Preliminary assessment of yaw alignment on a single point moored downwind floating platform

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Abstract. The ability of Single Point Moored Downwind platforms to align with the main wind direction, depends on the floater and wind turbine design. When co-directionality between wind, waves and current exists, there is no external loading that can difficult the floater alignment. On the other hand, when certain metocean conditions take place, such as a crosscurrent, a misaligning force can prevent the floater to face towards the main wind direction.

In this study, the PivotBuoy floater is used to evaluate the Single Point Moored platform’s ability to align with the main wind direction. The platform dynamics are assessed under irregular wind and wave conditions for current speeds ranging from 0.1 m/s to 1.5 m/s for different wind-current alignments. Two solutions for improving the platform alignment are presented and compared against the baseline case, for the extreme and unusual condition where the platform is operating with a crosscurrent of 90° and 0.4 m/s. Both proposed strategies, an active, based on Individual Pitch Control, and a passive where a static nacelle yaw offset is used, are able to reduce the mean alignment to be within 0.8° compared to the baseline case of 18.7°. The preliminary analysis show promising results for the proposed solutions but need to be further investigated in detail.

1. Introduction

The European commission targets carbon-neutrality by 2050 and identifies wind energy as a driving technology to fulfill the commitment [1]. The wind energy market is pointing towards solutions on deeper waters of which an important part will be covered by floating wind. Engineering, manufacturing, logistics and installation challenges arise when installing MW-floating concepts in deep waters [2] [3] [4]. Among the various existing innovative floating concepts, Single Point Moored (SPM) platforms bring to the table a series of innovations that overcome some of the floating-wind constraints previously defined.

The PivotBuoy platform, developed by X1 Wind, includes a SPM system which integrates mooring, anchoring system and electrical point in a single point. On the turbine side, a downwind concept is used to facilitate the platform alignment with the wind direction, also known as weathervaning effect, and unlocks additional advantages for large-scale offshore machines such as the possibility of increase blade deflection. However, the designed mechanism for platform self-alignment on a MW-machine might not be sufficient and can lead to undesired misalignment when certain metocean conditions occur. The concept is presented in figure 1.
This paper presents a preliminary assessment of the yaw alignment of the PivotBuoy floater with a 15MW turbine. Two solutions are presented: an active feature where the concept remains unchanged and Individual Pitch Control (IPC) is used to improve the alignment, and a passive solution, which consists on a static modification of the nacelle-yaw angle of the baseline PivotBuoy design.

2. Motivation

Modelling the dynamic response of floating wind turbines is a complex multi-physics problem which requires advanced numerical tools. Among others, FAST, Bladed and HAWC2 are examples of existing software capable to do so. The ability and accuracy of such codes to model offshore wind systems has been assessed in the Offshore Code Comparison Collaboration (OCCC), a framework where different participants shared their technical knowledge and compared their modelling capabilities. The modelling and comparison efforts allow to have aero-servo-hydroelastic tools capable to predict the platform dynamics and assess the feasibility of innovative concepts early in the design process.

In this study, the focus is on the ability of the platform to face the main wind direction, i.e. the floater alignment, which impacts the power production during operation. It is worth mentioning that the concept used in this study does not include a yaw controller and depends solely on the platform-turbine self-aligning design to rotate towards the main wind direction. The platform equilibrium of such downwind concept relies on multiple phenomenon which vary, among others, depending on the platform misalignment, wind speed, wave condition and current. Only the phenomena with higher influence are described here: (1) thrust-roll induced yaw moment, (2) aerodynamic restoring moment for yawed rotors, (3) passive aerodynamic drag and (4) the met-ocean conditions.

The first phenomena, the thrust-roll induced yaw moment, originates from the roll angle induced by the turbine torque which displaces the originally aligned axis between the aerodynamic thrust
and the platform rotation point. The higher the roll and the point of application is, i.e. hub height of the turbine, the larger the induced yaw moment will be. Even though the loading has a restoring effect if the floater rotates to the opposite direction than the exerted force, it should be considered as a counteracting force to the alignment since the yaw moment exists even for the aligned case as long as platform roll exist.

