A Blade Load Feedback Control For Floating Offshore Wind Turbines

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Abstract. The platform-pitch motions of Floating Offshore Wind Turbines are highly influenced by the blade-pitch controller. However, in rough sea state conditions, the platform-pitch motions are dominated by the incident wave dynamics. Then, the properties of the designed controller to reduce the platform-pitch motions can be changed due to the sea state conditions. In this study, the drawbacks of a previously designed Aerodynamic Platform Stabiliser controller performance in rough sea state conditions are analysed. Furthermore, an additional blade load feedback control loop has been designed to improve the performance of the controller in rough sea state conditions. The preliminary results presented here show the potential of the blade load feedback control loop effectiveness to improve the Aerodynamic Platform Stabiliser control loop performance in rough sea state conditions. The time-domain simulations were carried out with the NREL 5-MW wind turbine mounted on the ITI Energy’s barge in the fully coupled non-linear aero-hydro-elastic simulation tool FAST.

1. Introduction

Wind energy is becoming the real green energy alternative to the conventional fossil fuel sources, as the increment of the new wind farm projects worldwide reveals. The offshore wind presents many advantages compared to its onshore counterpart [1]. The current offshore wind farms are based in the bottom-fixed wind turbine technology; however, this technology is limited by the water depth. The bottom-fixed wind turbines can only be installed in water depths less than 60 m, so can they be only installed in shallow water coastal areas. Therefore, a solution to overcome this limitation is being developing in the last decades, i.e. the Floating Offshore Wind Turbines (FOWT). Several academic research were published and many FOWT prototypes were designed and tested in the last years, e.g. BlueH, Hywind, WindFloat, SWAY, VolturnUS, Kabashima, Mitsui, Shinpuu, Hamakaze and Floatgen [2]. After the worldwide first floating offshore pilot park operating since 2017, Hywind Scotland [3], other floating farms are currently being built, such as Windfloat Atlantic [4] or the second phase of the Kincardine project [5]. The current interest in this kind of energy production confirms the tendency of increasing FOWT projects and the consolidation of the wind energy as the main green energy source of the near future.

The FOWT technology is actually in development stage before it gets mature, so that there are many different platform models designed in recent years and different platform floater
dispositions [6], each one holding both pros and cons. The different floating technologies considerably differ in terms of building processes as well as in performance characteristics. In general, platforms with larger hydrostatic restoring stiffness and hydrodynamic damping cost more to build, mount and deploy, while less stable platforms can affect the FOWT’s performance [7]. The semi-submersible platforms provide several advantages for the platform construction, wind turbine installation and towing process. However, the coupling between the blade-pitch regulation and the platform-pitch motion, known as the platform negative damping [8][9], highly affects to the FOWT performance. Therefore, a number of different control solutions have been designed to improve the FOWT performance, such as the Aerodynamic Platform Stabliser (APS) control loop [10] designed to complement the detuned PI control loop [8] for the NREL 5-MW wind turbine mounted on the ITI Energy’s barge, among others.

The detuned PI control loop designed in [8] for FOWT systems is based in the conventional onshore wind turbine generator speed control via the blade-pitch regulation. The conventional onshore generator speed control loop PI gains can be obtained by analysing the wind turbine drivetrain equation of motion, as show in [8]. However, this equation does not contemplate the platform-pitch dynamics of the FOWT system. Thus, an additional modification is required to avoid the negative platform damping effect. This modification relies on detuning the PI gains to reduce the controller-response natural frequency below the platform-pitch natural frequency, as mentioned in [11]. Although the negative effect is avoided, and a considerable generator speed regulation improvement and platform-pitch motion reduction are achieved, further performance improvements are required to reduce the tower and blade loads due to the platform motions.

Therefore, the APS control loop was designed in [10] to reduce the FOWT tower loads by reducing the platform-pitch motions while not increasing the blade loads and improving the generator speed regulation at the same time. This control loop is based on the regulation of the blade-pitch angles via the measurement of the nacelle-pitch velocity. Remarkable improvements are achieved with the NREL 5-MW wind turbine model mounted on the ITI Energy’s barge, as well as with the DTU 10-MW wind turbine model mounted on the TripleSpar platform, presented in [12] and [15], respectively. The platform-pitch motions and the tower-base bending moments are reduced, not increasing the blade loads. The rotor speed regulation and, hence, the generated electric power are improved as well. The improvements, however, are registered under specific environmental conditions, i.e. in still or smooth sea state conditions. When the sea state turns rough, the APS control loop reduces the platform-pitch motions more than the natural motion induced by the waves, increasing the loads in blades. This is due to the APS control loop is not able to distinguish the platform-pitch motions produced by the wind from those induced by the waves. Thus, an additional control loop is required to compensate the negative effect of the APS control loop in rough sea state conditions and reduce the wind turbine blade loads.

