Open-Loop Control of Adjustable Tuned Mass Dampers for Floating Wind Turbine Platforms

Preprint

Daniel Zalkind,[1] Matt Shields,[1] Eben Lenfest, [2] Andrew Goupee, [2] and Christopher Allen[2]

1 National Renewable Energy Laboratory
2 University of Maine

Presented at the 31st International Ocean and Polar Engineering Conference
June 20–25, 2021

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5000-78839
June 2021

Open-Loop Control of Adjustable Tuned Mass Dampers for Floating Wind Turbine Platforms

Preprint

Daniel Zalkind,[1] Matt Shields,[1] Eben Lenfest, [2] Andrew Goupee, [2] and Christopher Allen[2]

1 National Renewable Energy Laboratory
2 University of Maine

Suggested Citation
Zalkind, Daniel, Matt Shields, Eben Lenfest, Andrew Goupee, and Christopher Allen. 2021. *Open-Loop Control of Adjustable Tuned Mass Dampers for Floating Wind Turbine Platforms: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP- 5000-78839. https://www.nrel.gov/docs/fy21osti/78839.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP- 5000-78839
June 2021

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

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 the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed herein 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.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Open-Loop Control of Adjustable Tuned Mass Dampers for Floating Wind Turbine Platforms

Daniel Zalkind[1], Matt Shields[1], Eben Lenfest[2], Andrew Goupee[2], Christopher Allen[2]
[1]National Renewable Energy Laboratory,
Golden, Colorado, United States
[2]Advanced Structures and Composites Center,
University of Maine, Orono, Maine, United States

ABSTRACT

In this study, we demonstrate the ability of adjustable tuned mass dampers (TMDs) to reduce the platform motion of floating offshore wind turbines (FOWTs). The TMDs are located in the hull and provide control authority by varying the amount of water ballast and compressed air in a reservoir over time. The optimal TMD settings depend on the wind and wave conditions of the FOWT. We present an open-loop control scheme that changes the TMD natural frequency based on sea state and a simple method for estimating the peak wave period and significant wave height. The performance of this open-loop control is compared to ideal control of the TMDs (set knowing the exact sea state), a TMD with a constant natural frequency targeting the design load case with the greatest platform motion, and a baseline set of simulations of the platform without TMDs. The constant natural frequency case performs nearly as effectively as the actively controlled case, suggesting that the TMDs can be simply designed for extreme load conditions and provide consistent control over a range of environments; however, the methods used to find the optimal TMD parameters and estimate sea state statistics could be used in other aspects of FOWT control and design.

KEY WORDS: offshore wind; structural control; floating wind turbines; tuned mass dampers

INTRODUCTION

This study examines the effect of tuned mass dampers (TMDs) on the performance of floating offshore wind turbines (FOWTs) using aeroelastic simulations. In an effort to improve system dynamics and structural loading on the tower and substructure, several control schemes for improving FOWT performance are presented. The control schemes use wave information to estimate sea state statistics that determine the natural frequency of the TMDs.

FOWTs can use the vast offshore wind resource located in water depths of more than 60 m (Musial et al., 2019). A challenge in the development of FOWTs has been the mitigation of wind- and wave-induced vibrations and responses on the turbine platforms. Traditionally, blade pitch control is used to regulate both the platform motion and generator power of the turbine. Because floating platforms can induce rotor motion, a non-minimum phase control problem prevents both the generator power and platform pitch motion from being adequately controlled (van der Veen et al., 2012); however, by using an additional actuator, better control solutions can be realized.

TMDs located in the floating platform, or hull, of a FOWT offer a promising solution because they can be collocated with the input wave disturbance of the system; further, unlike traditional blade pitch control, TMDs can be actuated when the turbine is parked during extreme conditions. A variety of hull-based TMDs with adjustable stiffnesses have been demonstrated in numerical simulations and wave tank tests (Allen et al., 2018) to reduce platform heave motion in FOWTs. Because the FOWTs must survive a variety of wave environments, it makes sense to adapt the TMD parameters to the sea state. In this study, we focus on platform pitching motion, which can affect the design of the FOWT tower, substructure, and rotor speed control.

