Aeroservoelastic stability of a floating wind turbine

T Vanelli[1,2], J Rinker[1] and D S Zalkind[3]

[1] Department of Wind Energy, Technical University of Denmark, Roskilde, Denmark
[2] Vestas Wind Systems A/S, Vestas Technology Center Porto, Portugal
[3] National Renewable Energy Laboratory, Golden CO, USA

E-mail: `thvae@vestas.com`

Abstract. The problem of negative damping undermines the aeroservoelastic stability of floating offshore wind turbines. The negative damping problem is most prevalent around rated wind speed, where the sensitivity of thrust to wind speed is the largest. This paper investigates the implementation of peak shaving, a controller feature that limits the rated thrust by pitching the blades before rated wind speed is reached. Two controller designs are investigated: a de-tuned controller and a nacelle-feedback controller. A time-domain metric is defined, inspired by Lyapunov theory, in order to compute and assess the stability of floating offshore wind turbines. The model of the International Energy Agency 15-MW reference wind turbine mounted on the University of Maine VolturnUS-S floater is simulated in HAWC2 with the National Renewable Energy Laboratory reference open-source controller. Peak shaving is applied to the two controller designs and stability is assessed. According to the chosen metric, peak shaving does not improve the stability of the system. This is due to the trade-off between loads and error tracking: although the loads and displacements in the fore-aft direction of the turbine are reduced, the rotor-speed tracking is poorer, which increases the shaft torsion fatigue load.

1. Introduction

In recent years, floating offshore wind turbines (FOWTs) have become an attractive alternative to fixed-bottom turbines. One of the major advantages of FOWTs is that they can be installed at water depths greater than 50 m, where fixed-bottom solutions become economically unfeasible [1], unlocking the possibility to harness a large amount of wind resources. In Europe alone, it is estimated that 80% of the offshore wind energy resource is located at water depths greater than 60 m [2]. Nevertheless, the technology comes with crucial challenges. Because the turbine is mounted on a floating foundation, the turbine system is increased by six additional degrees of freedom and the floater introduces a new set of frequencies and dynamics.

This paper focuses on the interaction between the pitch controller, the aerodynamic force, and the platform pitch mode, which causes the well-known negative damping problem of FOWTs [3, 4] and induces aeroservoelastic instability.

The negative damping problem is the most critical around rated wind speed, where the thrust curve slope with respect to wind speed is the largest. Therefore, the implementation of peak shaving on a FOWT is investigated as a method to limit the rated thrust and reduce the thrust slope around rated wind speed, therefore reducing the effect of platform pitch instability of the FOWT. Two pitch controller designs suggested in literature to avoid negative damping are considered in this work: (i) the de-tuned pitch controller, a classic onshore controller in which the pitch proportional-integral controller frequency is reduced lower than the platform pitch frequency [3, 5], and (ii) the nacelle-feedback controller, which consists of a pitch proportional-integral controller integrated with an additional nacelle-feedback loop—a method called parallel compensation [4, 5]. Peak shaving is applied to both these controllers and its effect on the turbine stability is assessed.

The commonly used eigenvalue approach to assess the stability of wind turbines is based on the linearization of a wind turbine model and disregards nonlinear dynamics; the damping of turbine modes in particular is not constant due to nonlinear effects. For this reason, this paper proposes a time-domain stability measure inspired by Lyapunov stability called the Lyapunov factor. The Lyapunov factor serves as a holistic measure of the boundedness of the states and captures the overall characteristics and trends of the studied system. Its definition is quite flexible and can be modified according to the design needs: more states can be added if of interest to the designer and the characteristic states can be weighted differently according to the objectives of the design. To the authors' knowledge, this is the first attempt to apply the Lyapunov factor to assess the stability of a FOWT.

