Identification and Validation of a Barge Floating Offshore Wind Turbine Model with Optimized Tuned Mass Damper

D. Villoslada[1], M. Santos[2] and M. Tomás-Rodríguez[3]

[1] University Complutense of Madrid, C/ Profesor G. Santesmases 9, 28040 Madrid, Spain
davillos@ucm.es
[2] University Complutense of Madrid, C/ Profesor G. Santesmases 9, 28040 Madrid, Spain
msantos@ucm.es
[3] City, University of London, London, UK
Maria.Tomas-Rodriguez.1@city.ac.uk

Abstract. Floating offshore wind turbines (FWOT) stand as a promising concept to expand the wind energy generation into the more productive deep-water areas, where conventional bottom-fixed turbines are infeasible. Barge-type floating wind turbines experience an inverted pendulum effect which produces a coupling with the wind turbine response, resulting in large structural loads. In this paper, we apply passive structural control in the form of a tuned mass damper, installed in the nacelle to mitigate the tower fatigue. A linear dynamics model for the barge-type offshore wind turbine is formulated based on Lagrange's equations. The parameter identification for this model is performed using the FAST-SC simulation software to produce synthetic experimental reference data. A thorough validation study was carried out to select the optimal free-decay initial conditions and test duration to obtain the most suited model parameters. It was found that the 3 degrees initial platform pitch tests began sufficiently far from rest to allow the dynamics to be characterized, but not so far to be affected by the unmodeled non-linearities. Once the model was ready to simulate the system properly, an optimization of the TMD parameters is carried out using genetic algorithms, taking the tower fatigue as a fitness function, derived from the tower top displacement. The results show this tuned conventional passive structural control can help to absorb the vibrations of the structure, reducing the tower fatigue by 50%.

Keywords: Identification, simulation, barge-type floating wind turbine, passive structural control, genetic algorithms.

1 Introduction

Wind energy production is experimenting a huge expansion in recent years. Land-based wind turbines have been widely installed all over the Earth's lands, covering the most suitable regions. However, while some drawbacks like strong visual and noise impact remain unsolved, the energy demand grows on parallel to the governments' commitment towards clean energy production. Consequently, wind turbines have been gradually pushed into the sea.

It is well known that offshore wind resources are of higher quality than those on land, with stronger, steadier and more frequent winds [1]. Near-offshore regions with shallow waters have been predominantly chosen for wind farm installation, using fixed-bottom structures such as monopiles and gravity foundations. This technology is well proved nowadays and found to be economically suitable for water depths up to approximately 60 meters [2]. Nevertheless, the sea bed in these areas suffers a relatively large footprint from the turbine's foundations [3] and shallow water resources constitute a minority compared to the entire sea wind potential.

Floating offshore wind turbines (FOWT) use new concepts of foundation, which are considered to be technically feasible for its deployment on waters from 60 to 900 meters. There are three main types of FOWT, depending on the restoring mechanism they rely on. The three main balanced mechanisms are buoyancy, ballasting and mooring. The derived floating foundation types are the barge, the spar buoy and the tension leg platform.

The present study focusses on the barge-type floating platforms, which stand out for their simplicity in design, assembly and maintenance. The stability of this concept is achieved through its waterplane area moment and is moored by catenary lines.

Preliminary loads analysis on floating wind turbines [4] have demonstrated that the wave and wind-induced motions increase the displacements and loads on the structure. A promising approach to reduce the FOWT loads is the application of structural control techniques, which have been used for years in civil engineering to protect structures from damage caused by dynamic loading due to earthquakes, wind or traffic [5]. In this context, structural control should be understood as an addition of a Degree Of Freedom (DOF) to the structure devoted to influence the structural behavior, instead of an intervention of the existing turbine's power production control system.

Among the three major types of structural control, which are passive, semi-active and active, we have implemented the passive one. Within this type, the energy dissipation devices are the ones of interest and, more specifically, the dynamic vibration absorbers. They typically consist of a mass resonant device attached to the structure by a spring and a viscous damper, usually referred to as Tuned Mass Dampers (TMD). The tuning of their parameters is crucial to absorb energy at one of the natural frequencies of the structure [6].