The second phenomena deals with the loading imbalance when skewed flow is present on a wind turbine. The rotor yawed towards the main wind speed direction encounters unaltered, therefore higher energy flow, creating a larger loading compared to the opposite side, facing disturbed or waked flow. This creates a restoring moment towards the main wind direction [5].

The third phenomena, passive aerodynamic drag, acts as restoring loading dependent on the wind speed and exposed area, the latest being driven by the wind-platform misalignment. This loading should be seen to have the same effect as a wind-vane: a yawing moment will occur if the centre of the drag loading is not aligned to the centre of the platform rotation.

Finally, the metocean conditions drive the overall platform motion, including pitch and roll, that are coupled with all previous phenomena. Additionally, if misaligning loading is included, for example currents that are not aligned with the main wind direction, the floater will encounter a constant loading that will difficult the platform alignment. A proper floater design ensures lower to non-existent misalignment when co-directional wind direction and current is present. On the other hand, when misaligning loading is present, the ability of the platform to align towards the main wind direction is not guaranteed.

3. Method
3.1. Software and platform model
The platform and turbine are modeled in DTU’s Wind Energy in-house aero-servo-hydro-elastic code HAWC2 [6]. The structural model is based on nonlinear multi-body formulation coupling different independent bodies together by algebraic constraints. The non-linearity comes from dividing each body in a set of Timoshenko beam elements with 6 DOF each. The aerodynamic model is based on improved Blade Element Momentum (BEM) theory with numerous corrections as Prandtl tip-loss factor, Glauert for heavily loaded rotors or Beddoes-Leishman dynamic stall model.

On the other hand, hydrodynamic forces due to the waves acting on floating or fully submerged members, are modelled using slender-body theory through Morison equation [7]. Therefore, three main terms are taken into account: the Froud-Krylov force, the water added mass and the drag force. Wave diffraction is not modelled in HAWC2. Nevertheless, as Morison equation is only valid for slender structures, when modelling semi-submersibles or platforms with very wide floating members where the diffracted wave field becomes significant, HAWC2 provides the possibility to include a correction on water particle acceleration, based on McCamy-Fuchs theory [8]. The software is also capable of including other corrections such as wheeler stretching, and the flexibility of the floating members.

In this study, both the platform and the turbine are modelled taking into account the flexibility of the different members. Moreover, the aerodynamic drag of the platform is also modelled by assigning aerodynamic drag coefficients to the truss elements. In HAWC2, the connection between the pivot top and the pivot bottom is modelled as a spherical bearing, allowing rotation in the 3 degrees of freedom, with a low friction value.

The reference model of the upwind IEA 15MW turbine [9] has a rotor tilt angle of 6°, a cone
angle of 4°, and the blades present prebend. In the PivotBuoy platform, the turbine is mounted as downwind, removing the tilt and blade prebend. Nevertheless, it has been assumed that hub would be kept the same as in the original design, therefore the turbine model keeps the 4° cone angle as in the upwind design. The main turbine characteristics are shown in table 1.

Table 1. IEA 15MW Downwind Configuration used for the PivotBuoy platform

| Parameter         | Units | Value |
|-------------------|-------|-------|
| Rated power       | MW    | 15    |
| Rotor diameter    | MW    | 240   |
| RNA mass          | t     | 1017  |
| Hub height        | m     | 140   |
| Nominal rotor speed| rpm  | 7.6   |
| Control           |       | Variable speed |
| Shaft tilt        | deg   | 0     |
| Cone angle        | deg   | 4     |

3.2. Active Alignment Strategy: individual pitch control (IPC)

Individual pitch control (IPC) is one of the popular active control methods for alleviating the turbine structural loads [10]. Typically, the blade pitch is controlled actively in response to the load measurements from the blade-root. In brief, the flap-wise blade-root bending moments are projected into a non-rotating frame of reference via Coleman transformation, resulting in the tilt and yaw moment of the shaft. Based on these tilt and yaw moments, the controller, either two Proportional-Integral (PI) or Multiple-Input-Multiple-Output (MIMO) design, is then developed to compute the blade pitch action in the fixed coordinate. By using an inverse Coleman transformation, the blade pitch reference signal is then projected back to the rotating reference frame and sent to the blade pitch actuator. The idea of active alignment strategy in PivotBuoy is to actively change the blade pitch angle individually in response to the turbine yaw misalignment with the wind direction. By exploiting the flexibility in the pivot top, the platform will rotate around the pivot top based on the IPC-induced yaw moment, as shown in figure 5.