2. Methodology

The FOWT model used in this work is the International Energy Agency (IEA) 15-MW reference wind turbine [6] (also referred to as IEA-15-240-RWT), mounted on the semisubmersible reference floating structure VolturnUS-S designed by the University of Maine [7]. The tower has been stiffened, increasing the Young's modulus in the original structural definition of the model to avoid resonance issues; its first natural frequency is 0.46 Hz. The model is simulated in the Horizontal Axis Wind turbine simulation Code 2nd generation (HAWC2), with the Reference Open-Source COntroller (ROSCO [8]) developed by the National Renewable Energy Laboratory. The de-tuned pitch controller is tuned at a natural frequency of 0.01 Hz and damping ratio of 1; the nacelle-feedback pitch controller has been tuned as suggested in [7] with tuning poles of 0.032 Hz and 1, and nacelle-feedback gain of -9.28 s. The PI gains of both NF and DT pitch controllers above rated wind speed are gain-scheduled. The torque controller is tuned with natural frequency of 0.02 Hz and damping ratio of 0.85. In above rated wind speeds, a constant torque is used, as it improves platform pitch stability [9].

Peak shaving is a control strategy that reduces the maximum thrust load on the rotor by implementing a minimum pitch angle schedule around rated wind speed that increases the blade pitch angles in this region. The peak-shaving percentages applied are 15 %, 20 %, and 25 %; larger peak shaving imposes larger blade pitch angles near rated. The pitch angles are computed based on the thrust coefficient surface for all operational tip speed ratios.

The floating IEA-15-240-RWT is simulated in a realistic wind-wave environment. A subset of the design load bases defined in the International Electrotechnical Commission (IEC) standard [10] is selected as the design load case (DLC). Since it is of interest to simulate the turbine in normal power production conditions, without faults or grid losses, DLC 1.2 is used to compute short-term fatigue loads and other statistical data that describe the operation of the turbine, as well as to calculate the annual energy production; DLC 1.3 is used to evaluate the boundedness of the solutions via the stability metric proposed, since the rotor overspeed and the tower fore-aft motion are higher for DLC 1.3 than for DLC 1.2, and the benefits of different controller designs can be appreciated the most. Six turbulent seeds have been simulated for each wind speed, ranging from 3 to 25 m/s.

The meteorological ocean (metocean) environment assumed for this investigation is that of a generic U.S. East Coast site, where the wave probability distributions are reported in [11]. The water depth is assumed to be 200 m. The irregular waves are generated with Wheeler stretching; the wave spectrum is the one from the Joint North Sea Wave Project (JONSWAP), with Gamma factor $\gamma = 3.3$ calculated from the JONSWAP equation [12]. One realization of waves is used for each wind speed.

The simulations have a total length of 900 s, from which the first 300 s are removed to avoid transient effects in the simulation. A damping force active for the first 200 s was implemented to reduce initial transient time.

The stability of the system is assessed through a metric called the Lyapunov factor (L_F) [13], which is inspired by Lyapunov stability and defined as:

$$L_F = \frac{||V(\mathbf{x})||_\infty}{||V_0||_\infty} \tag{1}$$

where $|| \sim ||_\infty = max(\sim)$, $V(\mathbf{x}) = [\mathbf{x}(t) - \mathbf{x}_{eq}]^T \mathbf{P} [\mathbf{x}(t) - \mathbf{x}_{eq}]$ is a function in the form of the Lyapunov function that is indicative of the stability of the system, and $||V_0||_\infty = V_0(t) - \overline{V_0}$ is the wind speed magnitude deprived of its mean. The Lyapunov function, $V(\mathbf{x})$, contains the term $[\mathbf{x}(t) - \mathbf{x}_{eq}]$, which represents the distance of the states from their equilibrium point at each time, t, and the matrix $\mathbf{P}$, which, according to Lyapunov theory, is positive definite for a stable system. The matrix, $\mathbf{P}$, is selected as:

$$P = \begin{bmatrix} 0.21\frac{1}{deg^2} & 0 & 0 & 0 & 0 & 0 \\ 0 & 36.63\frac{s^2}{deg^2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 520.83\frac{s^2}{rad^2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.49\frac{1}{deg^2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 52.63\frac{s^2}{deg^2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.73e+11\frac{1}{rad^2} \end{bmatrix} \tag{2}$$

where the diagonal factors are the average of the variances of the states across wind speeds, $\widehat{var}(\mathbf{x})$, and serve as normalization factors of the states; this is necessary because the states have different units and orders of magnitude, and the solution of the function $V(\mathbf{x})$ should be unbiased toward any state. Furthermore, having a common $\mathbf{P}$ matrix for all wind speeds is