The application of structural control to offshore wind turbines has been a topic of interest the last years [7]. One of the major contributions came from Lackner and Rotea, who upgraded the high-fidelity simulation code FAST to include structural control features and creating FAST-SC [8]. Then, Stewart and Lackner used FAST-SC to assess passive control solutions for both tension leg platforms and barge-type floating wind turbines [9]. Other studies include the application of hybrid and active structural control to mitigate loads [10].

This work explores the addition of a passive TMD to the nacelle of a barge-type floating offshore wind turbine. To that end, a reduced degree of freedom FOWT model is formulated based on Lagrange's equations and validated using FAST-SC reference simulation data. The dependence of the initial conditions is analysed, showing the range of values where the linear model is valid. The optimization of the TMD parameters is then performed using genetic algorithms to reduce the tower fatigue in the fore-aft direction.

The following sections are structured as follows. Section 2 describes the selected FOWT model, the software tools used for the simulations and presents a reduced model to be included in the optimization loop. In Section 3, the parameter identification is performed for the simplified model. Section 4 covers the TMD optimization and the results achieved on the vibration absorption. Conclusions end the paper.

2 FOWT dynamic model

The wind turbine selected for this study is the National Renewable Energy Laboratory (NREL) 5-MW wind turbine [11]. It is a horizontal-axis, three-bladed, upwind, variable speed, pitch-controlled turbine with a 126 meter rotor diameter and a 90 meter hub height. Some of its relevant properties are summarized in Table 1. This turbine has been adopted as a reference model by many research projects.

Table 1. Gross Properties for the NREL 5-MW Baseline Wind Turbine

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)

Table 2. Gross Properties for the ITI Energy Barge

Size (W×L×H)	40 m × 40 m × 10 m
Moonpool (W×L×H)	10 m × 10 m × 10 m
Draft, Freeboard	4 m, 6 m
Water Displacement	6,000 m3
Mass, Including Ballast	5,452,000 kg
Center of Mass (CM) below SWL	0.282 m
Roll Inertia about CM	726,900,000 kg·m2
Pitch Inertia about CM	726,900,000 kg·m2
Yaw Inertia about CM	1,453,900,000 kg·m2

The 5-MW wind turbine is mounted on a barge built by ITI Energy [12]. To ensure simplicity in manufacturing, the barge has a squared shape and is ballasted with sea water to achieve the designed draft. Eight catenary lines moored to the platform prevent it from drifting. The barge properties can be found on Table 2.

2.1 FOWT simulation model

Considering that the proposed FOWT is a benchmark, it is essential to be able to simulate its behavior with as much accuracy as possible. To that end, an aeroelastic computer-aided engineering tool called FAST, developed by the NREL, will be used. Moreover, there is an advanced version of FAST developed by Lackner and Rotea [8], called FAST-SC, which includes structural control capabilities.

FAST-SC software is overkill in terms of computational time if included in an optimization loop. Instead, a reduced degree of freedom (DOF) model will be generated based on the basic dynamics of the wind turbine. The main premises and assumptions of the dynamic model are the following:

- The system is considered a multibody dynamic system with a motion reference point P in accordance with the definition by Jonkman [13].
- There are three rigid bodies: the barge platform, the TMD and the turbine, this latter composed of the tower and the rotor-nacelle assembly.
- There are three DOFs considered in the model; TMD motion, platform pitch and tower bending. The two latter ones were selected according to Jonkman and Buhl [4], which proved that the first collective platform pitch-tower bending mode is the most susceptible to produce structural fatigue.
- The turbine is considered to be an inverted pendulum hinged to the platform at the tower bottom. The tower fore-aft flexibility is modeled with a spring and a damper with constant coefficients.
- The barge is modeled as a rigid solid, with a spring representing the summation of the hydrostatic restoring moment and mooring line stiffness. A damper is also included to accommodate the hydrodynamic damping, the wave radiation and viscous damping. Both the spring and the damper are considered constant, so this will imply some inaccuracies due to the non-linearity of the modeled moments.
- The rest of dynamics and external loads from wind and waves have not been considered for the model.

