Evaluation of control methods for floating offshore wind turbines

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Abstract. The challenge of controlling floating offshore wind turbines arises due to the soft support structures and complex environmental excitations. Reducing the generator speed and power fluctuation, damping the motions of the floating platform and alleviating the fatigue loads at the tower base have been investigated in recent projects. This paper reviews and summarizes a selection of methodologies that have been discussed over the past years. These methods are then evaluated on the TELWIND-5MW-FOWT. First, linear analysis of the closed-loop with different control approaches is performed. Next, coupled aero-hydro-servo-elastic simulations with Bladed are carried out and evaluated. The motions and loads with different control approaches will be compared, advantages and limitations of each method will also be discussed.

1. Introduction
When applying an onshore state-of-art blade pitch controller to the floating offshore wind turbine (FOWT), the instability problem of the platform pitch mode due to the negative aerodynamic damping is a well-known challenge [1]. From the viewpoint of control theory, the non-minimum phase behavior (or the right-half-plane zero) when feeding back generator speed to blade pitch at above-rated wind speed limits the control authority and performance [2], which leads to a larger generator speed fluctuation and higher tower base bending moment. Control methods addressing this problem can be summarized into four categories:

- Reduce bandwidth (single-input-single-output control): This method keeps the basic control structure with a single input and single output, the gains of the collective pitch controller are detuned so that the bandwidth of the controller is below the platform pitch natural frequency. Similar detuning procedures are updated by scheduling the detuning [3]. The reason is that the instability is only critical at certain operating points. For higher wind speeds, the reduced bandwidth doesn’t contribute to stabilizing the platform, but leads to a higher generator speed variation.

- Extra sensors (multi-input-single-output control): Additional loops by a feedback of the platform pitch velocity and tower top velocity to the blade pitch in [4] have proven their capability of improving the control performance. Feedforward control is another promising technology: the Lidar assisted feedforward control compensates for the effect of changing wind speed on the rotor speed with the help of wind preview [5].
• Extra actuators (multi-input-multi-output control): The benefit of controlling generator speed by regulating generator torque is that the aerodynamic thrust will not be directly influenced. It has shown that feedback of the nacelle velocity to the generator torque can compensate the non-minimum phase zeros [6], which is the origin of the instability problem.

• Other control algorithm: Model based control like LQ approach [7] [8], H-infinity approach [9] make it possible to systematically work with multi-input, multi-output system. Model predictive control [10] has also been adapted to floating wind turbines and shown good performance in damping the platform motions and reducing the loads. Disturbance accommodating controller (DAC) can minimize the influence of wind speed perturbations [8] and individual blade pitch control is proved to be effective to reduce the platform pitch motions [11], [12].

This paper will evaluate three different control approaches, which modify the conventional onshore feedback blade pitch controller, on the TELWIND-5MW-FOWT [13]. Each approach belongs to one of the categories mentioned previously. With the goal of investigating the performance of each approach, both linear analysis and coupled simulation will be carried out. The results will show the capacity and drawbacks of these approaches.

2. Problem description
Figure 1 shows a typical onshore feedback blade pitch controller, which has a proportional gain $K_p$ and an integral gain $K_p/T_i$. When this baseline-controller is applied to the FOWT, due to the negative aerodynamic damping, the platform pitch mode goes unstable, whose physical explanation can be found in [1] and [14]. From the point of view of control theory, this phenomenon can be described as a right-half-plane-zero (RHPZ) problem [2], [7]. Instead of describing in the time domain where time-based functions are used to model the physical system, the Laplace transfer function views this phenomenon as equations in the frequency domain. Figure 2 (left) presents the poles (roots of the denominator) and zeros (roots of the numerator) of the platform pitch mode on the s-plane. Since the poles represent the exponentially decayed sinusoidal signal $A \cdot e^{\sigma t} \cdot \sin(\omega t + \phi)$, where $\sigma$ and $\omega$ are marked in Figure 2, analyzing the complex roots of the transfer function can reveal information about the frequency response. If there is poles on the right-half-plane, where $\sigma$ is positive, the system response will be unbounded, i.e. unstable.

![Figure 1: Block diagram of the onshore baseline blade pitch controller.](image)

The poles in the platform pitch mode of the open-loop transfer function correspond to the pitch free decay damping and eigenfrequency. Thus the open-loop system is normally stable because of the sufficient hydrodynamic damping, which can be seen from Figure 2 (left). The unstable problem happens when closing the control loop with an onshore baseline-controller. It can be seen from Figure 2 (right), where the pole and zero of the closed-loop system with
different proportional gains $K_p$ are plotted. It is clear that the poles are moving towards the zeros along with the increasing gains and the system is unstable upon a certain gain. This is also the reason why it’s called RHPZ problem.