A computationally efficient frequency domain model is used to determine the best TMD parameters for each wave environment. The coupled, FOWT-TMD system is modeled in OpenFAST (OpenFAST v2.3.0, 2020), an aeroelastic wind turbine simulation tool. Using OpenFAST, we compare the performance of several control schemes, including a baseline case with no TMDs and a FOWT with TMDs that have a constant natural frequency. We then compare those cases to a FOWT with TMDs ideally tuned to a known sea state. Finally, we demonstrate procedures for estimating the peak wave period and significant wave height in real time using the current wave elevation information that can be obtained from a wave buoy. The sea state statistics are then used to control the parameters of the TMDs in the simulation. The effect of each control scheme is evaluated over a set of design load cases (DLCs) specified by the American Bureau of Shipping (ABS) for a north Atlantic environment (ABS, 2020; Viselli et al., 2015).

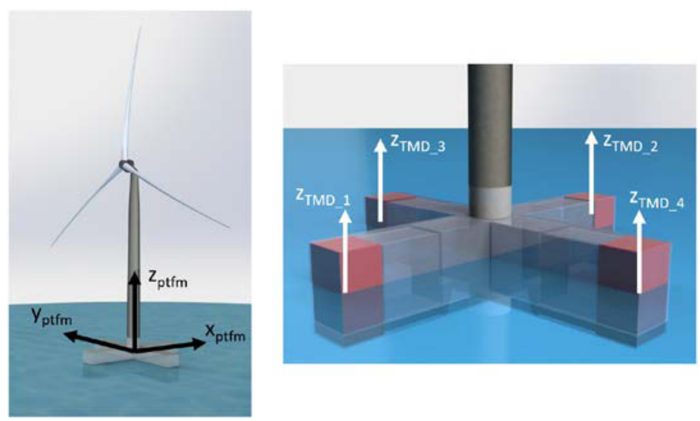

Fig. 1: Generic FOWT-TMD reference system (left) and a view of the floating platform (right) with each of the TMDs and their vertical degrees-of-freedom.

FLOATING WIND TURBINE AND TUNED MASS DAMPER MODELS

A generic, coupled FOWT system with TMDs was developed for this effort and is shown Fig. 1. The tower, turbine, and turbine controller are representative of the International Energy Agency 15-MW reference wind turbine (Allen et al., 2020; Gaertner et al., 2020). The platform is a cross-shaped barge platform with four TMDs, one in each leg, with the properties specified in Table 1.

Table 1. Platform TMD properties, with center-of-gravity locations (x_{cg}, y_{cg}, z_{cg}) relative to the tower base. The TMD degree of freedom is in the vertical z direction.

TMD Number	Mass (kg)	x_{cg}(m)	y_{cg}(m)	z_{cg} (m)
1	856640	41	0	-1.3
2	856640	-41	0	-1.3
3	856640	0	41	-1.3
4	856640	0	-41	-1.3

The response and effectiveness of the TMDs depends on their mass, m_{TMD}, damping, c_{TMD}, and spring constant, k_{TMD} (Rao, 2004). These physical parameters are related to the natural frequency of the TMD, ω_{TMD}, and damping ratio, ζ, such that:

$$k_{\text{TMD}} = \omega_{\text{TMD}}^2 m_{\text{TMD}} \tag{1}$$

and:

$$c_{\text{TMD}} = 2\zeta\sqrt{k_{\text{TMD}} m_{\text{TMD}}} \tag{2}$$

where m_{TMD}= 856640 kg is the mass of each TMD. The damping ratio is a constant $\zeta = 0.05$ in this study.

The optimal performance of a TMD is a multivariable design problem that considers the effects of its mass, stiffness, and damping properties. Further, the responses of the TMDs are highly sensitive to the dynamics of the platform and to external environments. Traditional applications of TMDs, such as their use in high-rise buildings or bridges, involve lightly damped systems that require the TMD to respond to a single frequency, and as such the optimal TMD parameters can be solved for directly (Chopra, 2007); however, this is not the case for FOWT platforms that experience significant and often nonlinear damping and are exposed to frequency-varying external wind and wave conditions. In these circumstances, the selection of the TMD's optimal parameters must consider a range of values (Connor, 2003).