The model is constructed based on Lagrange's equations of a non-conservative system with *n* generalized coordinates (DOFs), which are as follows:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i \qquad (i = 1,2,\ldots,n) \tag{1}$$

$$L = T - V \tag{2}$$

Where T is the total kinetic energy and V the total potential energy of the system. L is the Lagrange operator and Q_i is the generalized non-potential force within respect to coordinate i. Except for the damping forces, the rest of the system is conservative. The following equations express the kinetic energy, the potential energy and the generalized non-potential forces of the FOWT system [14].

$$T = \frac{1}{2} I_t \dot{\theta}_t^2 + \frac{1}{2} I_p \dot{\theta}_p^2 + \frac{1}{2} m_T \dot{x}_T^2 \tag{3}$$

$$\begin{gathered} V = \frac{1}{2} k_t \left(\theta_t - \theta_p\right)^2 + \frac{1}{2} k_T (R_T sin\theta_t - x_T)^2 \\ + \frac{1}{2} k_p \theta_p^2 + m_t g R_t cos\theta_t - m_p g R_p cos\theta_p \\ + m_T g [R_T cos\theta_t + (R_T sin\theta_t - x_T) tan\theta_t] \end{gathered} \tag{4}$$

$$\begin{cases} Q_{\theta_t} = -d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) - \frac{d_T R_T (R_T \dot{\theta}_t cos\theta_t - \dot{x}_T)}{cos\theta_t} \\ Q_{\theta_p} = -d_p \dot{\theta}_p + d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) \\ Q_{x_T} = d_T (R_T cos\theta_t \dot{\theta}_t - \dot{x}_T) / cos\theta_t \end{cases} \tag{5}$$

Where the generalized coordinates are the platform rotation angle (θ_p), the tower rotation angle (θ_t) and the TMD displacement (x_T). The k and d terms represent the spring stiffness and the damping coefficients, respectively. The application of equations (1) and (2) to the FOWT model results in the following system of equations

$$\begin{cases} I_t \ddot{\theta}_t = m_t g R_t sin\theta_t - k_t\left(\theta_t - \theta_p\right) - d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) \\ -m_T g (R_T sin\theta_t - x_T) / \cos^2 \theta_t \\ -k_T R_T (R_T sin\theta_t - x_T) cos\theta_t \\ -d_T R_T (R_T cos\theta_t \dot{\theta}_t - \dot{x}_T) / cos\theta_t \\ I_p \ddot{\theta}_p = -d_p \dot{\theta}_p - k_p \theta_p - m_p g R_p sin\theta_p \\ + k_t\left(\theta_t - \theta_p\right) + d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) \\ m_T \ddot{x}_T = k_T (R_T sin\theta_t - x_T) + m_T g tan\theta_t \\ + d_T (R_T cos\theta_t \dot{\theta}_t - \dot{x}_T) / cos\theta_t \end{cases} \tag{6}$$

This constitutes a nonlinear dynamic model of the barge floating wind turbine in the fore-aft direction. The model will be used for free decay tests, which will never exceed 10 degrees of pitch. Thus, small angle approximations can be used to obtain a linear version of the dynamic model as expressed in (7).

$$\begin{cases} I_t \ddot{\theta}_t = m_t g R_t \theta_t - k_t\left(\theta_t - \theta_p\right) - d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) \\ -m_T g (R_T \theta_t - x_T) - k_T R_T (R_T \theta_t - x_T) \\ -d_T R_T (R_T \dot{\theta}_t - \dot{x}_T) \\ I_p \ddot{\theta}_p = -d_p \dot{\theta}_p - k_p \theta_p - m_p g R_p \theta_p \\ + k_t\left(\theta_t - \theta_p\right) + d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) \\ m_T \ddot{x}_T = k_T (R_T \theta_t - x_T) + m_T g \theta_t \\ + d_T (R_T \dot{\theta}_t - \dot{x}_T) \end{cases} \tag{7}$$

3 Parameter identification of the linear limited DOF model

The physical parameters of the general reduced model have to be determined to describe the system response with the best possible accuracy. This will be done by applying an identification algorithm to find the optimum combination of parameters that minimize the difference between the model and the real system response. In an ideal scenario, the reference data for identification should come from experiments with the real system. As real experimental data are not available, FAST-SC will be used for simulating realistic system behavior. To ensure model correctness, the physical properties of the model without TMD were identified first using FAST-SC simulations and then validated by incorporating the TMD on both the model and FAST-SC, repeating the experiments in different conditions.

