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Model-Free Semi-Active Structural Control of Floating Wind Turbines

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***Abstract*—This paper addresses the load/vibration reduction problem of offshore floating wind turbines (FWTs). Based on the tuned mass damper (TMD), a novel semi-active control method is designed to mitigate the floating platform's structural vibration. Different from existing results, the proposed control method is model-free and insensitive to system uncertainties and unmodelled dynamics. We base our design on the model-free adaptive control (MFAC) method. A data-based surrogate model is developed to approximate the unknown FWT dynamical system through the dynamic linearization technique. In addition, a quadratic programming (QP) module is embedded in our MFAC-based semi-active structural controller for constraint handling and control allocation purposes. High-fidelity simulations of FWTs show that our model-free semi-active structural controller can address the limitations of existing results and significantly reduce the platform's vibration.**

***Index Terms*—Structural Control; Model-Free Adaptive Control; Floating Wind Turbine; Tuned Mass Damper.**

I. Introduction

Wind power is an essential source of global power generation. At the end of 2019, wind power's share of electricity usage has reached 5% worldwide and 14% in Europe. Particularly, the UK installed 2,393 MW of new wind power capacity in 2019, in which 74% was offshore [1] - almost triples its onshore counterpart. The UK figures indicate that offshore wind power has a much faster increase rate than onshore wind power. For now, offshore wind turbines are commonly with fixed-bottom substructures that have a water-depth limit of 60m. However, wind resources extremely concentrate in deep-water sea areas with depths up to 600m. In order to capture the wind resource with higher quality, offshore wind turbines are starting to be deployed in far offshore with the floating wind turbine (FWT) technology, which has the potential to install turbines in the sea with depth up to 900m. Some types of floating platforms are like boats, which can move easily and can reduce the construction and maintenance costs than the conventional fixed-bottom offshore wind turbines. Moreover, floating wind farms deployed further offshore have no visual pollution and can provide better accommodation for shipping and fishing lanes. But FWTs face severe challenges from fluctuating aerodynamic loading than their fixed-bottom versions due to their movable platforms. Thus load/vibration reduction is particularly important for FWTs.

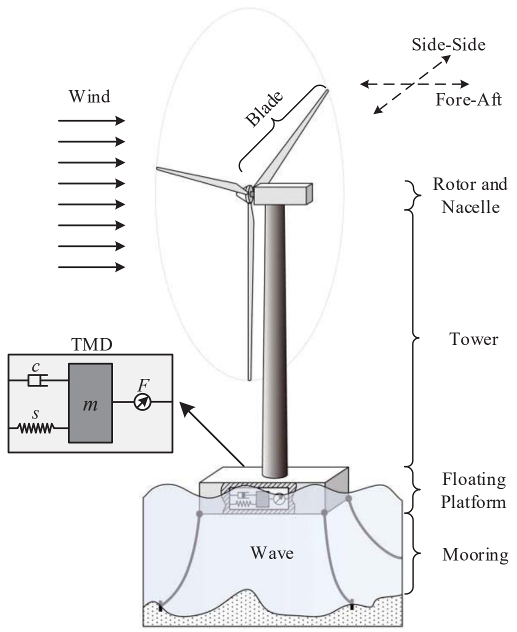

Figure 1: Illustration of a floating wind turbine with TMD structures (adapt from [2]).

Many control methods have been proposed to reduce the FWTs' loads/vibrations. A notable example is the blade pitch control, i.e., tuning the blade pitch angles given the measurements of certain variables like tower-top velocities. Nevertheless, blade pitch control has clear drawbacks. It interferes the power generation process of FWTs. In addition, it can also significantly increase the actuator usage, and therefore renders fatigue. Tuned mass damper (TMD)-based structural control is an effective alternative solution. This technique was initially designed and used by the civil engineering community to reduce the dynamical structural loads cased by winds, earthquakes and many other external sources. A typical TMD-FWT system is illustrated in Fig. 1. TMD is a dynamical structure which typically has a large mass along with a spring and a damper. The large mass module is usually connected to