![Figure 2: Pole-zero map of the open-loop transfer function from blade pitch to generator speed (left); Pole-zero map of the closed-loop transfer function from blade pitch to generator speed (right).](image)

3. Methods evaluation

This section will introduce the selected methods, which are briefly described previously, to solve the problem. The description of the TELWIND-5MW-FOWT is summarized in Section 3.1. The selected control approaches, as well as the simulation tools which are used for the evaluation are followed in Section 3.2 and Section 3.3 respectively.

3.1. Description of the TELWIND-5MW-FOWT

The TELWIND-5MW-FOWT is used for the evaluation of the control approaches, which is demonstrated in Figure 3. With the goal of reducing cost, the TELWIND-5MW-FOWT has quite a few innovative features: a telescopic tower, and an evolved spar-platform with two tanks. The relatively low platform pitch eigenfrequency adds extra challenge for the controller design. Table 1 has included the essential parameters of the FOWT. The main control objectives are to regulate generator speed and reduce platform pitching motion.

![Figure 3: Sketch of the TELWIND-5MW-FOWT.](image)

| Parameter                  | Value |
|----------------------------|-------|
| Rated Power [MW]           | 5     |
| Rated generator speed [rpm]| 490   |
| Rated wind speed [m/s]     | 12    |
| Optimal TSR [-]            | 9.2   |
| Rotor diameter [m]         | 132   |
| Hub height [m]             | 87.5  |
| Blades number [-]          | 3     |
| platform draft [m]         | 60    |
| Water depth [m]            | 320   |
| Platform pitch eigenfrequency [Hz] | 0.025 |

Table 1: Parameters of the FOWT.
3.2. Control approaches

Three control approaches are selected for the evaluation. Despite all the new control strategies like model based feedback control, Lidar based feedforward control or even individual blade pitch control etc., the focus of this paper is on the methods that modify the onshore baseline-controller. The block diagram in Figure 4 summarizes the selected control approaches, where $\dot{\beta}$ is the platform pitch velocity and $T_g$ represents the generator torque. The first approach has the same control structure as the baseline-controller, but the control gains will be detuned so that the system can reach the stability requirement. The second approach adds an additional loop feeding back the platform pitch velocity $\dot{\beta}$ to the blade pitch $\theta$, which is called platform-damper. The last one has the same signal feedback as the damper, but uses the generator-torque as an extra actuator.

3.3. Simulation tool

Two simulation tools are used for the evaluation of the control methods. A linear simplified low order model (SLOW [7]) with five degrees-of-freedom (DOF), i.e. platform-surge, heave, pitch, tower-top fore-aft displacement and generator speed, is used for linear analysis. Another is a fully coupled aero-hydro-servo-elastic model, which is implemented in Bladed V4.7. To verify the SLOW model, a step wind response at 16 m/s is shown in Figure 5. The good match between the two simulation models in platform pitch and generator speed allows the linear analysis to design the preliminary controllers effectively. The offset of the blade pitch is due to the simplified aerodynamic model, which is only a rigid disc.

![Figure 4: Block diagram.](image)

![Figure 5: Step wind response of the simulation tools.](image)

4. Results and discussion

All the control approaches which are introduced in the previous section are evaluated on the TELWIND-5MW-FOWT using both the linear model and the Bladed model. Results with each approach will be shown and discussed in this section.

4.1. Load cases

In order to simplify the environmental condition and understand the control methods, no wave load is applied to the simulation for the sensitivity study of different control approaches in this
section. The definition of the turbulent wind is based on the IEC standard, turbulence class is set to A. For the final comparison in section 5, irregular wave with significant wave height 5.7 m, peak period 11.5 s and peakedness 1.234 is applied, which is a site-specific operational wave condition.

4.2. Detuned gains
The idea of detuning is simply reducing the control gains. Since the higher gains make the system unstable, the gains will be reduced until the system stability limit is satisfied. If only the drivetrain mode of the FOWT is considered, the system closed with a baseline-controller (see Figure 1) can be presented as a second order differential equation

$$I_{\text{drive}}\ddot{\varphi} + \left(-\frac{\delta M_{\text{aero}}}{\delta \theta}\right)K_p\dot{\varphi} + \left(-\frac{\delta M_{\text{aero}}}{\delta \theta}\right)\frac{K_p}{T_i} \varphi = 0,$$

where $\varphi$ is the azimuth angle. It has been pointed out in [1] that the gains should be reduced so that the eigenfrequency of this closed-loop equation is lower than that of the platform pitch mode. Compared to the other approaches, this method requires the simplest implementation. Its functioning has also been proven by research work [14] and [15].