The working principle is described as follows. First, the yaw error is computed based on measured wind direction and yaw angle set-point, which is 0 deg in this case. Based on the yaw error signal, a PI controller is developed to compute the required yaw moment for mitigating the misalignment. Notice that the dynamics of the tilt and yaw moments of the shaft are typically strongly coupled [11], namely any changes in the yaw referred blade pitch angle would affect the tilt moments on the shaft. Thus, an inverse steady-state gain matrix, that consists of the sensitivity of the tilt and yaw moment with respect to the tilt and yaw referred pitch angle, is used for decoupling the tilt and yaw moment dynamics, which is valid based on an assumption that the dynamics of the whole process is slow. Notice that this steady-state gain matrix varies upon the operating condition (e.g. pitch), thus a gain-scheduling approach is employed. Eventually, the referred pitch angle signal in the fixed coordinate is projected into the rotating frame of reference via the inverse Coleman transformation and sent to the blade pitch actuator.

3.3. Passive Alignment Strategy: Offsetting

The concept of introducing a nacelle yaw offset aims to create a static restoring moment to improve the platform alignment. For a given specific site where the platform is to be deployed,
a power-assessment study can be performed to find the optimal nacelle yaw offset that would maximize the power production. When the static offset is introduced, the rotor is no longer aligned with the platform rotation axis, pivot connection, thus the thrust force creates a moment around the rotation axis. An illustration of the strategy concept is shown in figure 2, where $\theta$ is the yaw offset angle.

As opposed to a yaw controller, the static yaw offset is a passive strategy which does not require an actuator. It has the advantage that it can be adapted from the original system setup, without the addition of external actuators nor increasing the system complexity or weight. For a given baseline design with sufficient weathervaning dynamics, small yaw angle rotations are sufficient to mitigate severe metocean conditions. Therefore, a conventional yaw controller where the system is dimension to allow complete nacelle rotation, is not required and the proposed strategy offers a viable alternative to such mechanism.

4. Results

The platform alignment and its coupled dynamics are presented in this section under various metocean conditions. First, the weathervaning of the platform is assessed in the most simple case where the wind direction is aligned with the turbine. Then, misaligning loading is added to the set-up by including directionality between wind and current. Then, both active and passive solutions are presented and the alignment improvements analyzed. In this study, results for a single wind speed case of 8 m/s have been performed. The results are obtained for unsteady wind simulations with turbulence intensity of 9.5% using Mann’s spectral formulation [12] and a power law shear with an exponent $\alpha$ of 0.14. For the wave input, Jonswap spectrum has been used with a $\gamma$ value of 3.3, a significant wave height of 2 meters and a period of 10 seconds. The average values of six independent realization of 10 minutes simulations are presented. The proposed metocean values are considered significant for offshore conditions as presented in [13].

Co-directional wind and waves have been used, being the current direction and velocity the only varying parameter of the simulations. This simplification is made to illustrate the solely effect of current speed and direction on the platform misalignment. The range of analyzed current covers from normal speeds at which the turbine is expected to produce, to extreme speeds which are normally associated to storm events when the turbine is normally shut-down. All simulation results presented in the below sections are expressed in HAWC2 coordinate system, illustrated in figure 2. Zero degrees incident wind and waves are along the positive y axis. Current direction is expressed relative to wave direction in degrees, and is positive current when it comes from the right looking towards the incoming waves.