Considering the aforementioned upfront computational requirements to accurately select optimal TMD parameters, this effort used two numerical models of the FOWT-TMD system. The first model is a simplified numerical representation of the system and is used as a preprocessor to efficiently derive the optimal TMD parameters based on sea state. This tool addresses the need for computational speed by representing the FOWT as a reduced-order numerical system resolved into a two-dimensional reference frame. Additionally, the equations of motion are linearized for use in the frequency domain, which further increase efficiency compared to time domain methods. The derivation and definition of this model is provided in detail from Allen et al. (2021) and Pegalajar-Jurado et al. (2018).

Once the TMD optimal parameters have been deduced from the frequency domain model, the information is then provided as an input to the second numerical model, OpenFAST, for use in its time domain analysis. The currently available version of OpenFAST considers the platform as a single rigid member and is not suited for representing the TMDs within the hull body. As such, in this effort, we used an augmented version of OpenFAST that was developed to represent the floating platform as a multibody system comprising the hull and an arrangement of TMDs. Within the augmented model, the TMDs were represented as individual bodies separate from the platform and were free to move independently of the platform about a single degree of freedom. As with the aforementioned frequency domain model, the derivation of the augmented OpenFAST model is outside the scope of this effort. Further information can be found from previous work conducted by Allen et al. (2018).

DESIGN LOAD CASES

Wind turbine performance is evaluated in OpenFAST for several sea states and wind environments, described in Table 2; these loading conditions are representative of ABS design requirements for floating wind turbines (ABS, 2020). From the outputs of the OpenFAST simulations, we compare the generator power, translational nacelle acceleration in the fore-aft and side-to-side directions, and the platform motion of the various control schemes. Surge and sway motion are unaffected by the TMDs, and the yaw degree of freedom is disabled in these simulations. We also evaluate tower response, including the peak load in the fore-aft direction and fatigue in both the fore-aft and side-to-side directions. Fatigue loads are expressed in terms of the standard deviation of the load signals. In future studies, damage equivalent loading should be evaluated and extrapolated based on the probabilities of the DLCs occurring. For all cases, to account for startup transients in floating systems, the first 200 seconds of 800-second simulations are omitted from the analysis.

Table 2. DLCs analyzed in this study, based on a Class IIA site, where T_P is the peak wave period, and H_s is the significant wave height. DLC 6.5 was created specifically for this project.

DLC	Wind Model	Wave Model
1.2	Normal turbulence, with mean wind speeds from 4–24 m/s in 2-m/s steps, six turbulent wind seeds for each mean wind speed, and Class A turbulence	Normal wave model, with T_P from 6.9–9.0 s and H_s from 0.8–3.1 m, depending on the wind speed
1.6	Same as DLC 1.2	Extreme wave model, with T_P from 11.5–14.1 s and H_s from 6.3–9.8 m, depending on the wind speed
6.1	50-year wind speed (42.5 m/s) and six turbulent wind seeds with Class A extreme turbulence model (ETM) turbulence and ±8-degree yaw misalignment	50-year wave model (T_P = 14.2 s and H_s = 10.7 m) with wave directions of 0, ±45, and ±90 degrees
6.3	1-year wind speed (34.0 m/s) and six turbulent wind seeds with Class A ETM turbulence and ±20-degree yaw misalignment	1-year wave model (T_P = 11.7 s and H_s = 7.0 m) with a 0-degree wave direction
6.5	500-year wind speed (46.8 m/s) and six turbulent wind seeds with Class A ETM turbulence and ±8-degree yaw misalignment	500-year wave model (T_P = 15.0 s and H_s = 12.5 m) with wave directions of 0, ±45, and ±90 degrees

TUNED MASS DAMPER CONTROL SCHEMES

This study presents three different control schemes that aim to reduce platform pitching motion:

1. A TMD with a constant natural frequency
2. A TMD with an ideally selected natural frequency based on the known sea state
3. A TMD with a controlled natural frequency using an estimation procedure for sea state statistics.

These three cases are compared against a FOWT that does not have TMDs, which is modeled using the same OpenFAST model but with TMDs that have zero mass. In this baseline case, the mass of the TMDs is replaced with additional platform mass, so the drafts of all FOWTs are equal.

