while the last measured error is above a specified tolerance.

5. Results

The first test for the nacelle yaw controller investigates the stability of the controlled system. To do so, step variations in the wind direction are performed every 1000 s considering two different wind speeds, as shown in Figure 6: the wind speed was maintained at $V = 20$ m/s until 3000 s and then reduced to $V = 9$ m/s after that time. The wind is uniform and waves or current are not considered. In addition, the controller is tested with different monitoring intervals of time of the yaw misalignment: $\Delta T = 1.0$ s, 10.0 s, and 20.0 s.

The results indicate that the controller with yaw error measured every 1.0 s demonstrated exceptional aligning of the rotor towards the incoming wind direction. In this case, the power production was increased by 1.39% for $V = 9$ m/s when utilizing the yaw control, compared to the system without yaw control. This showcases the potential benefits of the yaw control system in enhancing energy generation efficiency, especially at low wind speed, where yaw misalignments may affect the power production. However, it was observed that increasing the time interval between error measurements resulted in undesired consequences. For larger sample intervals, ΔT (e.g., 10.0 s and 20.0 s), the rotor response exhibited oscillations and even unstable behavior. This represents a very strong limitation of this controller because continuous actuation of the yaw bearing mechanism every second may not be feasible in practice. Yawing at such a rate could lead to excessive wear of the components, thereby requiring frequent maintenance.

5.1. Saturated nacelle yaw actuation

An alternative to overcome the limitation of small sample intervals for the yaw controller is to saturate the maximum and minimum actuation yaw angles allowed for the yaw bearing

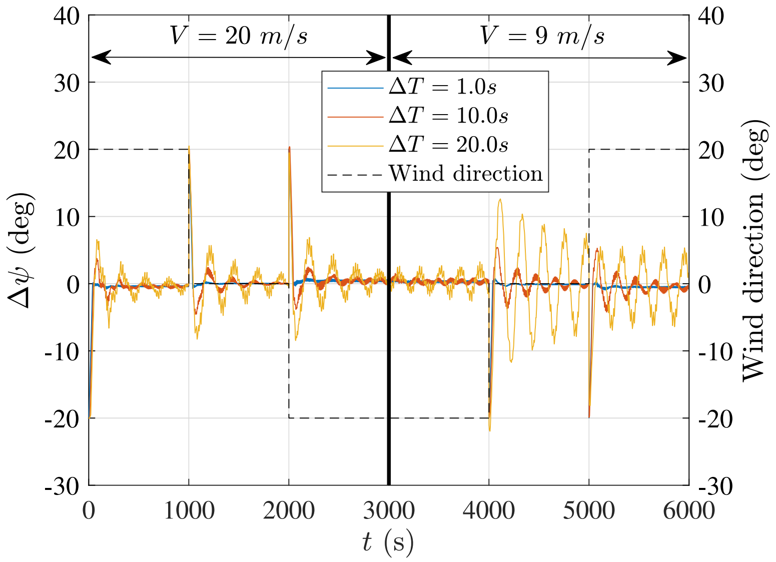


Figure 6: Error signal during a step response due to variations in the wind direction.

mechanism. In this sense, the saturated nacelle yaw actuation (SNYA) allows for larger sample intervals, ΔT. To test this approach, the minimum yaw angle allowed for the yaw actuation was set to 1°, permitting only positive angles in the yaw mechanism, and the maximum allowable actuation was set to 6.5°, that is, $1^{\circ} \leq \psi_{actuator} \leq 6.5^{\circ}$. This control strategy relies on the fact that, despite of the small and positive yaw actuation, the aerodynamic moment caused by the rotor drives the platform dynamics in such a way that the platform yaws itself into the wind. Considering a step response similar to that presented in Figure 6, and adopting $\Delta T = 20$ s, the corresponding actuation angle of the yaw mechanism is given in Figure 7. The motor usage in the latter case is reduced to 7% of the operational time.