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the main structure via the spring and the damper to achieve load/vibration mitigation. TMD can resonate and dissipate the main structure's energy via the damping effect, thus reducing the vibration/load of the main structure (e.g., the floating platform in our study). TMDs usually have three main types - passive, semi-active, and active, resulting in three major categories of TMD-based control approaches. The simplest and most straightforward approach is the passive TMD control. It employs non-changed TMD parameters (i.e. the spring stiffness s and the damping coefficient c). However, this design is inflexible and lacks adapting abilities. Active TMD control introduces an active control force to the system (see F in Fig.1), providing additional control freedom and rendering better vibration reduction performance than the passive TMD. However, this design may result in high power consumption and stability issues. In contrast, semi-active TMD allows the controller to adjust the TMD parameters (i.e. s and c) with acceptable power consumption in real-time. Thus it can take advantage of both passive and active TMD control methods while largely avoiding the drawbacks of them. However, due to the inherent complexities of the TMD-FWT system, the study on the structural control of floating wind turbines with semi-active TMDs is still very limited. In addition, the majority of the existing semi-active TMD-based control approaches are model-based. Thus they are sensitive to the system uncertainties and modelling errors and may result in a degraded performance in applications. Therefore, developing new semi-active TMD control strategies with enhanced adaptability, robustness, and effectiveness is important.

In this study, a novel structural control method with a semi-active TMD is proposed for FWTs. This new method is data-driven and model-free, which addresses the limitations/drawbacks of existing results. Specifically, we base our design on the model-free adaptive control (MFAC) approach [3]. MFAC is a systematic control algorithm design framework that can address the control problems of various plants without requiring analytical models. The main principle of MFAC is to establish a surrogate data-driven model for the nonlinear system via the dynamic linearization technique and the so-called pseudo partial derivative. To be more specific, the surrogate model is built and updated online by the plant's input/output measurements. Then one can estimate the pseudo partial derivative and accordingly design the one-step-ahead adaptive control policy. It is noteworthy that the constraint handling ability of MFAC is still immature. However, the parameters of semi-active TMDs must be adjusted within predetermined bounds. To address this issue, a quadratic programming (QP) module is embedded in MFAC. This module functions as a control allocator, it decides the changes of spring stiffness s and damping coefficient c at every time-step while strictly complying with their constraints. High-fidelity simulations with the NREL (National Renewable Energy Laboratory) Flow Analysis Software Toolkit (FAST) show that the proposed MFAC-based semi-active structural controller significantly reduces the platforms' vibrations under unknown system dynamics. The overall performance of it is clearly better than the passive TMD method and comparable to the H_∞-based active TMD control method.

We organize the remainder of this paper as follows. The model-free semi-active controller for FWTs is proposed in Sec.II. Numerical simulations with NREL FAST code are provided in Sec. III. We conclude this paper in Sec. IV.

II. Model-Free Semi-Active Structural Control of FWTs

A. Preliminaries of MFAC

As mentioned in the introduction, we base our model-free semi-active controller on the MFAC method [3]. Therefore, the main framework and principles of MFAC is briefly introduced in this subsection. MFAC relies on the idea that many nonlinear systems under discrete-time description can be built, organized, or reconstructed by the sequential input data and output measurements. Based on it, we consider the following nonlinear SISO systems under the discrete-time description:

$$y(k+1) = f(y(k), ..., y(k-n_y), u(k), ..., u(k-n_u)) \quad (1)$$

In this equation, $u(k)$ is the control input and $y(k)$ denotes the system output. We note that the system model f is unknown. In addition, n_y and n_u denote backward steps. This indicates that $\{u(k), u(k-1), u(k-2), ...u(k-n_y)\}$ and $\{y(k), y(k-1), y(k-2), ...y(k-n_y)\}$ are the sequential historic input data and output measurements of (1). It should be emphasized that, in MFAC, f, n_y and n_u are all unavailable for the control system design.

For ease of notation, we denote $U_L(k) = [u(k), ..., u(k-L+1)]^T$ as the historic input data vector in $[k-L+1, k]$, and here L is mentioned as the linearization length. We also define $\Delta y(k) = y(k) - y(k-1)$ and $\Delta U_L(k) = U_L(k) - U_L(k-1)$. Then, some common assumptions in MFAC [3] are given as follows.