Constant Tuned Mass Damper Setting

To determine the constant TMD best suited to controlling platform motion, we focus on the worst-case DLC. We sweep the natural frequency of the TMDs in DLC 6.5, which has the greatest amount of platform pitch motion (see Fig. 5g). The damping ratio of the TMD was not found to have a large effect on the platform motion, so it was set to a constant $\zeta = 0.05$. The platform motion of the twelve DLC 6.5 simulations at each TMD natural frequency is shown in Fig. 2. Based on the worst-case simulation at each TMD natural frequency (maximum of the dots in Fig. 2), a natural frequency of $\omega_{\text{TMD}} = 0.44$ rad/s performs best in terms of the platform pitch and roll motion. Platform heave motion is also reduced at low natural frequencies. Natural frequencies less than 0.4 rad/s result in large pitch and roll motions that translate into tower loads. Based on these results, natural frequencies less than 0.4 rad/s should be avoided.

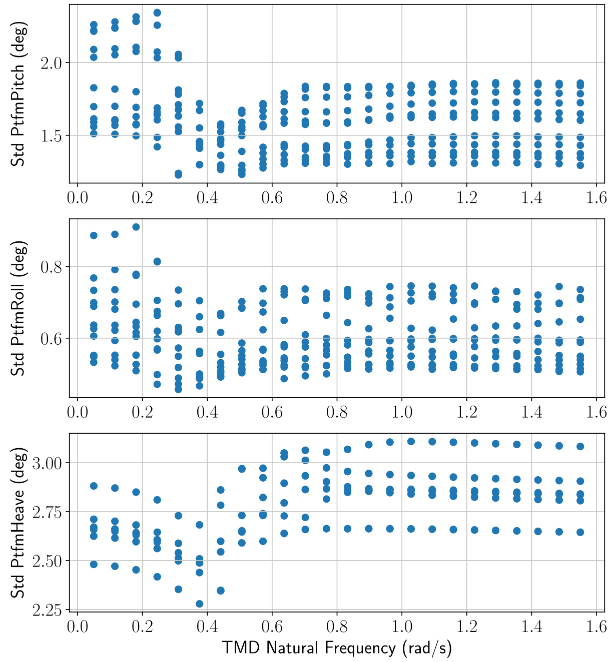

Fig. 2: The effect of the TMD natural frequency on the platform pitch, roll, and heave motion in terms of the standard deviation (std). Each DLC 6.5 simulation is represented by a dot.

Ideal Tuned Mass Damping Setting

Next, the effect of an ideally controlled, semi-active TMD is investigated. In a similar procedure to the natural frequency sweep previously described, the optimal ω_{TMD} was determined for each unique load case described in Table 2 by using the frequency domain model previously described. A piecewise linear function is used to interpolate between the evaluated points (Fig. 3). For each simulation, the peak period is assumed to be known, and the TMD natural frequency is set based on the control law prescribed in Fig. 3. This type of control could represent a semi-active control that would occur during longer time periods (e.g., hours). The ideally controlled TMDs also serve as a benchmark for the control law and the performance of actively controlled TMDs.

Sea State Estimation and Controlled Tuned Mass Damper

Because there is a potential benefit to controlling the natural frequency of the TMD based on the sea state and the actual sea state is not known in real time, we demonstrate a method for estimating sea state parameters. The significant wave height is related to the standard deviation of the wave elevation by:

$$\widehat{H}_s = 4\sigma_u, \tag{3}$$

where σ_u is the standard deviation of the wave elevation (Casas-Prat, 2008); this is implemented in Fortran with a buffer containing the past 200 seconds of wave elevation information; the buffer is initialized with zeros.