![Figure 2. Coordinate system used for the results. In red, $\theta$, is the nacelle yaw offset.](image-url)
4.1. Baseline Model - Cross Currents

The platform alignment for a range of current velocities from low sea-state, $V_c$ lower than 0.4 m/s, moderate sea-state, $V_c$ between 0.6 m/s and 1 m/s, and extreme state, $V_c$ larger than 1 m/s, for the complete range of current-wind misalignment is shown in figure 3.

![Figure 3](image-url)

**Figure 3.** Average platform rotation as function of current-wind misalignment for unsteady wind and waves at 8m/s.

The average platform rotation results, shown in figure 3, are aligned to the physical phenomena described in section 2. As a general trend, the larger the current velocity and misalignment is, the larger the angle where the platform finds equilibrium is (platform rotation) is. It is also worth mentioning that the platform rotation is not zero for low currents aligned with the wind speed, as seen in the left sub-panel of figure 3. However, for the three lowest current velocities presented, the average values are lower than 2.5°.

The modest platform rotation, when current and wind directions are aligned, originates from this particular turbine design. The periodic gravity effects, coupled with a highly-flexible turbine blade, results in a non-zero yaw moment which induces a platform rotation even with aligned loading. This effect is also noticeable in the asymmetry of the platform rotation for opposite wind-current direction misalignment. In example, when subjected to a current of 0.4 m/s and 90° misalignment, the platform finds equilibrium at 18° while for the opposite current direction, -90°, the equilibrium is found at 16°.

As this study is a preliminary assessment of an active and passive solution to platform misalignment of a downwind single point moored platform, the highest current velocity during operation, $V_c = 0.4$ m/s, along with the current misalignment which results into the highest platform rotation, 90°, is used to assess the performance of the proposed solutions.

4.2. Proposed solutions

The active and passive solution presented in section 3 are compared to the baseline in this section. In order to determine the static nacelle yaw offset required to compensate the platform
misalignment under the studied scenario, the platform is simulated with different nacelle offset angles. Then, the platform rotation and the rotor alignment is analyzed to choose the best performing case.

![Graph](Image)

**Figure 4.** Mean platform and rotor misalignment for different yaw offset angles under the studied scenario.

Figure 4 shows the mean of the 6 simulation results obtained for a selected number of angles, from -4 to -0.5°. It is important to mention that the platform misalignment relation to nacelle yaw offset is nearly linear only for small offset angles such as shown in figure 4. However, it becomes non-linear for higher yaw offset angles, both positive and negative. As observed, for the baseline case where 90° wind-current misalignment is present, the nacelle yaw offset that allows the closest rotor alignment, is -2.5° (see figure 2 for coordinate system reference). Therefore, this is the selected static offset used for the comparison against the baseline and the IPC strategy. The active solution is also analyzed for the baseline case, and the mean and standard deviation comparison results for selected performance parameters are presented in table 2.

| Case                        | Baseline | IPC        | Yaw offset |
|-----------------------------|----------|------------|------------|
| Platform misalignment [°]   | Mean     | Std        | Mean       | Std        | Mean       | Std        |
| Power production [MW]       | 5.81     | 2.29       | 6.34       | 2.33       | 6.36       | 2.31       |
| Blade pitch [°]             | 0.00     | 0.00       | 0.00       | 2.43       | 0.00       | 0.00       |
| Flange yaw moment [kNm]     | -3171.52 | 6171.88    | -4809.02   | 6878.72    | -195.57    | 5819.33    |
| Thrust [kN]                 | 1099.92  | 282.64     | 1222.36    | 315.99     | 1222.86    | 310.08     |

Regarding the platform-wind alignment, it can be observed that while for the baseline case a mean misalignment is present, it is corrected by both proposed solutions. This is reflected in a better performance of the turbine, producing more than 8 % higher power when using the proposed strategies compared to the baseline. Nevertheless, analyzing the misalignment standard deviation, it can be emphasized that the IPC is the strategy capable of reducing the deviation the most, as a consequence of being an active mechanism.