2. Objectives
An additional control loop is required to counteract the negative effect of a previously designed APS control loop in rough sea state conditions. This additional control loop must alleviate the excessive APS blade-pitch control allowing the free platform-pitch motion induced by the waves. Since the FOWT tower is designed to mechanically resist the extreme wave heights of 50-years recurrence [16], the tower loads can be slightly increased during the wind turbine normal performance. This allows a blade load reduction at the cost of increasing the platform-pitch motions via the reduction of the rotor thrust in rough sea states. Furthermore, the new control loop must not be detrimental for the APS control loop performance in still and smooth sea conditions and, it must be designed to work in the above rated wind speed region.
3. Control design
The blade load feedback control loop presented in this article, named Wave Rejection (WR), contributes to the baseline Detuned PI and APS control loop blade-pitch regulation via the measurement of the blade-root-flapwise bending moments, as shown in Figure 1. Each control loop has been independently tuned: first, the APS control loop is tuned to improve the performance of the baseline Detuned PI control loop [12]; and second, the WR control loop is designed to improve the other two control loops performance in rough sea state conditions. The blade-root-flapwise bending moments of the blades are measured via an internal measurement unit, e.g. strain gauges, located in each wind turbine blade. The blade-root-flapwise input signal for the WR controller is obtained by averaging the measurement of the three blade-root-flapwise bending moments. In this way, the effect of the tower shadow in the input signal of the WR controller is minimised, improving the control performance results. This measurement provides an early detection of the thrust in the wind turbine rotor enabling a vigorous blade-pitch regulation to reduce the large blade-root-flapwise bending moments.

![Figure 1. Control scheme block diagram.](image)

The WR control loop has been tuned shaping the FOWT transfer function from the blade-pitch angle to the blade-root-flapwise bending moment. This controller has been designed to capture the wave dynamics through the blade-root-flapwise bending moment measurement. The DNV-GL offshore standard [16] prescribes the frequency band applicable to floating offshore structures located in the wave active zone, corresponding to the frequency range of the incoming waves, typically with periods between 4 and 25 s (0.04 - 0.25 Hz). Thus, the transfer function has been shaped in that frequency range to capture the wave dynamics. The controller is based on a band-pass filter tuned to increase the blade-pitch angle proportionally to the blade-root-flapwise bending moment throughout the mentioned frequency range, as shown in the Bode diagram of Figure 2. Then, the blade-pitch action is considerably increased in the range where the blade-root-flapwise bending moments are affected by the wave dynamics, reducing the thrust in the rotor of the wind turbine and, hence, increasing the wind turbine pitch motion.

To check the FOWT frequency-domain performance, in relation to the wind, Figure 3 shows the Bode diagrams of the closed-loop transfer functions from wind to the platform-pitch angle (top) and to the generator-speed (bottom). One can see how the platform-pitch regulation is improved with the implementation of the previously designed APS control loop, as explained in [12]. Furthermore, the WR control loop does not negatively affect the APS control improvement, while it further reduces the magnitude at the platform-pitch resonance frequency around 0.084 Hz and also the magnitude between the frequencies 0.1 to 0.4 Hz. The same improvement can
be also seen in the wind to generator speed Bode diagram. Note that these Bode diagrams are obtained with the linearised transfer functions with a constant wind speed and still water conditions as explained in [13] and [14]. Therefore, time-domain simulations with stochastic wind speeds and irregular wave heights are run to fully check the designed controllers performance.

**Figure 2.** Wave Rejection control loop Bode diagrams.

**Figure 3.** Bode diagrams of the closed-loop transfer functions from wind to platform-pitch angle (top) and to generator speed (bottom).
Some interferences are observed between the APS and WR control loops during the time-domain simulations. Mainly in rough sea state conditions due to the large control action of the APS loop. The WR control loop increments the blade-pitch angle proportionally to the blade-root-flapwise bending moments, increasing the platform-pitch motions, while the APS control loop tries to reduce the platform-pitch motions proportionally to the nacelle nod velocity. Then, opposing control actions have been registered between the APS and WR control loops. This commonly happens between control loops which do not communicate with each other [17]. Therefore, a control switching method is required between these two additional controllers to regulate the contribution of each control loop.