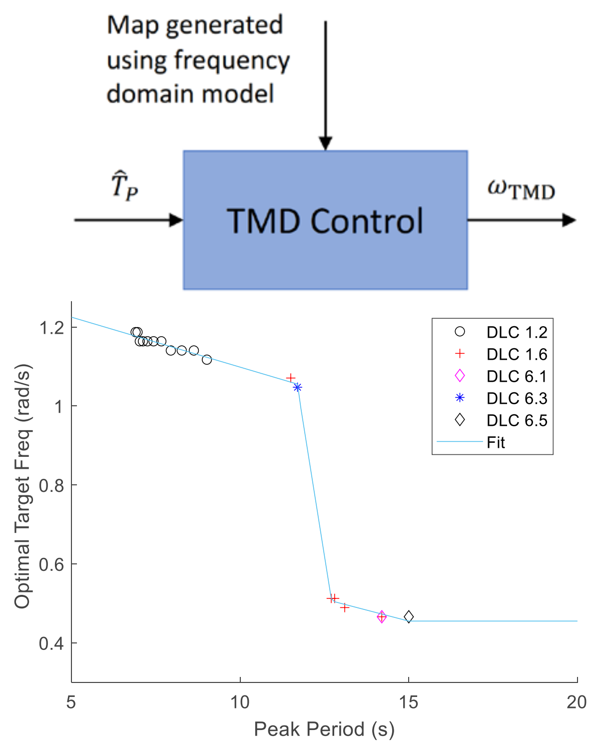

Fig. 3: Control law used for open-loop control, where the estimated peak period, $\hat{T}_P$, is mapped to the natural frequency, ω_{TMD}, of the TMD.

We use the current wave elevation at the base of the tower, but this information could be obtained from a wave buoy, somewhere in the wind power plant, because the sea state estimate varies slowly over time. In our simulations, the wave elevation is generated by the HydroDyn module of OpenFAST (OpenFAST v2.3.0, 2020), based on the significant wave height, H_S, and peak period, T_P, but the controller does not know the true values of H_S and T_P.

The peak wave period can be estimated using a frequency-locked loop (FLL). The FLL integrates the wave elevation signal twice and uses a pseudo-integral control to match the original and integrated signals using the estimated frequency (Garcia-Rosa et al., 2018). The states of the FLL are determined by:

$$\begin{bmatrix} \dot{\xi} \\ \dot{\nu} \end{bmatrix} = \begin{bmatrix} -\kappa\widehat{\omega} & -\widehat{\omega}^2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \xi \\ \nu \end{bmatrix} + \begin{bmatrix} \kappa\widehat{\omega} \\ 0 \end{bmatrix} u, \quad (4)$$

where u is the wave elevation, and ξ and ν are the states of the FLL, determined using a forward integration of the above differential equation. The outputs of the FLL:

$$\begin{bmatrix} \xi \\ \xi^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & \widehat{\omega} \end{bmatrix} \begin{bmatrix} \xi \\ \nu \end{bmatrix}, \quad (5)$$

are used to estimate the frequency of the wave elevation signal:

$$\dot{\widehat{\omega}} = -\gamma(u - \xi)\xi^* \widehat{\omega}, \quad (6)$$

where $\gamma = 0.10$ and $\kappa = 3.4$ are parameters of the FLL that determine the rate of convergence and frequency content of the estimate, respectively. The estimated peak period is:

$$\hat{T}_P = sat\left[LPF\left(\frac{2\pi}{\widehat{\omega}}\right)\right] \quad (7)$$

where LPF$(\cdot)$ is a low-pass filter with a time constant of 200 seconds, used to smooth the noisy frequency estimate, $\widehat{\omega}$, and reflect the slow changes in sea state over time. The output is saturated so that only peak periods between 5 and 15 seconds can be outputted, which is the known range of wave periods for this site. The equations are implemented in Fortran, and the control law in Fig. 3 is used to determine the control natural frequency, ω_{TMD}.

RESULTS

Sea State Estimation Performance

The demonstration in Fig. 4 shows that the methods for estimating peak period and significant wave height work well and converge to the true values. The controlled natural frequency switches between high and low natural frequencies, a drawback of using a non-smooth function for a control law. The benefit of low natural frequencies on heave motion can be seen between 250 and 300 seconds.

In the future, significant wave height could be used to determine ω_{TMD} because it appears easier to estimate, though it has less of a direct relationship to ω_{TMD}. The FLL could be improved with a better integration method for Eqs. (4) and (6), and both estimation methods would benefit from using improved initial conditions.