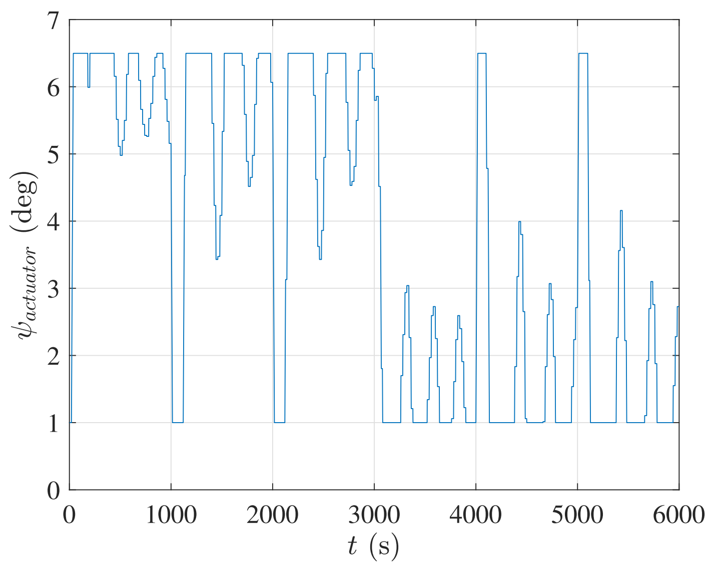


Figure 7: Saturated control output during a step response due to variations in the wind direction.

5.2. Comparison of control strategies

Figure 8 compares the performance of SNYA and IPC during a step response similar to that presented in Figure 6. The IPC adopts gains $k_P = 1.5$ and $k_I = 1 \times 10^{-8}$. The strategy of saturating the yaw actuation leads to a good response following the error signal, that is, the rotor is capable of following the wind direction with good accuracy. Besides, the platform also reaches stability. Indeed, for practical purposes, the saturation angles can be defined by observing the maximum and minimum steady-state values of the angles between the hub and the platform throughout the range of wind speeds of operation. This result proves that despite of the error signal being positive or negative, the combination between platform dynamics and saturated nacelle yaw actuation always leads the system to align with the main wind direction. The comparison between the yaw nacelle control and IPC reveals that the latter reaches stability faster than the nacelle yaw control, thereby offering higher stability to the floating system.

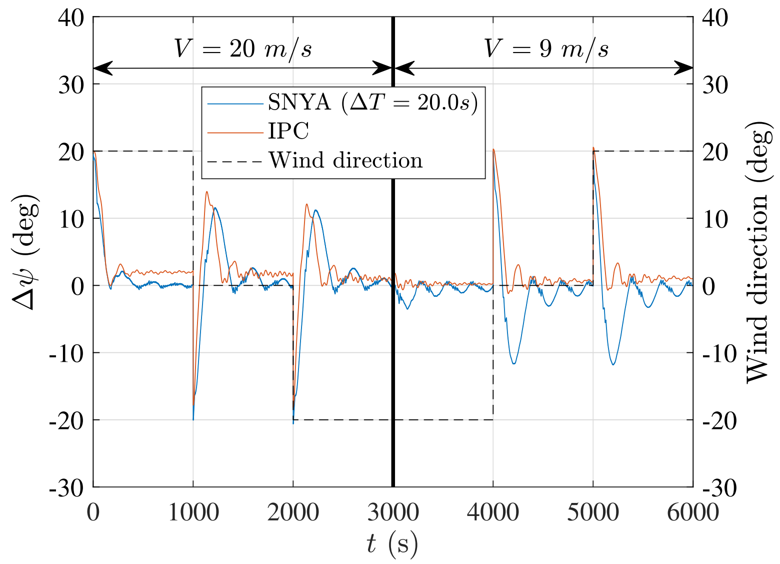


Figure 8: Error signal of the saturated controller during the step response.