Assumption 1: The partial derivatives of the unknown function f w.r.t the sequence $u(k), ..., u(k-L+1)$ are assumed to be continuous.

Assumption 2: The plant described by (1) follows the generalized Lipschitz condition, i.e., 1) $|\Delta y(k+1)| \leq b \|\Delta U_L(k)\|$ for all k; 2) $\Delta U_L(k) \neq 0$. Here $b > 0$ is time-invariant.

Then, as discussed in [3], one can find a so-called pseudo partial derivative (PPD) vector $\xi_L(k) = [\xi_1(k), ..., \xi_L(k)]$, and the original system model in (1) can be equivalently described by a surrogate model in the following equation.

$$\Delta y(k+1) = \xi_L(k)\Delta U_L(k) \quad (2)$$

Based on (2), the SISO MFAC algorithm [3] are designed in (3)-(5), and some explanation are given as follows.

1) Eqs. (3) and (4) are the PPD vector estimation algorithm, and these equations are deduced by solving the minimization problem with respect to the cost function in the following equation:

$$\begin{aligned} J_{\xi(k)} = &\left|\Delta y(k) - \hat{\xi}_L^T(k)\Delta U_L(k-1)\right|^2 \\ &+ \mu\left\|\hat{\xi}_L(k) - \hat{\xi}_L(k-1)\right\|^2 \end{aligned} \quad (6)$$

$$\hat{\xi}_L(k) = \hat{\xi}_L(k-1) + \frac{\zeta \Delta U_L(k-1)}{\mu + \|\Delta U_L(k-1)\|^2} * (\Delta y(k) - \hat{\xi}_L^T(k-1)\Delta U_L(k-1)) \tag{3}$$

$$\hat{\xi}_L(k) = \hat{\xi}_L(1), \quad \text{if } \left\|\hat{\xi}_L(k)\right\| \le \varepsilon, \text{ or } \|\Delta U_L(k-1)\| \le \varepsilon, \text{ or } \mathrm{sign}(\hat{\xi}_1(k)) \neq \mathrm{sign}(\hat{\xi}_1(1)) \tag{4}$$

$$u(k) = u(k-1) + \frac{\rho_1 \hat{\xi}_1(k)(y_r(k+1) - y(k))}{\lambda + \left|\hat{\xi}_1(k)\right|^2} - \frac{\hat{\xi}_1(k)\sum_{i=2}^{L}\rho_i \hat{\xi}_i(k)\Delta u(k-i+1)}{\lambda + \left|\hat{\xi}_1(k)\right|^2} \tag{5}$$

2) Eq. (5) is the control policy, in which $u(k)$ is deduced by solving the minimization problem with respect to the following cost function with a weighted one-step-ahead form:

$$J_{u(k)} = |y_r(k+1) - y(k+1)|^2 + \lambda|u(k) - u(k-1)|^2 \tag{7}$$

where y_r is our reference signal. Besides, we also employ a constant α to scale every $u(k)$ and apply the resulting controller into the system.

In (3)-(5), λ, μ, ρ_i, and ζ are user-defined parameters, with $\lambda > 0$, $\mu > 0$, $\rho_i \in (0, 1]$, and $\zeta \in (0, 2]$. One can refer to [3] for the detailed convergence analysis and proof of this MFAC algorithm.

B. MFAC-Based Semi-Active Structural Control of FWTs

The main goal of this study is to employ the semi-active TMD to mitigate the vibration/load (in term of the pitch angle) of the floating platform. A TMD is installed on the platform along the fore-aft direction, as illustrated in Fig. 1. The active force is set to be zero, i.e., $F \equiv 0$. Besides, the spring stiffness k and damping coefficient d are assumed to be continuously and independently variables. This assumption has been utilized in many relevant studies and there are many devices that support this assumption.

Now we transplant the semi-active control problem into the MFAC framework. The system output $y(k)$ is the platform's pitch angle. We set the reference output $y_r \equiv 0$ based on the fact that the controller aims to reduce the pitch angle (i.e., reduce platform's vibrations). Then, instead of directly employing the spring stiffness s and damping coefficient c as the control input, we design u to be a virtual active force. The main advantage of such a design is that it renders a SISO structure, which is consistent with the one in MFAC. Though the MFAC method for MIMO systems has also been investigated in some studies, the stability analysis of the MIMO-MFAC has not yet been established. It should be emphasized that this virtual active force is not applied to the TMD. Instead, after $u(k)$ is derived by (5) at any time step k, a QP module is employed to decide the specific $s(k)$ and $c(k)$ while strictly complying with their constraints. The QP problem is formalized as follows.