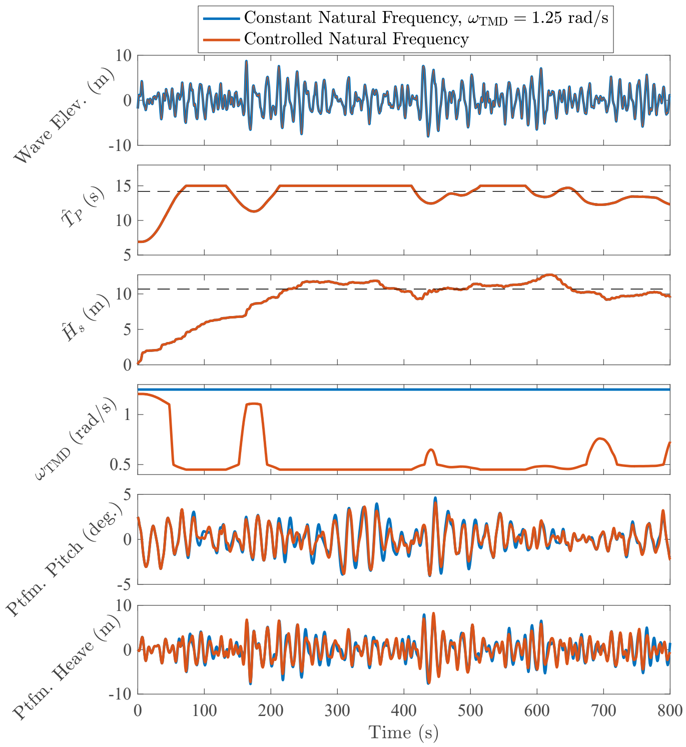

Fig. 4: TMD control demonstration from a DLC 6.1 simulation. The wave elevation is used to estimate the peak period ($\hat{T}_P$) and significant wave height ($\widehat{H}_S$), which determines the natural frequency of the control, ω_{TMD}. The true values of T_P and H_S are shown for reference, along with the platform (Ptfm.) pitch and heave motion.

Tuned Mass Damper Control Performance

A summary of the control performance for all the cases is shown in Fig. 5. The key performance indicators are aggregated across the DLCs and compared for the various control schemes. For each control scheme, we show:

- The average generator power across all simulations in each DLC
- The average standard deviation of the nacelle acceleration, tower load, and platform motion signal in each simulation of each DLC
- The maximum fore-aft tower base load for each DLC.

Using TMDs shows a negligible change (less than 0.1%) in the power capture of DLCs 1.2 and 1.6 (Fig. 5a). Constant TMDs reduce fore-aft nacelle acceleration, especially in DLCs 6.1 and 6.5, which is expected because the TMDs are tuned for the DLC with the greatest peak period and wave height (DLC 6.5). In DLC 6.5, for the constant and ideal TMDs, there is an average decrease in the fore-aft acceleration standard deviation of 13.7%. In DLC 6.1, where nonzero wave directions are evaluated, there is an average reduction of 7.9% in side-to-side acceleration standard deviation, showing the multidirectional benefits of the TMDs.

Platform pitch motion (shown in Fig. 5g) is reduced as desired, especially in DLCs 6.1 (a 14% reduction in standard deviation, on average) and 6.5 (a 22% reduction in standard deviation, on average). Platform roll is reduced, especially when the wave direction is nonzero (12.8% in DLC 6.1).