Since the APS control loop improves the baseline Detuned PI controller performance in still and smooth sea state conditions [12] and, on the contrary, it negatively affects to the WR controller in rough sea state conditions, a collector between the two controllers has been implemented for weighting the contribution of each controller and preserve the controller quality in any sea state condition. Figure 4 shows the block diagram of the designed control switching collector. This collector gradually increments the contribution of the WR controller while weakening the APS controller output according to the current wave height. The platform vertical acceleration is measured and filtered via a Low-Pass Filter (LPF) to obtain an estimation of the current wave height and, according to the weight factor \( a \), the contribution of each control loop is assigned.

![Figure 4. Aerodynamic Platform Stabiliser and Wave Rejection collector block diagram.](image)

Furthermore, as explained for the APS control loop implementation in [12], since the WR control loop is proportional to the blade-flapwise bending moments it will be working in all wind turbine operating regions (below and above rated wind speed) unless its use is limited. Thus, the use of the WR control loop has been limited to work in the above rated wind speed region as the Detuned PI and the APS control loops actually do. For such a purpose, the conventional blade-pitch control loop is taken as a reference to enable the WR one. The final blade-pitch angle from the sum of the three control signals is:

\[
\theta = \theta_{PI} + \theta_{APS} + \theta_{WR}
\]

(1)

with:

\[
0^\circ \leq \theta_{PI} \leq 90^\circ
\]

(2)

\[
-\theta_{PI} - \theta_{WR} \leq \theta_{APS} \leq 90^\circ - \theta_{PI} - \theta_{WR}
\]

(3)

\[
-\theta_{PI} - \theta_{APS} \leq \theta_{WR} \leq 90^\circ - \theta_{PI} - \theta_{APS}
\]

(4)

where \( \theta_{PI} \), \( \theta_{APS} \) and \( \theta_{WR} \) are the blade-pitch angles of Detuned PI, APS and WR control loops, respectively, and \( \theta \), is the final blade-pitch angle.
In the block diagrams of Figures 1 and 4, one can see the gain-scheduling (GS) included in order to adapt the gains of the Detuned PI controller. The GS of the baseline Detuned PI control loop as well as the generator torque control are here adopted unchanged from [8].

4. Simulations
The simulations have been run with FAST8, from 13 to 25 m/s stochastic wind speed, and irregular sea state, from 0 to 6 m mean wave height. The time-domain simulations are 1-h (3600 s) long. All the appropriate and available FOWT Degrees Of Freedom (DOF) are enabled, 22 in total: three platform translations (surge, sway, and heave) and three rotations (roll, pitch, and yaw)(6DOF); first and second fore-aft and side-to-side tower modes (4DOF); nacelle yaw (1DOF); variable generator speed and drivetrain rotational-flexibility (2DOF); and, first and second blade-root-flapwise modes and first blade-root-edgewise mode for each blade (9DOF).

The wind profiles are generated with the TurbSim module, with the highest turbulence wind type (turbine class - A) according to the IEC61400-1 standard [18]. The sea state is derived from the JONSWAP wave spectrum according to the FAST8 HydroDyn module. Figure 5 shows the Standard Deviation (STD) values of the most representative FOWT parameters for the performance evaluation in time-domain simulations with a mean wave height of 6 m. The simulations with mean wave height higher than 6 m have not been included due to the platform-pitch maximum angles exceed the 10° of inclination, taken as a threshold for the maximum inclination, as mentioned in [7].

An increment in the platform-pitch inclination ($\theta_{yP}$) with the implementation of the WR is registered, which is the main objective of the WR control loop design as mentioned above: the increment of the wind turbine pitch motions at rough sea states and, hence, the reduction of the blade-root-flapwise bending moments ($M_{yB}$). One can see how the platform-pitch angle has been increased in comparison to the APS control loop results. However, in comparison to the Detuned PI, the results are higher except at high wind speeds. The blade-root-flapwise bending moment shows the best STD results with the WR control loop implementation at any wind speed conditions. A gradual improvement is shown by the blade-root-edgewise bending moment ($M_{xB}$), but always showing results lower than those of the other two controllers. The increment in the platform-roll angle ($\theta_{xP}$) represents the increase in the wind turbine roll motions, however, the values are clearly smaller than those of the platform-pitch angle. The wind turbine rotor speed regulation ($\Omega_r$) has been also improved with the WR controller at any wind speed, and hence, the generator power ($P_g$) production too. The generator electric torque ($M_g$) also shows a smoother regulation as a consequence of the improvement in the $\Omega_r$ regulation. Finally, the blade-pitch angle ($\theta$) also shows a smoother regulation as depicted by the lowest STD results.