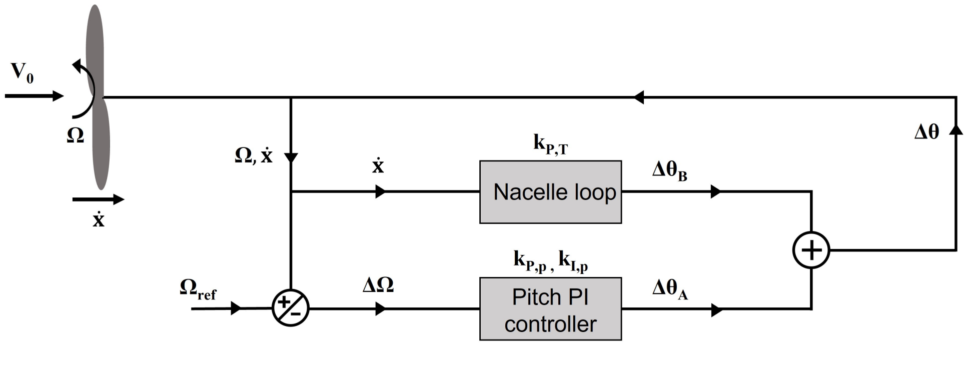


Figure 1. Closed-loop model of the FOWT above-rated region, where V_0 is the incoming wind speed, $\dot{x}$ is the velocity of the turbine tower top, $k_{P,T}$ is the nacelle-feedback gain, $k_{P,P}$ and $k_{P,I}$ are the pitch controller proportional and integral gains, Ω_{ref} is the reference rotor speed, $\Delta\theta_A$ and $\Delta\theta_B$ are the pitch angle contributions from the pitch controller and nacelle loop, respectively, which sum to the total pitch angle prescribed, $\Delta\theta$.

preferable so that the metric is comparable at different wind speeds as well. The variance is taken from the results of the DLC 1.3 simulations, with the ROSCO nacelle-feedback controller design. The characteristic states $\mathbf{x}$ are derived from a closed-loop model of the FOWT displayed in figure 1, which includes the dynamics of the drivetrain, the pitch actuator dynamics, and the fore-aft tower dynamics. The states are pitch angle (θ), pitch angle velocity ($\dot{\theta}$), platform pitch displacement (ξ_5) and velocity ($\dot{\xi_5}$), rotor speed (Ω), and integrated pitch error (e_I).

The Lyapunov factor is used to evaluate the boundedness of the states of the closed-loop system: the smaller the Lyapunov factor, the more stable the system is, as its states are closer to the equilibrium point. Instead of looking at single signals, the Lyapunov factor offers a holistic measure of the aeroservoelastic stability of the system.

3. Results and discussion

To evaluate the effect of peak shaving on stability, the IEA-15-240-RTW is simulated with ROSCO, and peak shaving is applied to two controller designs: a nacelle-feedback controller and a de-tuned controller. Peak shaving is a feature that limits the maximum thrust by pitching the blades of the turbine before rated wind speed. As a consequence, the turbine no longer