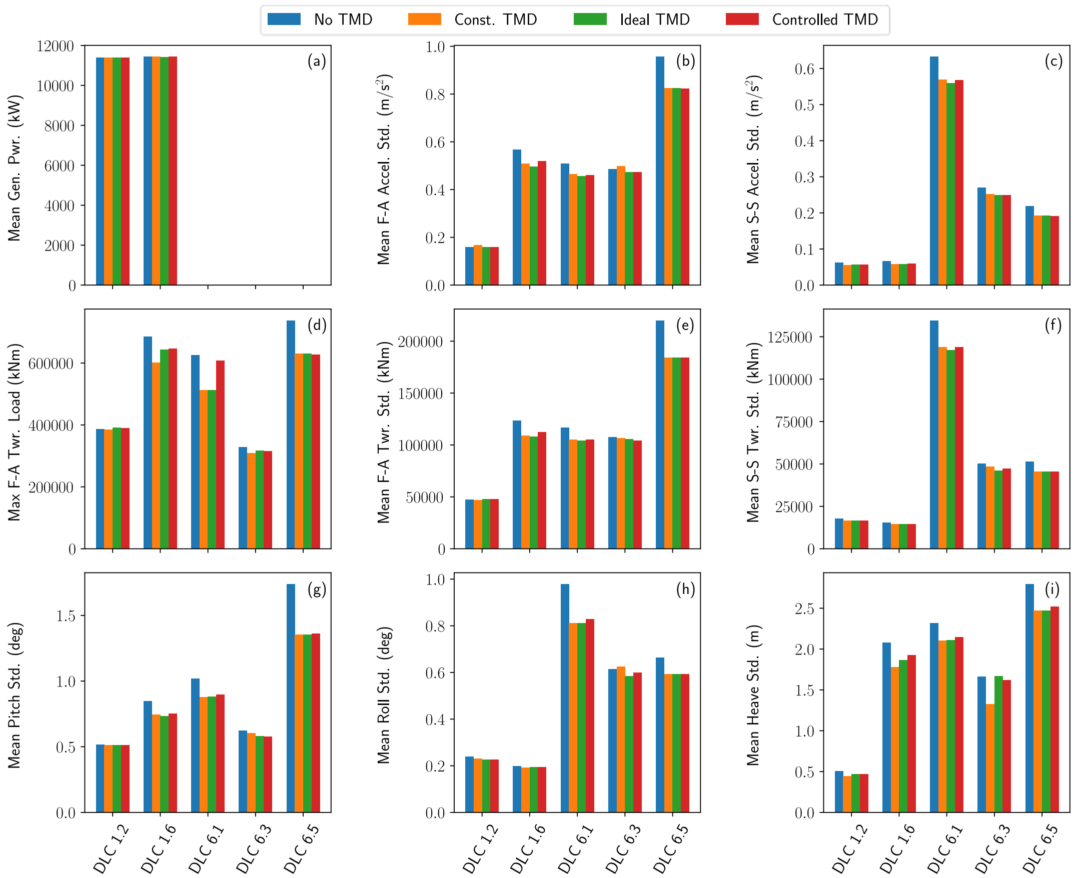

Fig. 5: Aggregated key performance indicators versus DLCs. We show the mean generator power (Gen. Pwr.) and standard deviation (std.) of the fore-aft (F-A) and side-to-side (S-S) nacelle accelerations, averaged over each DLC. The maximum (max) tower F-A load of each DLC is shown, along with the average std. of the F-A and S-S tower base loads. Finally, the mean pitch, roll, and heave motion stds. are shown for each DLC.

The reduced platform motion results in lower tower fatigue loads, especially in the parked DLCs (6.1, 6.3, and 6.5), but the overall effect on the turbine lifetime requires further analysis. Tower peak loads in DLC 1.6 are reduced during the constant and ideal TMD cases by 11%. When the TMD is controlled using sea state estimates, nonideal natural frequencies diminish the ability of the controlled TMDs to reduce tower peak loads. The maximum tower fore-aft load occurs near 430 seconds in the demonstration of Fig. 4.

We would expect to see the greatest difference in performance between the ideal (and controlled) TMDs, compared to the constant TMDs, in the DLCs where the ideal natural frequency is different than the constant natural frequency: DLC 1.2, 1.6, and 6.3 in this study. In DLC 1.2, there is a negligible change in platform pitch motion and a slight decrease in roll motion. In DLC 1.6, compared to no TMDs, constant TMDs reduce the average platform pitch motion by 12.0%, ideal TMDs by 13.4%, and controlled TMDs by 11.2%. In these cases, nonideal, controlled natural frequencies diminish the performance of the FOWT, compared to a constant TMD. In DLC 6.3, compared to no TMDs, constant TMDs reduce the average platform pitch motion by 3.5%, whereas ideal TMDs reduce motion by 6.7%, and controlled TMDs by 7.5%. DLC 6.3 highlights the benefits of using controlled TMDs; in this case, operational wind turbine control is not active and the ideal natural frequency can change significantly.