Minimize:

$$\begin{aligned} V =& a_s(s(k) - s_r)^2 + a_c(c(k) - c_r)^2 \\ &+ a_u[y(k)(s(k) - s_r) + \omega(k)(c(k) - c_r) - u(k)]^2 \end{aligned} \tag{8}$$

Subject to:

$$s_{\min} \le s(k) \le s_{\max} \tag{9}$$

$$c_{\min} \le c(k) \le c_{\max} \tag{10}$$

Here the constants s_r and c_r denote the reference values of $s(k)$ and $c(k)$, respectively. In (8), $\omega(k)$ is the pitch angular velocity at step k, it can be derived by $(y(k) - y(k-1))/T$, and here T is the time interval between steps. Moreover, $s_{\min}, s_{\max}, c_{\min}$, and $c_{\max}$ are the bounds of $s(k)$ and $c(k)$. Besides, a_s, a_c and a_u are user-defined constants for weighting purposes.

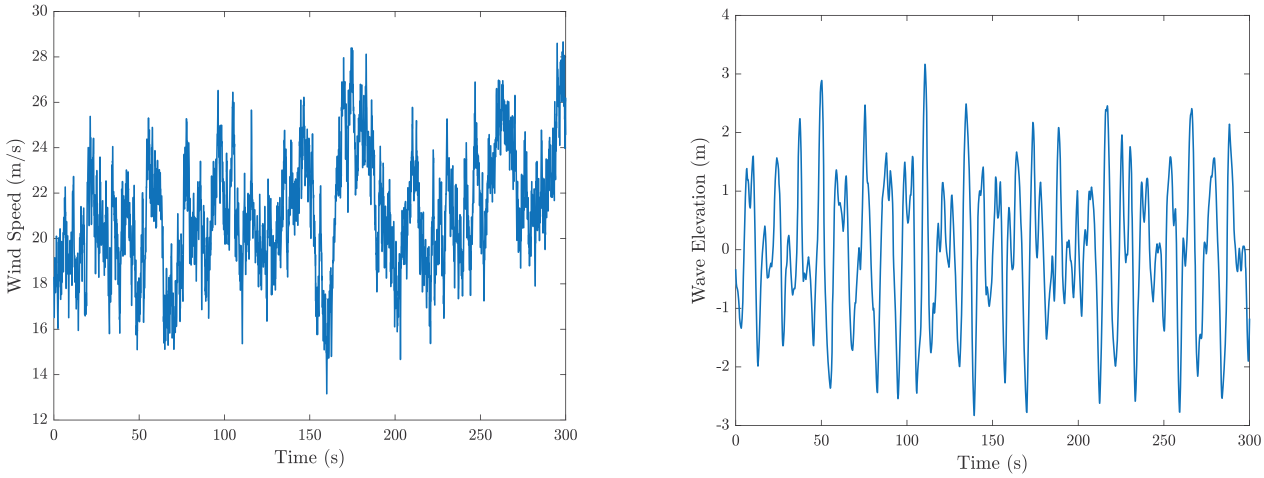
Eq. (8) indicates that, at every time step k, we aim to find the optimal values of $s(k)$ and $c(k)$ to track the virtual active force u. At the same time, we also make a trade-off between the control cost $(a_s(s(k) - s_r)^2 + a_c(c(k) - c_r)^2)$ and the control performance $(a_u[y(k)(s(k) - s_r) + \omega(k)(c(k) - c_r) - u(k)]^2)$. Besides, by employing this QP algorithm, the actual control input signals $s(k)$ and $c(k)$ are always within predetermined bounds, i.e., $s(k) \in [s_{\min}, s_{\max}]$ and $c(k) \in [c_{\min}, c_{\max}]$.