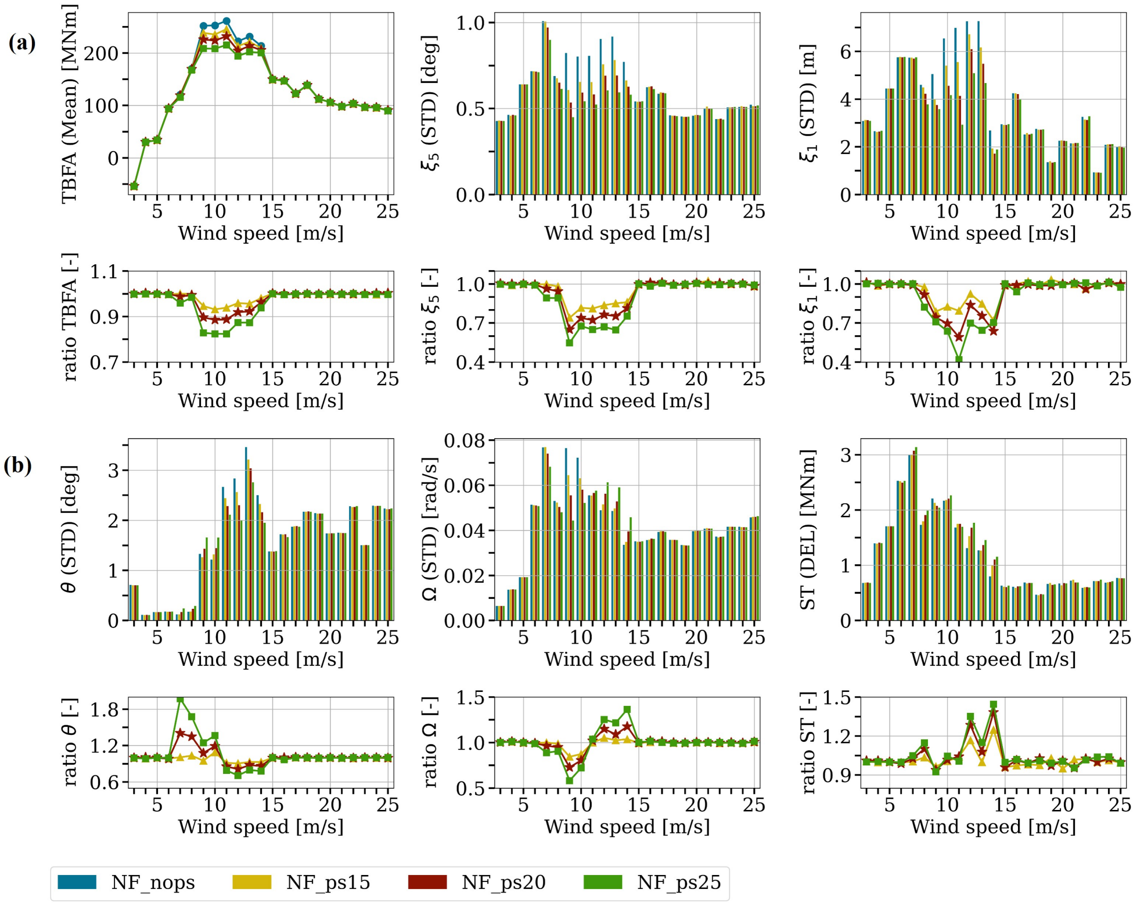


Figure 2. Results from DLC 1.3 for the nacelle-feedback (NF) controller with different peak-shaving percentages: (a) tower-base fore-aft (TBFA) mean load and standard deviation of the platform pitch (ξ_5) and surge (ξ_1) displacements; (b) standard deviation of the pitch angle (θ), rotor speed (Ω), and shaft torsion (ST) DEL. The ratios between the output from different peak-shaving percentages over the no-peak-shaving output are plotted respectively under each figure.

operates at optimal conditions and the rotor speed and power production decrease at near rated wind speeds.

Three peak-shaving percentages are applied: 15%, 20%, and 25%. Two sets of DLC 1.3 results are presented: (1) a comparison of response parameters for the nacelle-feedback controller with different peak-shaving levels, and (2) an analysis of the Lyapunov stability parameters for both types of controllers and different peak-shaving levels.

3.1. Nacelle-feedback response parameters for DLC 1.3

A selection of response parameters for the nacelle-feedback controller with four different levels of peak-shaving percentages (0%, 15%, 20%, and 25%) is presented in figure 2. The results for the de-tuned controller are very similar and are therefore not presented for brevity. For easier comparison, the ratio of each response parameter to the baseline (no peak shaving) is provided in the small subplots.

Several important observations can be made from the figure. First, the addition of peak shaving significantly reduces the mean tower-base fore-aft moment and the standard deviation of the platform pitch and surge displacements. This is an expected outcome, as higher levels of peak shaving reduce the peak thrust, resulting in a reduced thrust slope that decreases platform motion. The surge displacement in particular is significantly impacted, with a 60% reduction in the standard deviation near rated wind speed.