CONCLUSIONS

Hull-based TMDs improve FOWT performance in terms of platform motion and tower fatigue loading. The benefits that TMDs provide in reducing platform motion and tower loads are most apparent in cases where the turbine is parked, and the operational control is disabled while the blades are pitched to feather. Platform motion is also greatest in these extreme DLCs that directly affect the design of the FOWT. TMDs that adapt to different wave environments provide a relatively small benefit compared to the benefit of having a TMD with a constant natural frequency.

In the future, a full fatigue analysis should be performed to quantify the benefits of hull-based TMDs in terms of lifetime or substructure design changes. In reality, a greater variation of sea states affects the turbines; the DLCs evaluated in this study are based only on the most likely significant wave heights and peak periods in each DLC, so greater performance benefits could be realized with a greater variety of environments. The sea state parameter estimator shows promise and could be used in other aspects of FOWT operational and supervisory control.

ACKNOWLEDGMENTS

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 the U.S. Advanced Research Projects Agency – Energy award number DE-AR0001188. 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

ABS. (2020). Guide for Building and Classing Floating Offshore Wind Turbines (Tech. Rep.). American Bureau of Shipping. Spring, TX.

Allen, C. K., Goupee, A. J., Lindner, J., & Berry, R. (2018). Simulation of a Floating Offshore Wind Turbine with an Integrated Response Mitigation Technology, In *Proceedings of the 1st International Offshore Wind Technology Conference*, San Francisco, CA, American Society of Mechanical Engineers.

Allen, C. K., Goupee, A. J., & Viselli, A. (2021). A Computationally-Efficient Frequency Domain Model of a Floating Wind Turbine with Hull-Based Tuned Mass Damper Elements, In *Proceedings of the 31st International Ocean and Polar Engineering Conference*, Rhodes, Greece, International Society of Offshore; Polar Engineers.

Allen, C. K., Viselli, A., Goupee, A. J., Dagher, H., Gaertner, E., Abbas, N., Hall, M., & Barter, G. (2020). Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine (Tech. Rep. NREL/TP-5000-76773). National Renewable Energy Laboratory. Golden, CO.

Casas-Prat, M. (2008). *Overview of Ocean Wave Statistics* (Master's thesis). Universitat Politechnica de Catalunya. Barcelona, Spain.

Chopra, A. K. (2007). *Dynamics of Structures: Theory and Application to Earthquake Engineering*, Third Edition. Upper Saddle River, NJ, Pearson Education, Inc.

Connor, J. J. (2003). *Introduction to Structural Motion Control*. Upper Saddle River, NJ, Pearson Education, Inc.

Gaertner, E. et al. (2020). Definition of the IEA 15-Megawatt Offshore Reference Wind Turbine (Tech. Rep. NREL/TP5000-75698). National Renewable Energy Laboratory. Golden, CO.

Garcia-Rosa, P., Ringwood, J., Fosso, O., & Molinas, M. (2018). Comparison of Frequency Estimation Methods for Wave Energy Control.

Musial, W., Beiter, P., Spitsen, P., Nunemaker, J., & Gevorgian, V. (2019). 2018 Offshore Wind Technologies Market Report (Tech. Rep.). U.S. Department of Energy. Oak Ridge, TN.

OpenFAST v2.3.0. (2020). National Renewable Energy Laboratory. https://github.com/openfast.

Pegalajar-Jurado, A., Borg, M., & Bredmose, H. (2018). An Efficient Frequency-Domain Model for Quick Load Analysis of Floating Offshore Wind Turbines. *Wind Energy Science*, 3, 693–712.

Rao, S. (2004). *Mechanical Vibrations*, Fifth Edition. Upper Saddle River, NJ, Pearson Education, Inc.

van der Veen, G., Couchman, I., & Bowyer, R. (2012). Control of Floating Wind Turbines, In *Proceedings of 2012 American Control Conference*, Fairmont Queen Elizabeth, Montreal, Canada, IEEE.

Viselli, A., Forristall, G., Pearce, B., & Dagher, H. (2015). Estimation of Extreme Wave and Wind Design Parameters for Offshore Wind Turbines in the Gulf of Maine Using a POT method, *Ocean Engineering*, 104, 649– 658.