Remark 1 (Stability Analysis): The mechanism of the TMD is that they can resonate and dissipate the energy of the main structure via the damping effect of TMD. Therefore, passive TMDs have no negative influence on the stability of the main structure. This is also the main reason why passive TMDs have been widely utilized. As mentioned in the introduction, semi-active TMDs inherit the merit of passive TMDs, as long as s and c are changed within proper bounds. Since the QP module can guarantee this requirement, our model-free semi-active controller also has no negative influence on the stability of the TMD-FWT system. Besides, if the external disturbance is bounded, the platform's pitch angle and angular velocity are always bounded, i.e., $y, \omega \in \mathcal{L}_\infty$. Therefore, we can guarantee the closed-loop system's boundedness.

III. High-Fidelity Simulations with NREL FAST

The NREL 5MW FWT model [4] embedded in the FAST code is employed in this study. The turbine is installed on an ITI Energy barge, and a semi-active TMD is integrated into this barge platform, which moves in the fore-aft direction to suppress the corresponding vibration (i.e., the platform's pitch angle). One can refer to [4] for the detailed specifications of the FWT as well as the ITI barge platform. Some main settings of the FWT system and TMD are provided in Tables I and II.

It is noteworthy that s_r and c_r in Table II are the optimal parameters for a passive TMD of our FWT system, and



(a) Wind speed (b) Wave elevation

Figure 2: Wind and wave conditions.

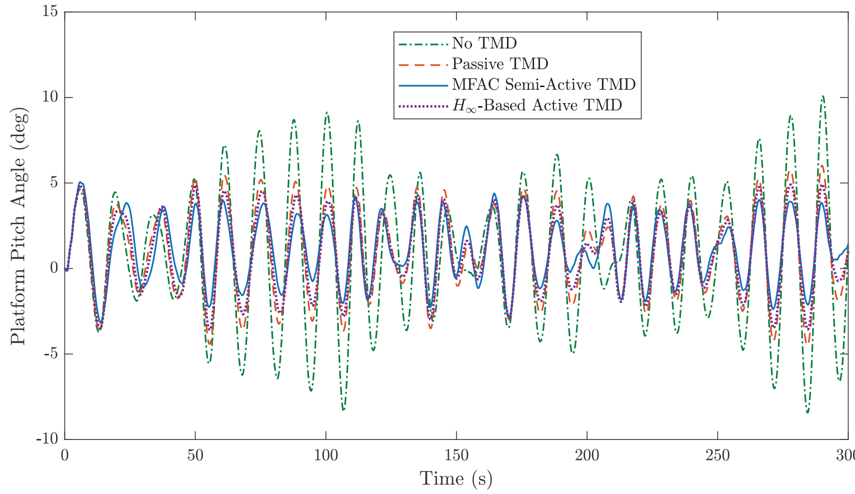
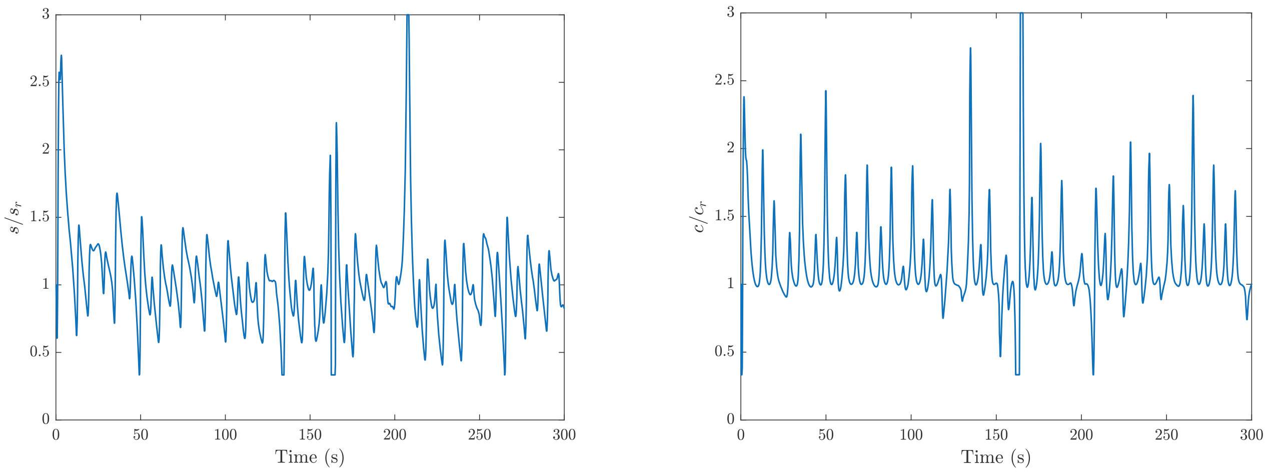


Figure 3: Simulation results of the platform pitch angles.