Another parameter analyzed is the blade pitch activity. There is no such activity for both the baseline case and the yaw-offset strategy as a consequence of the turbine operation below rated, 8 m/s, while for the IPC strategy, as expected, it can be observed that the mean is zero.
but the blades pitch activity standard deviation is 2.43°, being the principle mechanism that enables an active platform-wind alignment. Figure 5 presents the blade pitch activity and the platform rotation for a single simulation of the selected study case. Note that the statistics in table 2 are only computed with the last 600 seconds of each simulation, but the total simulation length of 1200 seconds with the initial transient is shown in the figure, to illustrate the start of the IPC action.

![Blade pitch activity and platform yaw rotation for a single baseline case](image)

**Figure 5.** Blade pitch activity and platform yaw rotation for a single baseline case

The flange yaw moment and the turbine thrust are also compared in table 2. The better the platform-wind alignment, the higher the thrust is. As observed, that is consistent with the obtained results, where for the 2 selected strategies, the thrust is 11% higher than in the baseline. The thrust deviation from the mean is very similar for the 3 cases, as it is driven by the wind turbulence which is the same in all cases. Regarding the flange yaw angle, for the baseline case where the platform-wind alignment is not zero, -3171 kNm of yaw moment is present as consequence of the downwind configuration aerodynamic forces created due to the wind incident angle on the rotor. However, the moment is even higher (in absolute value) when using the IPC strategy. That is explained by the fact that, despite the rotor being aligned with the wind for this case, the three blades are actively pitching to create a restoring yaw moment that keeps the platform aligned, hence the flange yaw moment observed is the consequence of the total blade pitch action.

Finally, using the yaw offset strategy, it can be observed that the flange yaw moment is significantly reduced. That is a consequence of being a passive strategy which does not induce additional yawing moment once the rotor is aligned with the wind. Nevertheless, even though the mean moment is low, there is still a big standard deviation as present in the baseline and IPC cases, which is caused by the simulated unsteady wind conditions and the big deviations from the mean value, 8 m/s, that directly influence the platform alignment.

5. Conclusions
This paper presents the predominant phenomena that govern the weathervaning effect of a single point moored downwind floating platform. The aerodynamics, hydrodynamics and its coupled effects are discussed in section 2. The model used for this analysis is the PivotBuoy platform developed by X1 Wind, designed to produce 15MW rated power as described in section 3. The
software used in this study and the platform modelling are described in section 4, together with the active, Individual Pitch Control, and passive, yaw offsetting, solutions to improve the platform misalignment.

Irregular wind and waves simulations are presented in section 5, where the platform alignment for different current velocities and misalignment is shown in figure 3. The results show a good platform stability when co-directionality between current and wind is present, demonstrating a proper platform design. For realistic misalignment and current speeds, the platform still presents reasonable stability points, where, for example, a cross-current of 30° at 0.2 m/s rotates the platform around 5° under 8 m/s wind.

In order to show the alignment advantages of the proposed solutions, an extreme case, where the current velocity is 0.4 m/s with a direction offset of 90°, is chosen as the baseline for improvement. Both proposed solutions, the IPC and the nacelle-offset, are capable of keeping the turbine aligned with the main wind direction, but only the IPC, as an active strategy, can reduce significantly the deviation from the mean as well. The impact of the platform alignment can be observed both from comparing the thrust, which is around 11% higher than the baseline for the 2 strategies, but also with the power production, 8% higher when the rotor is aligned.

Nevertheless, when using the IPC active strategy, it can be observed that the blade pitch activity is, as expected, increased with respect to the baseline case and the passive strategy. The same is observed with the flange yaw moment, which is the highest (in absolute terms) when using the IPC as consequence of the active pitch activity to create a restoring yaw moment on the platform. However, while from this results it is possible to conclude that the yaw offset passive strategy is the optimal, it is important to highlight that only a single wind speed case is analysed in this work.

In a more realistic set-up where wind speed and wind direction change is present, the IPC as an active strategy will always be able to align the platform. On the contrary, with the passive static yaw-offset strategy, one would have to choose a single design angle for the specific site, resulting in a less overall power outcome compared to the IPC strategy. This could be quantified and analysed in an extended and more realistic study, as part of future work.

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