Loop shaping based robust control for floating offshore wind turbines

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Abstract. In this work, a thorough and complete methodology for the widely used SISO controller is described for floating offshore wind turbines (FOWTs). The motivation is to develop clear, easy implementable and automated design criteria of blade pitch control design, which takes both stability and performance into account for FOWTs without adding new sensors. The primary design criteria is to achieve a similar dynamic step response behaviour, i.e. overshooting, rise time and settling time across the operating points above rated wind speeds. The proposed design procedure can be performed by lower order numerical models with only two degrees of freedom, which can be derived analytically. The minimal required system information eases an early stage controller design, as well as the system engineering and integrated substructure design. The proposed design procedure is evaluated on three state of the art floating wind turbines. The resulting gain scheduling is quite different from the one for onshore turbines. The overall response is satisfying and comparable with an existing stability-oriented robust SISO controller at operation points where stability is critical. An improved performance is found for higher wind speeds.

1. Introduction

Modern multi-megawatt wind turbines are commonly blade-pitch controlled. For onshore blade-pitch controllers, the approach often used in literature is to target a constant closed loop frequency and damping across the above rated wind speeds \cite{1}, \cite{2}, \cite{3}. So that the overshoot, rise time, as well as the settling time for step response remain similar at different operating points (i.e. wind speeds). This means the control design is performance oriented. When adapting an onshore state of the art blade pitch controller to a floating offshore wind turbine (FOWT), the instability problem of the platform pitch mode due to the soft substructure, is a well-known challenge. This phenomenon called negative aerodynamic damping was firstly discussed in \cite{4}. From the viewpoint of control theory, the non-minimum phase behaviour or the right-half-plane zero (RHPZ) problem when feeding back the generator speed to blade pitch at above-rated wind speed limits the control authority and performance. This leads to a larger generator speed fluctuation and higher tower base bending moment. Thus, stability becomes a driving factor for FOWTs.

A variety of methods addressing the mentioned problem have been studied in recent years. As a pioneering solution, provided by \cite{4}, the bandwidth of frequencies, at which the controller is effective, should be smaller than the pitch natural frequency of the floater. This implies a significant reduction of the control bandwidth compared to onshore turbines. This straightforward and easily implementable method has been nevertheless used by many other
researchers until today. The research community encounters more difficulty when the turbine gets larger and the natural frequency of the correspondingly growing size of the supporting floater gets lower. Further reduction of bandwidth of the blade pitch controller leads to an insufficient performance of the generator speed tracking [5].

Most recent research moves to more complex control approaches by adding extra sensors, actuators or using model based control algorithm. However, these advanced controllers are still in the scope of academic research. It is difficult to implement them for early demonstrators, partially due to the difficulty accessing the controller provided by the turbine manufacturer, and partially due to the reliability of the additional sensors and robustness of a complex control system. Thus, single input single output (SISO) PI blade-pitch controller is still widely used in the wind industry.

In this paper, a thorough methodology for the widely used SISO controller is described for floating wind turbines. The goal of this work is to develop clear, easy implementable and automated design criteria of blade pitch control design, which take both, stability and performance into account for floating turbine turbines without adding new sensors. This allows a similar dynamic step response behaviour, i.e. overshooting, rise time and settling time across the operating points. Such design criteria are important for System Engineering or controls co-design, where the controller is adjusted during the FOWT design.

2. State of the art approach

Due to the above-mentioned stability issue, using a SISO controller requires a time-consuming tuning procedure, which is turbine and floater dependent. Concerning the strong coupling effect between the controller and the floater, it is important to include the controller iteration during the integrated substructures design or System Engineering procedure. Therefore, developing general design criteria of the blade pitch control design for floating offshore wind turbines, which are independent of characteristics of turbine and floater, is essentially needed.