(a) s/s_r (b) c/c_r

Figure 4: Time responses of s/s_r and c/c_r.

Table I: FWT Parameters

Parameters	Values
Rating Power, MW	5
Cut-in, rated, cut-out wind speed, m/s	3, 11.4, 25
Cut-in, rated rotor speed, rpm	6.9 12.1
Rotor diameter, m	126
Hub heigh, m	90
Tower mass, kg	347,460
Platform mass, kg	5,452,000
Platform size, m	40×40×10
Number of mooring lines, -	8
Anchor depth, m	150

Table II: Semi-active TMD parameters

Parameters	Values
TMD mass m, kg	400,000
Reference spring stiffness s_r, N/m	103,019
Reference damping coefficient c_r, N/(m/s)	60,393
$s_{\min}$, N/m	103,019/3
$s_{\max}$, N/m	103,019×3
$c_{\min}$, N/(m/s)	60,393/3
$c_{\max}$, N/(m/s)	60,393×3

they are employed as the reference values of our semi-active controller.

Moreover, the turbulent wind is provided by the IEC Kaimai Spectral Model with NTM in the TurbSim module, and the wave condition is obtained from the FAST's HydroDyn module. The specific wind and wave parameters are provided in Table III.

Table III: Wave & Wind conditions

Parameters	Values
Hub-height longitudinal wind speed, m/s	22
Turbulence intensity of wind, -	B
Peak-spectral periods of wave, s	11.2
Significant wave height, m	5.5

Under the condition in Table III, the wind speed and wave elevation responses are given in Fig. 2.

For the MFAC-based semi-active controller proposed in this paper, we set $L = 3$, $a_s = 1$, $a_c = 2$, $a_u = 10$, $\alpha = 100,000$, $\lambda = 5$, $\eta = 1$, $\mu = 1$, and $\rho_i = 0.15$, $i = 1, 2, 3$. Besides, to show the effectiveness of our semi-active structural controller, three other structural control strategies are also employed in simulations:

1) The free vibration responses without TMD, which is the benchmark in structural control studies.
2) The passive TMD method with optimal settings, i.e. $s \equiv$ 103019N/m and $c \equiv$ 60393N/(m/s).
3) The active H_∞ structural control method proposed in [2]. This strategy is designed by the H_∞ technique with a linearized system model.

Simulation results of the platform's pitch angles under all the control approaches are illustrated in Fig. 3. One can see that our semi-active structural control algorithm has a better performance than the no-TMD and passive-TMD cases. On average of a 300s simulation, it leads to 49.35% and 27.71% vibration reductions with respect to no-TMD and passive-TMD cases, respectively. Besides, it also has a comparable performance when compared with the H_∞-based active structural control method. Finally, the time responses of s/s_r and c/c_r are provided in Fig. 4.

All these show that the proposed semi-active structural controller can sucessfully mitigate the vibration of the floating platform. It has an effective performance as the active control method while ensuring the closed-loop stability as the passive control method.

IV. Conclusion

The load/vibration reduction problem of floating wind turbines was address in our study. Specifically, a new semi-active structural controller was proposed, which can mitigate the vibration of the floating platform by adjusting the TMD's damping coefficient and spring stiffness in real-time. More importantly, the proposed controller was data-driven and model-free. It was based on the MFAC technique, and an additional quadratic programming module was employed to allocate control efforts within predetermined bounds. High-fidelity simulations with NREL FAST showed that the proposed model-free semi-active controller was effective. It can address the limitations of existing results and significantly reduce the platform's vibration. Future work in this direction will consider the additional restrictions on the changing rates of spring stiffness and damping coefficient.

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