Taking into account that the model does not consider any disturbance force, free decay tests have been chosen to feed the identification process. This consists on the observation of the system's natural evolution from certain initial conditions which are out of the rest position. The configuration for FAST-SC to generate the free-decay tests had all DOFs deactivated except for the first fore-aft tower bending mode (TwFADOF1) and the platform pitch tilt rotation DOF (PtfmPDOF). All initial conditions were set to zero except for the initial pitch tilt rotational displacement of the platform (PtfmPitch). The parameters to be identified are the spring stiffness, the damping coefficient and the inertia moment of both the barge platform and the tower.

The simulation results were exported to Matlab, where the Levenberg-Marquardt least squares search method was used for the identification.

Once a solution for the model parameters is reached, the identification has to be validated. This was done by incorporating the TMD to the model and comparing the response for free decay tests to the simulation of FAST-SC with a TMD on the nacelle in the fore-aft direction.

The identification process fits the response of a nonlinear system to a linear model, so there will be some unmodeled dynamics or inaccuracies expected. There are several variables that can be tuned within the identification process to ensure the best possible fit. Concerning the initial platform tilt, free decay tests must begin from a position sufficiently far from rest to allow the dynamics to be characterized but not so far that the non-linearities would be significantly large. Additionally, the amount of data used for identification, i.e. the tests duration, can be chosen as desired. Taking advantage of the FAST-SC flexibility to produce free-decay results, several identifications and validations were made to select the more precise configuration. The best simulation time was found to be 100 seconds. Concerning the initial conditions selection, Table 3 shows the mean squared error (MSE) of the Tower Top Displacement (TTD) of the validation tests, where each row contains the validation results of the system identified with an initial platform pitch noted in the left column. The TTD, which is the translational deflection of the tower measured at its top, is used as reference variable as it is positively correlated with tower fatigue loads and, therefore, it will be the most important variable to simulate. The model identified with an initial platform pitch of 3 deg was selected as it provided the best validation results in all tests (row highlighted in green in Table 3).

Table 3. Mean Squared Error of TTD of the identified systems validation with different initial conditions.

MSE of TTD using TMD for validation (m)				
	3 deg	5 deg	8 deg	10 deg
2 deg identification	0.00048	0.00068	0.00230	0.00630
3 deg identification	0.00047	0.00064	0.00220	0.00620
5 deg identification	0.00051	0.00074	0.00250	0.00670
8 deg identification	0.00056	0.00087	0.00280	0.00700
10 deg identification	0.00059	0.00095	0.00290	0.00710

The TMD parameters used for validation were the ones proposed by [8], which are 20,000 Kg of mass, 5,000 N/M of spring stiffness and 9,000 Ns/m of damping coefficient. The parameters of the final identified model are listed in Table 4.

Table 4. Identified parameters of the dynamic limited DOF FOWT model.

k_t (N/m)	k_p (N/m)	d_t (Ns/m)	d_p (Ns/m)	I_t (kgm^2)	I_p (kgm^2)
$1.4635{\cdot}10^{10}$	$2.0016{\cdot}10^{9}$	$2.5415{\cdot}10^{7}$	$5.6431{\cdot}10^{7}$	$3.4523{\cdot}10^{9}$	$2.1613{\cdot}10^{9}$

The validation results of the identified system are presented in Fig. 1. The results show the response of the system incorporating the TMD device and starting from an initial platform pitch of 5º, which should be noted that is different from the 3º test used for identification. It is clear that the limited DOF model is accurate enough to simulate the FOWT dynamics related to the tower fatigue.

4 Tuned Mass Damper optimization

The wind turbine is equipped with a TMD passive structural control, which is installed in the nacelle to mitigate vibrations in the fore-aft direction. Such device has to be tuned to reduce the tower fatigue loads, specifically its spring and damper parameters.

To that end, the FOWT model is included in an optimization loop with the standard deviation of the Tower Top Displacement, σ(TTD), as fitness function. The TTD is proportional to the tower bending moment, so its standard deviation serves as an indicator of the fatigue experienced by the tower.