Work of [4] [6] has reduced the closed loop natural frequency below floater pitch natural frequency, so that the stability satisfies the requirement. However, the control performance is significantly deteriorated. The trade-off between the control performance and the system stability has been proven based on graphical analysis, as well as coupled simulation in [5]. An improved stability-oriented gain scheduling method was introduced by [7]. Instead of simply reducing the control bandwidth, a constant sensitivity margin of the open loop transfer function across the operating points was used for a better compromise between stability and control performance. With the study case of the DTU 10MW reference turbine [8], it was also found that the stability above 19 m/s was no longer a critical driven factor, so the authors use the time constant $\tau = 1/\zeta\omega_n$ of the drivetrain mode as a design indicator at higher wind speeds. This method addresses for the first time both of the stability and performance criteria. However, the performance criterion $\tau = 13s$ comes from time simulations and the selection consideration is not discussed. The drivetrain mode of FOWTs at higher wind speeds is highly over-damped, and thus time constant $\tau$ is not sufficient to characterize the control performance, e.g. even constant $\tau$ can lead to different step responses.

3. Design methodology

A simple control loop of wind turbines consists of a plant (dynamic system) which is a transfer function in the complex s-plane and a SISO feedback controller. As is shown in figure 1, $G$ and $S$ are notations for the plant and the controller respectively.

The general layout of the original controller is a standard PI controller using the generator speed error as input and blade pitch as output [3]:

$$K(j\omega) = k_p + \frac{k_i}{j\omega},$$

(1)
where $k_p$ and $k_i$ are proportional gain and integral gain respectively. The generator torque is kept constant [4], rather than calculating the demanded generator torque to maintain a constant power. This strategy is different from the one used for most onshore turbines, which keeps the power constant by adjusting the generator torque. This is due to the negative impact of the instantaneous rotor speed on the fore-aft dynamics. The gains are scheduled for each operating point, characterized by the proportional gain $k_p$ and integral gain $k_i$ as functions of the blade pitch angle $\theta$.

### 3.1. Quantification of stability

The stability of the blade pitch control loop is crucial to the FOWT system. Due to the strong coupling between the platform pitch motion and aerodynamics, a not well designed blade pitch controller could excite the platform motion response, and eventually increase the structural loads. Further, a certain robustness of the control loop is required due to the uncertainties of the engineering model simulating the FOWT system. Especially the hydrodynamic damping which is important to the controller stability, can change over different sea states. The determination of hydrodynamic damping also remains a big challenge within the research community. Therefore, sufficient stability margin which allows model uncertainties is required.

Industrial specifications provide several rules of thumb, which can quantify the closed loop stability. The Nyquist criterion is one of the widely used methods. The transfer function defining the relation between the input and output in frequency domain is the complementary sensitivity:

$$H(j\omega) = \frac{Y(j\omega)}{X(j\omega)} = \frac{G(j\omega)K(j\omega)}{1 + G(j\omega)K(j\omega)}.$$  \hspace{1cm} (2)

where $G(j\omega)$ and $K(j\omega)$ are the plant and controller which are denoted in figure 1. To make sure that the output does not reach infinity, $L(j\omega) = G(j\omega)K(j\omega)$ should be away from the point of $(-1, 0)$ on the complex plane. Thus, based on the frequency response of the transfer function $L(j\omega)$ of the open loop defined in figure 1, it is able to determine whether the system is close to critical point $(-1, 0)$. According to the Nyquist criterion, a system without poles at the RHP becomes unstable, when the contour line of the open loop system $L(j\omega)$ encircles the critical point $(-1, 0)$ in the complex plane. To ensure the closed loop stability, the $L(j\omega)$ contour should not only exclude $(-1, 0)$, but also keep a certain distance from $(-1, 0)$ which allows sufficient robust stability. To quantify how far the nominal loop from the instability is, it is common to use the nominal sensitivity peak $M_s$, with $1/M_s$ describing the closest distance from nominal open-loop frequency response to the critical stability point $(-1, 0)$. Therefore, the larger $M_s$, the closer the closed loop to instability is. According to [7], the distance $1/M_s$ decreases for increasing $k_p$, indicating the decreasing robustness of the closed loop system. The criterion for $1/M_s = 0.4$ is selected in [7]. The same criteria will be used in this. Nevertheless, instead of gaining for a constant sensitivity margin, $1/M_s = 0.4$ is used only as a constraint to ensure a certain robustness.