![Figure 6: Proportional gain $K_p$ and time constant $T_i$ of the PI blade pitch controller.](image)

However the implementation on the 5MW TELWIND FOWT has problems at higher wind speeds due to the negative gains, which can be seen from the $K_p$, $T_i$ plots in Figure 6. The reason behind is that the RHPZ problem differs from the operation point, since the linear system is strongly influenced by the aerodynamic character. Thus, the detuning approach should be based on the wind speed (or steady blade pitch angle), which is the main idea of scheduled detuning [3]. At this point, the simple detuning with a drivetrain model describing the FOWT system is insufficient. To schedule the detuning at different operating point, SLOW is used for the linear analysis. It has shown that the instability is only critical at some of the operating points (between 14 m/s and 20 m/s).

Based on the linear SLOW model, the gain margin (Gm) and the phase margin (Pm) which are the quantitative measurement of the system stability are investigated. Figure 7 shows how the change of the proportional gain $K_p$ and the time constant $T_i$ influence the Gm and the Pm at the wind speed 16 m/s, where solid-line represents the Pm, the dashed-line is the Gm, the red-dot-line describes the drivetrain closed-loop eigenfrequency and the blue-dotted-line is the damping of the drivetrain closed-loop. In overall, a relatively high time constant $T_i$ and
lower proportional gain $K_p$ make the system more stable with larger gain- and phase- margins. However, the stability will come at the cost of the control performance, which can be seen from the decreasing control frequency (red-dot-line), which is why a detuning procedure is always a trade-off between the platform pitch and generator speed. The benefit of scheduled detuning is that the gains are reduced only to ensure a critical margin, which differs from the operation points. The scheduled detuning process follows several criteria. First, the $G_m$ is greater than $1\,dB$ and the $P_m$ is over $5\,deg$. It is possible to achieve a higher stability (as a rule of thumb: $G_m > 6\,dB, P_m > 45\,deg$) by choosing larger $T_i$ and smaller $K_p$, however the bandwidth of the control loop will be extremely reduced so that it yields a large overshoot of the generator speed, which will be shown later by comparing the control performance between higher stability and relatively low stability margins. The second criterion is defined based on the control performance, i.e. the damping of the drivetrain closed-loop should be larger than 0.6, which is normally used for on-shore turbines. At last, the eigenfrequency of the drivetrain closed loop will be chosen as high as possible. With this gain scheduling, the calculated gains $K_p, T_i$ are presented with blue lines in Figure 6.

4.3. Feedback platform pitch to blade pitch

The previous method is based on the single-input-single output control structure. A significant drawback is the trade-off between the generator speed and the platform pitch due to the positive zeros. Thus, an extra sensor is used, i.e. the platform pitch velocity $\dot{\beta}$. An extra loop, parallel to the baseline-controller, by using a proportional gain is added to the baseline-controller. In order to understand the contribution of this extra loop, the closed-loop of the linear system with different gains is analyzed. Figure 9 shows the influence of this additional loop at wind speed 16 m/s, where a hard damper means a higher feedback gain. On the left, the poles and zeros of the system with the additional loop using different proportional gains are shown. As can be seen, the poles of the platform pitch mode are moving left, which indicates an increasing stability.

Based on the result of the linear analysis, more detailed coupled simulations have been carried out to evaluate the performance of the damper. A bandpass filter was added to roll-off the
signals in wave frequency region according to [16]. The responses in frequency domain with the additional loop are presented in Figure 9 (right). It is evident that the trade-off between the generator speed and the platform pitch cannot be mitigated, increasing stability still leads to a reduction of control performance. The explanation lies on the pair of positive zeros which cannot be removed by feeding back the $\dot{\beta}$ to the $\theta$. This will limit the control bandwidth which is the same as the detuning procedure. According to both, the linear analysis and the coupled simulation, it can be seen that a damper works with a similar theory as reducing directly the gains of the baseline-controller regarding the stability problem. A big difference lies on the fact that the damper can be designed to work in a limited frequency region by different filters.