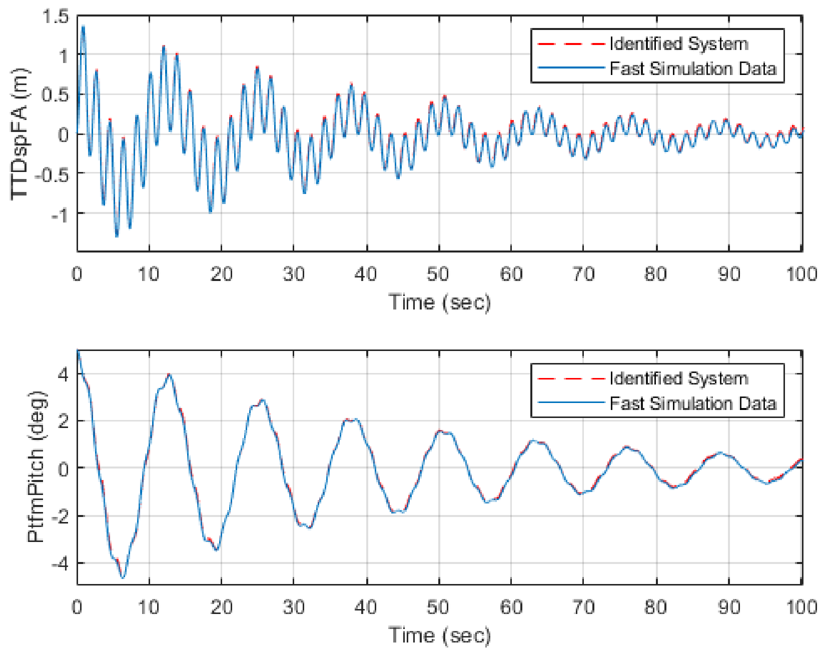

Fig. 1. Validation results of identified system (red) and FAST-SC simulation (blue) using a TMD and starting from 5 degrees of platform pitch.

Genetic algorithms (GA) were used to find the optimum global configurations of the TMD as they have been proved efficient in many applications [15]. The GA has a population size of 50 individuals, rank scaling and stochastic uniform selection with a crossover probability of 0.8.

Initially, the TMD mass was also added as an optimization variable, but it was found that the optimum solution tends always to the maximum mass [16]. Hence, the mass was fixed to a value of 40,000 kg, which is a 0.65% of the total mass of the structure or a 5.7% of the Wind Turbine mass. This represents a plausible value near to the mass proportions used in civil engineering. The optimal TMD parameters are listed in Table 5 together with the suppression rate of the σ(TTD) in 1000 seconds of free-decay test from 5 degrees of initial platform pitch with respect to the system without TMD.

Table 5. Optimal TMD parameters.

Mass	Spring Stiffness	Damping Coefficient	Suppression Rate
40,000 kg	8,292 N/m	9,766 Ns/m	50.12 %

The response of the FOWT system with the optimized TMD in comparison to the system without TMD is shown in Figure 2. The platform pitch is completely stabilized in 40 seconds with the TMD, whereas without TMD the platform continues oscillating for 800 seconds. Regarding the TTD, which is composed of two vibrating modes, it can be seen that the first dominating one is damped out substantially more than the second one. This can be observed also from the spectral analysis of the TTD from FAST-SC simulations in Figure 3.