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**Figure 1.** The open loop (left) used for stability analysis and the closed loop (right) used for performance quantification.
3.2. Quantification of performance of a second order system

Stability criteria only ensure a stable system, which means the output of the control loop will always converge under different disturbances. However, it does not characterize the control performance, i.e. how long does it take for the system to converge to a steady state, how large the oscillation amplitude during the transient period is. These are important factors, which determine the system response under environmental disturbances. To quantify the ability of disturbance rejection, the closed loop reacting to unit step wind, as is shown in figure 2, is analysed, which is also a common approach for onshore turbines. The corresponding model for onshore turbines includes only the drivetrain degree of freedom (DoF). The transfer function from wind disturbance to the output generator speed is a second order system. Thus, the analytical solution for control performance overshoot $M_{pt}$, rise time $T_r$ and settling time $T_s$ can be calculated according to the second order system natural frequency and damping. As a general procedure, closed loop shaping ensuring a constant step response, i.e. $M_{pt}$, $T_r$ and $T_s$, are the basis of the design procedure.

The standard form of the transfer function of a second order system with infinite zero is:

$$ G(s) = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2}. \quad (3) $$

If the system is stable, depending on the roots of the characteristic equation $s^2 + 2\zeta\omega_n s + \omega_n^2 = 0$, three different cases exist, i.e. underdamped system when $\zeta < 1$, critically damped system when $\zeta = 1$, as well as the overdamped system when $\zeta > 1$. For a underdamped system, the settling time (assuming 2% of the settled steady response) and the corresponding percent overshoot can be approximated by:

$$ T_s = \frac{4}{\zeta\omega_0}, $$

$$ T_r = \frac{\pi - \tan^{-1}(\sqrt{1-\zeta^2}/\zeta)}{\omega_0\sqrt{1-\zeta^2}}, $$

$$ M_{pt} = 1 + \exp(-\zeta\pi/\sqrt{1-\zeta^2}). \quad (4) $$

As can be seen, these performance criteria are all functions of $\omega_0$ and $\zeta$. Best practice designing a scheduled onshore blade pitch controller is therefore to fix the $\omega_0$ and $\zeta$ for the above rated operation range, which ensures a similar step response for different operation wind speeds.

In the case of an over damped system, the step response does not oscillate with a certain frequency, the settling time $T_s$ (within 2% of the steady response) can be calculated by solving the equation:

$$ 0.02 = \frac{s_2}{s_2 - s_1}e^{s_1 T_s} + \frac{s_1}{s_1 - s_2}e^{s_2 T_s}, \quad (5) $$

where $s_1 = -\zeta\omega_0 + \omega_0\sqrt{\zeta^2 - 1}$, $s_2 = -\zeta\omega_0 - \omega_0\sqrt{\zeta^2 - 1}$ are the roots of the characteristic equation.

3.3. Influences of extra degrees of freedom

SISO blade pitch control design for onshore turbines generally uses one DoF equation of motion, i.e. the rotation of the rotor. The closed loop transfer function including a PI controller from wind to generator speed is therefore a second order system. As detailed in section 3.2, it’s convenient to characterise the response of the closed loop system analytically. For FOWTs, since the platform motion has large influence on the coupled response, these dominant modes have
to be included to the transfer function used for the control design. This introduces additional poles and zeros influencing the step response of the transfer function, which means a higher order system should be used for loop shaping. The more complex a transfer function is, the more difficult it is to characterize the response analytically as is presented in section 3.2. Thus, a model which only captures the most influencing physical effect is preferred, which means a minimal required fidelity of control oriented linear model shall be investigated. A general rule according to the dominant pole approximation implies that when the extra poles lie enough distance from the imaginary axis, it is possible to ignore the effects of these poles and zeros when considering the system responses.

Simulations and linear analysis are conducted to better understand the dominant poles. Figure 2 shows the step response simulated by models with various DoFs. The DoFs considered here are the rigid body rotation of the rotor which is simply represented as the drivetrain rotation (DrTr), platform pitch (PtfmPitch), tower top fore-aft motion (TwrFA), as well as platform surge (PtfmSurge). According to the step response, it is essential to add the platform pitch motion to get a realistic dynamic response. The locations of the extra poles of different DoFs are plotted in figure 3. By comparing to figure 2, the most significant impact is introduced by the platform

**Figure 2.** Comparison of the step responses from wind to generator speed with different DoFs included ($V_0 = 14$ m/s, $k_p = 0.3$ s, $T_i = 9$ s).