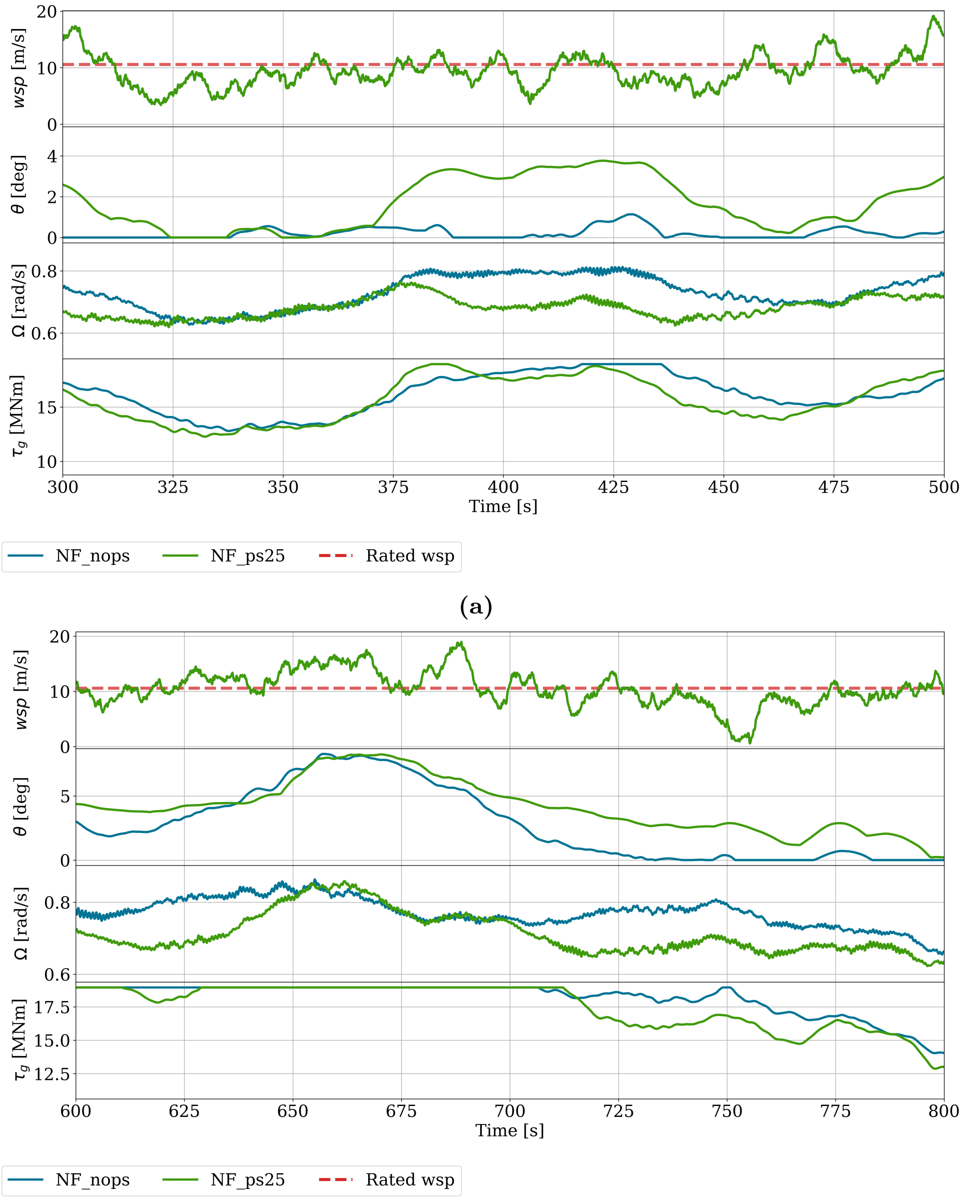
The impact of peak shaving upon pitch angle, rotational speed, and shaft torsion DEL is also considered. The pitch angle and rotational speed indicate a dependency on the control region. Below rated wind speed, the deviation in pitch angle increases with higher levels of peak shaving, whereas the deviation in rotor speed decreases. Above rated wind speed, there is a decreased pitch-angle deviation and an increased rotor-speed deviation. This inverse relationship between the deviation in pitch angle and deviation in rotor speed is expected: more aggressive pitch control actions will regulate the rotor speed more quickly, reducing the variation in standard deviation. This behavior is a direct result of the peak shaving and is highlighted by the time series in figure 3. In figure 3(a), the peak-shaving response demonstrates the premature pitching characteristic of peak shaving, which clearly results in a higher standard deviation than the pitch curve with no peak shaving. Figure 3(b) shows a similar plot but for a mean wind speed of 11 m/s: we can see that the higher minimum pitch value for the peak-shaving curve results in a lower pitch deviation. Finally, the addition of peak shaving has a mixed impact on the shaft-torsion DEL below rated wind speed but results in a substantial increase in DEL above rated wind speed. This increased DEL is directly caused by the increase in rotor speed variation: larger rotor variations cause more frequent and more substantial deviations below rated wind speed, increasing the variation in the shaft torque (figure 3(b)).