Figure 6 shows the extreme load values of the tower-base-pitch, blade-root-flapwise and -edgewise bending moments of the overall time-domain simulation results. The implementation of the WR control loop shows a slight increment in the maximum of the tower-base-pitch bending moment, as expected, due to the objective of increasing the platform-pitch motions. Note that the maximum value is not higher than 2.65% according to that obtained with the baseline Detuned PI controller, while the minimum it remains below, around 6.78% less. The blade-root-flapwise and -edgewise bending moments have been successfully reduced thanks to the WR control loop, not only compared to the APS control loop, but also to the baseline Detuned PI. The maximum and minimum blade-root-flapwise bending moment reductions are around 11 and 5.1%, respectively, compared with those obtained with the Detuned PI baseline controller. In addition, the maximum and minimum blade-root-edgewise bending moments have been reduced around 13.9 and 5.6%, respectively.
Figure 5. Standard deviation results of the time-domain simulation series at 6 m mean wave height.

5. Load analysis
The load analysis is based on the short-term fatigue calculations of the obtained time-series results. The Damage Equivalent Loads (DEL) are calculated under the same conditions for all the different FOWT control performance results, to obtain comparable values. Figure 7 shows the DEL results of the APS controller performance, normalised with respect to those of the Detuned PI baseline controller. One can see the drawback of the APS controller in the blade-root-flapwise DEL deterioration according to the wave height ($H_s$) increment. In still and smooth sea state conditions the APS controller improves the Detuned PI baseline DEL results; however, the loads are increased in rough sea state conditions. The worst blade-root-flapwise DEL results are registered with high waves and low wind speeds. The same tendency is shown in the blade-root-edgewise DEL results, although the deterioration is smaller. The tower-base-pitch
Figure 6. Extreme load values of the time-series simulations. In each subplot, Detuned PI (left, dark-green), Detuned PI & APS (centre, blue), and Detuned PI & APS & WR (right, dark-red) control results are shown.

DEL show a great reduction throughout the overall wind speed and wave height. This is due to the excessive APS control action explained above, which reduces the platform-pitch motions more than the natural motion induced by the waves. This is consistent with the platform-pitch angle STD results shown in Figure 5.

Figure 7. Normalised DEL analysis of the Aerodynamic Platform Stabiliser control loop results.

Figure 8 shows the DEL results with the implementation of the WR control loop to the APS controller. One can see how the blade-root-flapwise has been improved reducing all DEL results below the reference, corresponding to the Detuned PI controller. The blade-root-edgewise DELs have been also improved achieving similar results or even better than the Detuned PI ones. The cost of this improvement is the increment of the tower-base-pitch DELs, as expected due to the increment of the platform-pitch motions depicted by the STD shown in Figure 5. This
deterioration only affects to some particular wind and wave conditions, which are hardly probable according to [8] and [19]. Finally, it is demonstrated that the WR control loop has the capability of reducing the blade loads, but at the cost of the tower load increment. Therefore, it is essential to obtain an agreement between the APS and WR controllers to achieve the reduction of both, tower and blades loads below the Detuned PI controller results.

![Figure 8. Normalised DEL analysis of the Wave Rejection control loop results.](image)

6. Conclusions and Outlook
In previous studies the APS control loop was designed to improve the platform-pitch motion produced by the Detuned PI controller blade-pitch regulation in the NREL 5-MW wind turbine mounted on the ITI Energy barge [10]. The tower-base-pitch and blade-root loads were reduced whereas the rotor speed regulation and power production were improved [12]. This was possible in still and smooth sea state conditions; however, in rough seas the platform-pitch motion was reduced more than the natural motion induced by the waves increasing the loads in the blade-roots. This was due to the APS control loop, which was not able to distinguish the platform-pitch motions produced by the wind from those induced by the waves. Thus, an additional control loop was required to compensate the negative effect of the APS control loop in rough sea conditions and restrain the wind turbine blade loads. Then, in this paper, the additional WR control loop has been presented with such a purpose. Several time-domain simulations have been carried out throughout the overall above rated wind speed and irregular wave conditions. The time-domain blade extreme loads have been reduced not only below the APS results, but also below the reference Detuned PI ones. The rotor speed regulation and electric power production have been improved in the overall wind speed conditions as shown by the STD results. The blade-root-flapwise and -edgewise DEL have been reduced below the reference Detuned PI controller results. However, all these improvements have been possible at the cost of the tower-base-pitch load increment as shown by the extreme load and DELs analysis. The increased tower loads will increase the fabrication cost of the FOWT, since the substructure is expected to drive the cost as compared to the blades. Therefore, the optimisation of the controllers performance to improve the tower-base as well as the blade-root loads below the reference Detuned PI results is currently dealt with in IK4-IKERLAN.
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