**Figure 3.** Poles of the closed loop transfer function with different DoFs included ($V_0 = 14$ m/s, $k_p = 0.3$ s, $T_i = 9$ s).

**Figure 4.** Comparison of the sensitivity margin with different DoFs included ($V_0 = 14$ m/s, $k_p = 0.3$ s, $T_i = 9$ s).
pitch motion. For the one DoF model, an overdamped system is indicated by the poles located on the real axis, as well as a non-oscillating step response. When extra poles of platform pitch motion are introduced to the transfer function, additional dynamics are observed in the step response. The poles of the drivetrain mode are lying on the real axis which indicates an over damped behaviour, the oscillating response shows the dominance of the platform pitch motion. Poles of other DoFs do not have an obvious impact on the step response.

Although only two DoFs are of significant importance to shape the close loop behaviour of the FOWT, the robustness of stability shows different requirements, see figure 4. The sensitivity margin of the open loop transfer function changes over included DoFs of the transfer function. The sensitivity margin becomes stable only after including four DoFs, i.e. drivetrain, platform pitch, platform surge, tower top fore-aft motion. Nevertheless, depending on the purpose of the control design, it is also possible to get reasonable result only using a 2DoF model. The advantage is that the approach does not require a complex linear model, neither the detailed system properties, which can be beneficial for data exchange within industrial partners. An example of building up a 2DoF model can be found in [6].

3.4. Control performance of a higher order system

The impact of adding extra poles and zeros (i.e. including extra modes) to the transfer function used for control design can be divided into two parts. At lower wind speeds, the platform pitch motion will drive the stability (sensitivity margin). Depending on the mooring design, surge motion could be important as well. At higher wind speeds, due to the platform motions, the system becomes overdamped, which is also sufficiently distinguished from onshore turbines.

According to the step response in section 3.3, a linear model with at least two DoFs is required to characterize the system time response, which means a forth order transfer function is a minimum requirement. It is easy to manipulate the response behavior of a second order system analytically, as is discussed in section 3.2. Nevertheless, these equations do not apply for a higher order system. To establish the quantification of the controller performance, direct time simulations with unit wind disturbance are carried out and important parameters including overshoot, settling time and peak time are measured for each control parameter.

3.5. Design procedure

Figure 5 shows the design procedure combining both of the stability and performance criteria. As a first step, a lookup table is established storing the criteria quantifications for each combination of the control gains $k_p$ and $T_i$. For the stability, sensitivity margin $M_s$, introduced in section 3.1, is the only measurement. For the performance, rise time $T_r$, settling time $T_s$ and overshoot $M_{pt}$ are the design basis.

The workflow starts with determining the proportional gain $k_p$ for each wind speed and integral time constant $T_i$, which allows a constant desired rise time $T_r$. This step yields a subset of combinations of $k_p$ and $T_i$ for each design wind speeds. The overshoot constraint, which should be kept under 15%, as well as the sensitivity margin $M_s > 0.4$ are evaluated for the subset. For those combinations within the subset which cannot achieve the required stability, the proportional gain $k_p$ is primarily chosen to satisfy the stability requirement. When the combination satisfies all the predefined constraints, minimal settling time will be the target to determine the unique combination of control gains.

4. Evaluation on state of the art FOWTs

The proposed method is evaluated by a nonlinear coupled aero-hydro-servo-elastic simulation tool SLOW [9] on three state of the art 10 MW FOWTs.
4.1. System properties and load cases
The FOWTs used here are the TripleSpar design from the INNWIND project [10], the OO-Star and the Nautilus concepts developed within LIFES50+ project [11]. A summary of the essential system characteristics of the three FOWTs are listed in table 1. These load cases are selected according to a site of LIFES50+ and listed in table 2 [12].