An additional test of the controllers considered extreme environmental conditions with waves, current and turbulent wind. Turbulence levels of 17% and specific waves (significant wave height $H_s = 6.5$ m and peak period $T_p = 12.6$ s) and current (sea current surface speed $u_c = 0.635$ m/s) representing site C from the LIFES50+ report [11] were applied. The mean wind speed is 20 m/s. The results are shown in Figure 9 considering SNYA with $\Delta T = 20$ s and the IPC.

The results indicate a major improvement in the alignment between the rotor and the wind direction when using the controllers. Besides, despite of the challenging environmental conditions, SNYA with $\Delta T = 20$ s still ensures a good performance of the nacelle yaw controller. Deviations from the predominant wind direction indicate situations where the dynamics of the platform are faster than the time taken by the controller to turn the rotor towards the wind direction. Similar results are achieved with IPC, thereby suggesting that if IPC is taken as the main control system for yaw drift in SPM floating wind turbines, a yaw nacelle control can be defined as a redundant system in case of fail of the IPC and vice-versa.

Future works could investigate the viability of the presented control methods by evaluating its performance under more realistic and comprehensive environmental conditions. Additionally, inputs from manufacturers of yaw bearing mechanisms and wind turbine generators may help to enhance the controller within the operational limitations. Finally, comparisons between

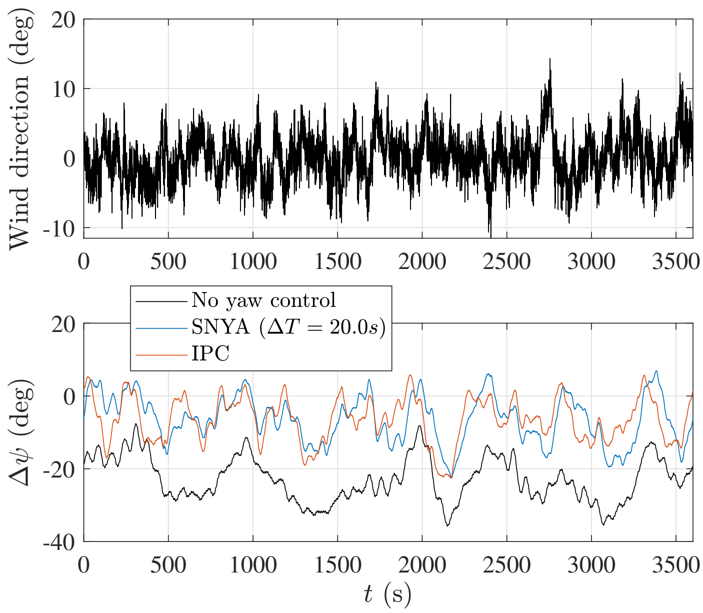


Figure 9: Upper plot: wind direction; lower plot: error signal during the extreme environmental condition.

loads and power production of SPM floating wind turbines with yaw control systems and standard floating systems with three mooring lines may indicate the advantages of SPM over the traditional design.

6. Conclusions

This work shows the main sources of yaw drift of a SPM floater hosting an IEA 15 MW reference turbine. An aerodynamic moment that occurs due to different local velocities on both sides of the rotor - similar to the effect observed in helicopters in forward flight - tends to yaw the system. A solution to the problem was proposed by using the yaw bearing system to control the yaw behavior of the floating wind turbine. This approach requires saturation of the maximum and minimum values of yaw actuation in order to reach a lower usage of the yaw bearing mechanism. The saturated nacelle yaw actuation was compared with individual pitch control of the blades. The controllers were tested in step responses and cases with turbulent wind, waves and current. Both strategies improved the alignment between the rotor and the direction of the incoming wind. Therefore, a yaw nacelle control can serve as a redundant system to individual pitch control, or vice-versa, to mitigate the yaw drift in single-point moored wind turbines.

Acknowledgments

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