In summary, peak shaving shows a mixed benefit on the response of the floating turbine. It substantially reduces fore-aft loads and displacements, as desired, but has a mixed effect on the controller regulation and shaft-torsion DELs.

3.2. Comparison of Lyapunov factors

The final analysis in this study is a comparison of the Lyapunov factors for the de-tuned controller (figure 4) and the nacelle-feedback controller (figure 5), for different peak-shaving percentages. Comparing the two plots, it is immediately apparent that the nacelle-feedback controller shows generally better stability than the de-tuned controller, as its Lyapunov factors are generally significantly lower than the other controller.

Furthermore, there are two different trends that can be identified comparing the Lyapunov factor of the two controllers: a decreasing trend for the nacelle-feedback controller and an increasing trend for the de-tuned controller. Around rated wind speed, the nacelle-feedback controller and the de-tuned controller designs give very similar results in terms of Lyapunov factor. The solutions of the system are equally bounded. Evaluating the standard deviation of the states (figure 6), it is seen that the higher variability of the rotor from the de-tuned controller caused by the slow tuning frequency is balanced by a decreased standard deviation of the other states. The pitch angle and the pitch bearing velocity are lower, and at these wind speeds, it helps enhance the platform pitch motion. Slowing down the controller seems to improve the platform pitch stability more than having a fast-responsive controller with parallel compensation. As soon as the region with high thrust slope is surpassed, the contribution from the tower-top feedback is definitely more beneficial: the tracking of the rotor speed is highly



(a)

(b)

Figure 3. Time series of the wind speed (wsp), pitch angle (θ), rotor speed (Ω), and thrust during a turbulent wind simulation with average wind speed of 10 m/s (a) and 11 m/s (b), for the nacelle-feedback controller with no peak shaving (NF_nops, blue line) and with 25 % peak shaving (NF_ps25, green line). The mean wind speed is plotted in the wind speed plot (dashed red line).

improved, even if at the cost of higher pitch angle variation. The platform motion benefits as well, partly because the thrust slope is smaller compared to the rated region. In the de-tuned controller, the stability problem shifts from near rated to high wind speeds, where its control action is degraded because of the low responsiveness. As a consequence, the rotor speed tracking is worsened and the platform pitch undergoes larger variation, moving the states further away from their equilibrium.

The two figures also reveal that peak shaving does not enhance the stability of the floating IEA-15-240-RWT significantly or consistently across wind speeds for either controller. At rated wind speed, the states defined for the system (data shown for pitch angle, rotor speed, and platform pitch) show more bounded solutions when peak shaving is applied (lower standard deviation), with the exception of the pitch angle. As discussed above, the minimum pitch

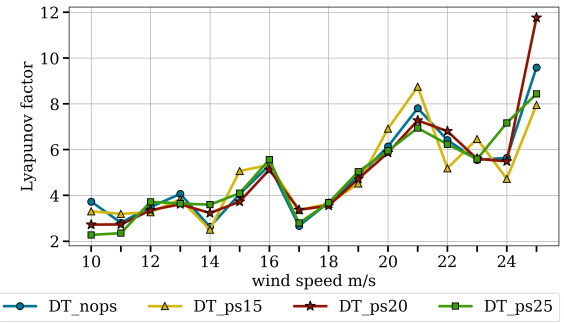


Figure 4. Results from DLC 1.3. Lyapunov factor for the de-tuned (DT) controller without peak shaving and with different peak-shaving percentages above rated wind speed.