![Figure 6. FOWTs for evaluation: INNWIND.EU TripleSappr (left); LIFES50+ OO-Star Wind Floater Semi 10MW (center); LIFES50+ NAUTILUS-DTU10 MW FOWT (right).](image)

4.2. The resulting control design
Following the design workflow in figure 5, the baseline blade pitch controller is designed for each substructure design in figure 6. The resulting control gains are plotted in figure 7, the reference controller marked with purple colour is the robust gain scheduled controller presented in [7]. As can be seen, the performance oriented control design has further reduced the control gains at lower wind speeds, whilst the gains at higher wind speeds are increased. This phenomenon is quite different compared to the onshore design, where the control gains decrease over wind speeds to ensure a constant overshoot $M_{pt}$ and rise time $T_r$. According to the best practise, a
Table 1. System properties of the FOWTs used for evaluation.

| Properties                  | TripleSpar | OO-Star | Nautilus |
|-----------------------------|------------|---------|----------|
| wind turbine                | DTU 10MW   | DTU 10MW | DTU 10MW |
| platform material           | concrete   | concrete | steel    |
| pitch natural period [s]    | 28         | 33      | 32       |
| displaced water [t]         | 29.205     | 23.448  | 8.795    |

Table 2. Environmental conditions for operational load cases.

|                      | Mean wind speed $v_{hub}$ [m/s] | 12  | 16  | 20  | 24  |
|----------------------|---------------------------------|-----|-----|-----|-----|
| Significant wave height $H_s$ [m] | 2.6  | 3.7  | 5.2  | 7.6  |
| Wave peak period $T_p$ [s]       | 8.7  | 9.8  | 11.3 | 12.2 |

Figure 7. Proportional gain (left) and integral gain (right) for different wind speeds and FOWTs.

reasonable rise time $T_r$ should be slightly below the platform pitch natural period. A thoroughly optimisation of the design criteria is however not executed, instead, the simple rule is used, thus $T_r$ for the TripleSpar, OO-Star and Nautilis are 26s, 30s and 30s respectively.

4.3. Simulation with combined turbulent wind and irregular wave

The numerical model used for evaluation has six DoFs, i.e. platform surge, heave, pitch, tower top displacement, rotor speed and blade pitch actuator. First order wave forces using potential flow theory and second order wave forces approached by Newman approximation are used. In addition, linear damping coefficients are used to ensure the same physical assumption between the models used for control design and evaluation. Mooring lines are modelled as a quasi-static system.

The controllers in figure 7 are compared to the reference controller proposed in [7] under stochastic wind and wave conditions. Figure 8 shows the normalized relative maximum (MAX) system performance and the standard deviation (STD) is presented in figure 9. The performance at each wind speed with the reference controller is used as basis. Further comparison to other control strategies of the reference controller can be found in [7], a good balance of performance
Looking at the results, the performance oriented controllers are capable of delivering satisfying performance, especially for both of the concrete design TripleSpar and OO-Star. More stabilized platform pitch motion, as well as more constant rotor speed are achieved at higher wind speed. For lower wind speeds where stability is critical, the newly designed controller tends to stabilize the platform at the cost of the rotor speed, but within a limited extent, i.e. smaller than 20%. This trade-off phenomenon has been discussed in [5]. However, the maximum value is not deteriorated. This trade-off relation is more evident with the steel Nautilus concept. The performance oriented controller has better stabilized platform motion, but higher fluctuation is and robustness can be concluded.

Figure 8. Relative maximum system responses.

Figure 9. Relative standard deviation of the system response.
found at the rotor speed sensor. Again, the trade-off do not apply the maximum responses.

It is important to mention that the active ballast system of the Nautilus design is not included in this study. Instead, the ballast distribution at rated wind speed is used for all the load cases. The inaccurate hydrostatic stiffness and inertial properties could explain the different behaviour of the Nautilus design at higher wind speeds and should be further investigated.

Although a significant benefit compared to the stability oriented controller proposed in[7] for the overall control performance is not evident, the design procedure, especially the required linear model, is much simplified. For example, the integral time constant in [7] is determined from brute force optimisation, which requires a large amount of simulations.

5. Results and conclusions

A performance oriented control loop shaping methodology for SISO blade pitch controller for FOWTs is proposed in this work. The resulting new controllers are applied to three different state of the art FOWTs. Result shows robust performance which is comparable with a stability oriented SISO controller at relatively lower wind speeds where stability is critical. At higher wind speeds, the new procedure provides better overall performance of the platform pitch motion and rotor speed. Additionally to the satisfying control performance, the more simplified and automated design procedure can contribute to the system engineering of FOWT and integrated substructure design in future works.

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