4.4. Feedback platform pitch to generator torque
Although the additional loop by feeding back the platform pitch velocity to the blade pitch increases the stability, but the problem with the RHPZ has not been solved since the positive
Figure 10: Linear analysis (left) and coupled simulation (right) with different RHPZ-compensators.

zeros will limit the bandwidth of the control loop. It has been shown that the feedback of the nacelle velocity to the generator torque can compensate the RHPZ [6]. This method is also evaluated on the TELWIND-5MW turbine. Since the platform pitch velocity sensor captures much better the platform movement, which is critical to the stability problem, the platform pitch velocity has been used instead of the nacelle velocity. Similar to the platform-damper, a simple proportional controller is used. The linear closed-loop system is analyzed and the pole and zero of the pitch mode are plotted in Figure 10. Not only the poles but also the zeros can be moved towards the left-half-plane. If the generator capacity is unlimited, a RHPZ-compensator can solve the trade-off problem by moving the positive zero to the left s-plane. However the generator cost is generally highly influenced by the maximum allowed generator torque, which will be limited. Thus, the compensator has a saturation restricting the maximum generator torque within the 120% of the rated generator torque. The bandpass filter is also used in this additional loop to avoid extra loads in the wave frequency region.

The coupled Bladed simulation with the compensator was performed to identify the capacity of the compensator. The feedback of the platform pitch velocity to the generator torque in Figure 10 has shown a very good performance in stabilizing both of the generator speed and the platform pitch motion, as well as the tower base bending moment. The only disadvantage goes to the maximum generator torque.

5. Comparison of different control approaches
So far, variety of research work has been done to solve the stability problem. It has been shown that by adapting the on-shore controller to the floating system, the motion and load responses are significantly reduced. However, how the increase of stability influences the control performance has not been detailed addressed. This section will show the comparison of system responses with the previously investigated control approaches. Each approach is optimized by the coupled Bladed simulation. As a reference, the simple detuning is modified by increasing the closed-loop eigenfrequency at higher wind speeds, which avoided negative gains and is marked as realistic detuning in Figure 6. Both of the additional loops have a bandpass filter which captures only the motion at platform pitch eigenfrequency. A saturation of 120% of the rated generator torque is set as a safety limitation of the compensator.

The power spectral density (PSD) at wind speed 16 m/s is shown in Figure 11. This
operating point is critical concerning the system stability which has been proven by the linear analysis. Compared to the simple detuning, all other three approaches will reduce the platform pitch motions at lower frequencies, as well as the tower base bending moment, which is highly correlated with the pitch motion. Concerning the generator speed, scheduled detuning has a higher response, which is the cost for the more stabilized pitch motion. Both the damper and compensator have reduced the generator speed, which can also be reflected by the higher blade pitch activity. It is worth to notice that the simple detuning has almost the same pitch activity as the damper but higher pitch motion, generator speed, as well as the generator torque. This proves that although an additional sensor cannot mitigate the trade-off problem due to the positive zeros, it can extend the control capability. In regard to the generator torque, although a compensator allows a higher maximum torque, the overall response is reduced. This is because of the better controlled generator speed and pitch motion.

The standard deviation (STD) and the maximum (MAX) are presented in Figure 12 and Figure 13 respectively. It is notable that all the control approaches have much better performance than the simple detuning, which means that pole placement control design based on a simple linear model only with the drivetrain mode is insufficient. It could provide the system acceptable stability but unoptimized compromise on the control performance. Both of the damper and the compensator prove the benefit of adding the additional loops, i.e. extra sensor and actuator. A compensator can reach a much higher blade pitch activity without aggravating the platform pitch motion. The drawback is the maximum generator torque. The damper can either reach a better control performance or a better pitch motion by tuning the feedback gain of the extra damper loop, but due to the trade-off phenomenon as mentioned previously, an optimization of one sensor will be at the cost of the other sensor.

6. Conclusion
This paper evaluates three different control strategies for FOWTs by modifying an onshore baseline-controller. It has been shown that system motions and loads are strongly influenced by the controller. These can be significantly reduced by a well designed controller. Additional
loops can improve the control performance. However, all of the state-of-art approaches have drawbacks. One important reason is that the additional loops do not communicate with each other. Considering this point, there is still capacity of improvement by designing a model-based multi-input-multi-output controller using the same sensor and actuator. Improvement of control performance in the wave frequency region is difficult with current sensors and actuators. For future work, wave feedforward control of the floating wind turbine might solve wave-induced large motions and loads. We will further focus on extra actuators like active tower damper and platform damper which are promising to remove fundamental limitations in control performance of floating wind turbines.

Figure 12: Standard deviation over wind speed with different control strategies.

Figure 13: Maximum over wind speed with different control strategies.
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