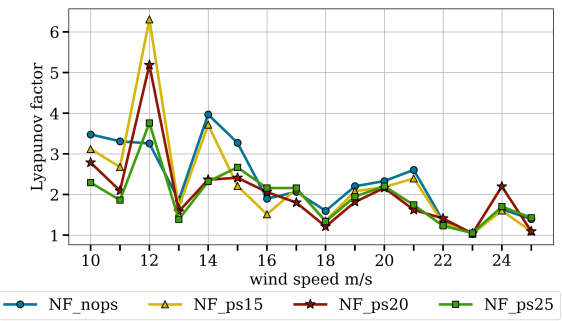


Figure 5. Results from DLC 1.3. Lyapunov factor for the nacelle-feedback (NF) controller without peak shaving and with different peak-shaving percentages above rated wind speed.

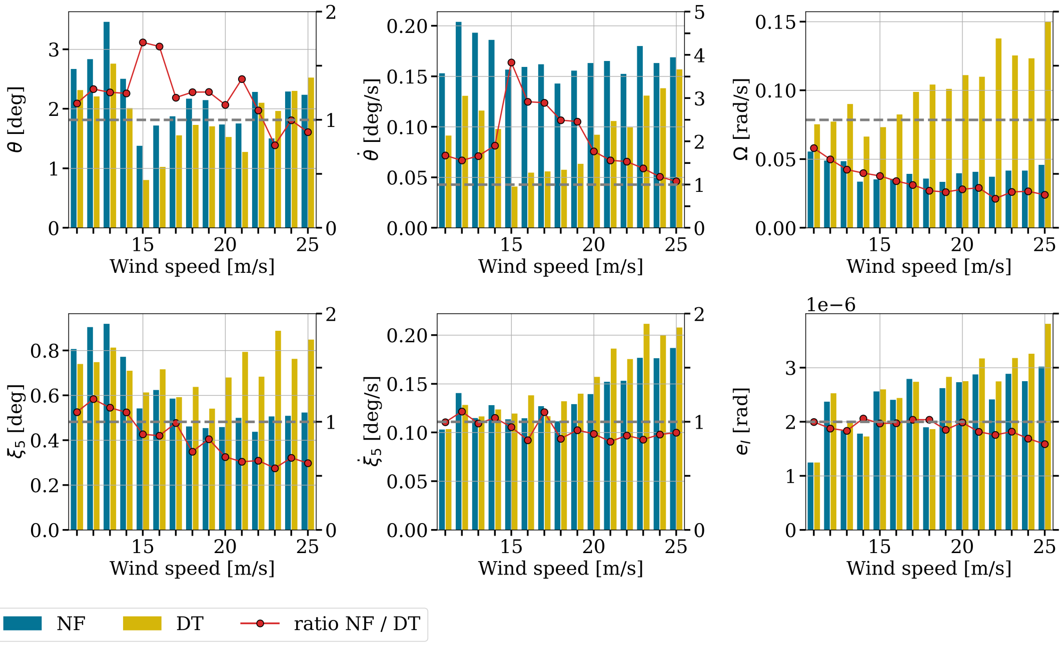


Figure 6. Results from DLC 1.3. Standard deviation of the pitch angle (θ), pitch angle velocity ($\dot{\theta}$), rotor speed (Ω), platform pitch displacement (ξ_5) and velocity ($\dot{\xi_5}$), and integral rotor speed error (e_I) for the de-tuned (DT) controller and the nacelle feedback (NF) controller.

prescription forces the pitch angle to distance from its optimum and increases its spread compared to the controller without peak shaving. Just above rated wind speed, the presence of the minimum pitch causes the rotor speed to undergo larger variation, which moves the rotor speed further away from its equilibrium. In both operating regions, the increased variation of one state is counterbalanced by the decreased variation of the others for different peak-shaving thresholds; therefore, the overall stability has a similar trend. From 15 m/s the states' bounds are very similar; in this region the steady-state thrust and pitch angle curves converge, and peak shaving is no longer a key component in the controllers' action.