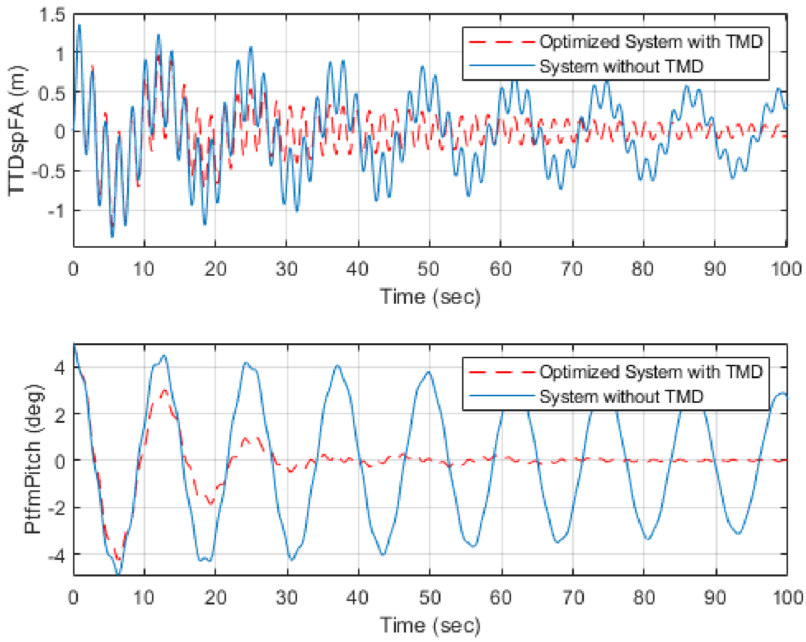

Fig. 2. Simulation results of the FOWT system with optimized TMD (red) and without TMD (blue) in a free-decay test with 5 degrees of initial platform pitch.

Some studies tend to tune the spring stiffness coefficient so that the natural undamped frequency of the TMD is equal to the first collective platform pitch-tower bending mode [10]. This mode is the rigid body platform pitch mode and has a frequency of about f_n=0.086 Hz, so the corresponding spring stiffness for a 40,000 kg TMD would be 11,680 N/m. Although this is a good practice, it seems to be more convenient to include the stiffness as another variable in the optimization loop to find the exact value which guarantees a global optimum solution to minimize σ(TTD). The reason to that may be the imprecise determination of the exact frequency of the first collective mode.

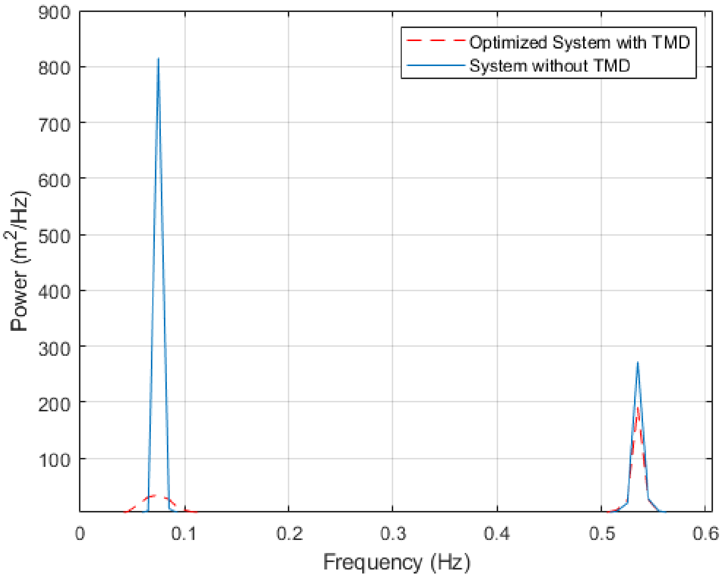

Fig. 3. Power Spectral Density of the Tower Top Displacement with optimized TMD (red) and without TMD (blue) in a free-decay test with 5 degrees of initial platform pitch.

6 Conclusions and future work

This article presents the heuristic optimization of the parameters of a tuned mass damper, installed in the nacelle of a barge-type floating wind turbine to reduce tower fatigue in the fore-aft direction.

The optimization process included a reduced degree of freedom dynamics model of the FOWT to evaluate its response in the dominant mode of the structure, which is the collective platform pitch-tower bending mode. The model was identified using FAST-SC synthetic experimental data. The free-decay test duration and initial conditions were carefully selected to ensure the best model identification accuracy.

The optimization cost function used was the standard deviation of the tower top displacement due to its dependency with the tower fatigue. A genetic algorithm was used to obtain the optimal TMD tuning coefficients. It was found, as expected, that the larger the mass, the larger the load reductions reached. Then, the TMD mass was fixed to a suitable value of 40 tones and the optimized TMD achieved fatigue suppression rates of 50% compared to the FOWT without TMD.

The proposed passive structural control method shows promising results to mitigate tower loads from the barge-type floating wind turbines. Nevertheless, further studies may be performed to consider the TMD physical installation constraints, to characterize the FOWT response on standardized Design Load Cases and to assess advanced structural control devices and techniques.

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