In summary, the nacelle-feedback controller is generally found to be more stable than the de-tuned controller when evaluated using a Lyapunov-inspired stability metric. The addition of peak shaving, however, does not offer any clear impact on stability.

4. Conclusion

According to the proposed definition of the Lyapunov factor, peak shaving does not improve the stability of the floating IEA-15-240-RWT. Peak shaving has shown great potential for reducing the loads in the fore-aft direction as well as the platform displacement in pitch and surge, thus enhancing the FOWT fore-aft motion stability. Furthermore, it enhances the pitch angle standard deviation, which ultimately alleviates the fatigue loads on the blade pitch bearings. However, peak shaving worsens the tracking of the rotor speed, thus increasing its variation, which in turn increases the fatigue load of the shaft torsion. The Lyapunov factor captures the dynamics of the system holistically, thereby accounting for both these dynamics. Furthermore, around rated wind speed the turbine no longer operates at optimal conditions and the power output is reduced, thus reducing the turbine's annual energy production. Future research will be addressed to assess the costs saved on materials, components, and maintenance because of reduced loads versus the power production loss to assess whether peak shaving is a valuable controller strategy.

Finally, the tuning used for the de-tuned controller and for the nacelle-feedback controller produce similar Lyapunov factors around rated wind speed: the enhanced rotor speed tracking with the nacelle-feedback controller is balanced by the reduced pitch angle and platform pitch oscillations from the de-tuned controller. The nacelle-feedback controller is the most beneficial to stability at high wind speeds, where the de-tuned controller action is degraded and produces instabilities.

Acknowledgments

The authors would like to thank Anders M Hansen for his support with the model and HAWC2, which has been greatly appreciated and added a lot of value to this project. This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

References

[1] Collu M, Kolios A J, Chahardehi A and Brennan F 2010 *Conf. Proc. on Marine Renewable and Offshore Wind Energy* (London: Royal Institution of Naval Architects) pp 63-74
[2] Wind Europe 2017 Floating offshore wind vision statement

[3] Larsen T J and Hanson T D 2007 *J. Phys.: Conf. Series* **75** 012073

[4] Van der Veen G J, Couchman I J and Bowyer R O 2012 *Conf. Proc. on American Control Conference* (Montreal: IEEE) pp 3148-3153

[5] Fleming P A, Wright A D, Pineda I, Rossetti M and Arora D 2014 *Conf. Proc. on ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering* (San Francisco: Ocean Renewable Energy)

[6] Gaertner E, Rinker J, Sethuraman L, Zahle F, Anderson B, Barter G, Abbas N, Meng F, Bortolotti P, Skrzypinski W, Scott G, Feil R, Bredmose H, Dykes K, Shields M, Allen C and Viselli A 2020 *Tech. Rep.* (Golden: National Renewable Energy Laboratory)

[7] Allen C, Viselli A, Dagher H, Goupee A, Gaertner E, Abbas N, Hall M and Barter G 2020 *Tech. Rep.* (Golden: National Renewable Energy Laboratory)

[8] Abbas N, Zalkind D, Pao L and Wright A 2021 *Wind Energy Sci. Discuss. Preprint wes-2021-19*

[9] Jonkman J 2010 Definition of the Floating System for Phase IV of OC3 (Golden: National Renewable Energy Laboratory)

[10] International Electrotechnical Commission 2019 IEC 61400-3-1:2019 *IEC Standard*

[11] Stewart G M, Robertson A, Jonkman J and Lackner M A 2016 *Wind Energy* **19** 1151-59

[12] Hasselmann K, Barnett T P, Bouws E, Carlson H, Cartwright D E, Enke K, Ewing J A, Gienapp H, Hasselmann D E, Kruseman P, Meerburg A, Müller P, Olbers D J, Richter K, Sell W and Walden H 1973 *Deutsche Hydrographische Zeitschrift* A **18**

[13] Murray R M, Li Z and Sastry S S 1993 *A Mathematical Introduction to Robotic Manipulation.* CRC Press.