


## Article

# Analysis of the Effects of the Location of Passive Control Devices on the Platform of a Floating Wind Turbine

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**Abstract:** Floating offshore wind turbines (FOWT) are subjected to strong loads, mainly due to wind and waves. These disturbances cause undesirable vibrations that affect the structure of these devices, increasing the fatigue and reducing its energy efficiency. Among others, a possible way to enhance the performance of these wind energy devices installed in deep waters is to combine them with other marine energy systems, which may, in addition, improve its stability. The purpose of this work is to analyze the effects that installing some devices on the platform of a barge-type wind turbine have on the vibrations of the structure. To do so, two passive control devices, TMD (Tuned Mass Damper), have been installed on the platform of the floating device, with different positions and orientations. TMDs are usually installed in the nacelle or in the tower, which imposes space, weight, and size hard constraints. An analysis has been carried out, using the FAST software model of the NREL-5MW FOWT. The results of the suppression rate of the tower top displacement and the platform pitch have been obtained for different locations of the structural control devices. They have been compared with the system without TMD. As a conclusion, it is possible to say that these passive devices can improve the stability of the FOWT and reduce the vibrations of the marine turbine. However, it is indispensable to carry out a previous analysis to find the optimal orientation and position of the TMDs on the platform.

**Keywords:** wind power; floating wind turbines; TMD (tuned mass damper); vibration; structural control; hybrid power systems



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## 1. Introduction

In recent years, society is experiencing an unprecedented growth in the consumption of resources. The energy demanding is increasing and, therefore, the necessity of new generation power plants. At the same time, the latest studies on pollution and the contribution of fuel consumption fossils to climate change warn about the imminent ecological damage if the current emissions of greenhouse gases continue. It is not enough to stop the installation of these fossil-based energy power plants, but rather replace the current ones by clean alternatives. This fact considerably increases the need to use renewable energy [1]. Further research and development of renewable energy resources is needed.

Among the renewable energies, wind power is experimenting a great boom in many countries, due to the availability of this resource. Indeed, onshore wind energy can be considered a mature technology [2]. Some of its advantages are, for instance, that it is a clean and inexhaustible resource, and that it reduces the energy dependence of a country, as it is an indigenous resource. However, it presents a series of drawbacks, such as the fact that the supply is not always guaranteed as the wind is variable and random. Besides, its storage is not possible yet and, in the case of on-land wind turbines, they have a strong visual and acoustic impact, as well as a negative effect on local fauna and flora, and even on the soil, aquifers, and nature in general [3].

This has led the energy engineers to search for solutions by installing wind turbines (WT) in the sea (offshore), initially in shallow waters near the coast (offshore bottom-fixed) and, more recently, in deep waters (floating offshore wind turbines, FOWT). In the latter, the wind is stronger and more stable due to the absence of obstacles; the visual and acoustic impact is eliminated as the location is far away from any population, and the installation area is even wider [4]. In addition, floating turbines reduce the cost of installation and maintenance when compared to bottom-fixed ones [5]. Moreover, floating wind turbines do not require shallow waters, with a drop depth that is smaller than 50 m and a distance from the coast of several km, as the coastal ones do. This has opened the possibility of installing this type of wind energy devices to many countries, where the sea drop-off is very pronounced.

The floating offshore wind technology is currently under development, with some prototypes or small floating farms already being installed. The floating wind turbines are powerful, but strongly non-linear and complex, systems [6], with important engineering problems to face, such as the transport of electricity to large distances by underground cables, the effects of the power control strategies on the stability and efficiency of the turbine [7–9], vibrations in the structure due to strong loads from wind, waves, currents, ice, [10], mooring lines [11], etc. This implies, on the one hand, great structural wear and fatigue, and the necessity of using more long-lasting, and possibly more expensive materials. On the other hand, it is necessary to design control strategies that reduce these vibrations and, at the same time, which allow the turbine to obtain the maximum energy possible.

A possible way to enhance the performance of these wind energy devices that are installed in deep waters is to combine them with other marine energy systems. As a part of a research project that we are working on, the authors of this paper have the long term goal of installing energy wave converters in mind, which have limited profitability, on floating turbines, in such a way that they share installation and energy transport cost. To do so, we would first like to test the hypothesis of whether the installation of some devices on the platform of a barge-type turbine would give greater stability to the floating structure and, therefore, help to reduce the fatigue and make them more efficient.

In order to explore that possibility, in this work, the effects of placing two structural control devices, Tuned Mass Damper (TMD), on the platform of a FOWT are studied. Tuned mass dampers are passive control devices that have been widely used in civil engineering for large structures to reduce vibrations. These control devices have been also applied to FOWT, installing them in the nacelle or, much less frequently, in the tower of the turbine, which imposes space, weight, and size limitations. Moreover, it has been proved that the mass is the TMD parameter most directly related to vibration damping, but it is not possible to increase it as much as it would be desirable due to space limitations and the difficulties of installing very heavy devices in those parts of the wind turbine.

Thus, in this paper, one and two TMDs are configured and optimized to be installed on a floating turbine platform. The main contribution is the analysis of the effects of the location of those control devices in the reduction of the vibration. Different positions of the TMDs, moving them in the fore–aft and side–side directions, are tested. As far as we know, studies using two TMDs are hardly found in the related literature, and the analysis of the effects of moving them has not been carried out.

The National Renewable Energy Laboratory 5 MW wind turbine model has been used. The barge-type wind turbine has an ITI Energy platform. The open-source FAST (Fatigue, Aerodynamics, Structures, and Turbulence) v8 software, developed at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA, has been applied for the configuration and simulation of the whole wind turbine and structural control devices. The TMD parameters have been optimized for this type of turbine using genetic algorithms (GA).

The results obtained here prove the effectiveness of this proposal to reduce vibrations and, fundamentally, the need to carry out an analysis for the optimal positioning of the

TMDs on the floating structure. This study might allow for generalizing the results to active control devices. This way, it is possible to study the effect of placing various masses that can absorb energy on the platform, and to see how it would affect its dynamics and, specifically, the vibrations. This study is very valuable as a preliminary analysis for the achievement of a hybrid device for wind and marine energy, which may have great potential.

The organization of the rest of the paper is as follows. In Section 2, a brief summary of the state of the art is presented. Section 3 describes the barge-type floating wind turbine, as well as the TMD passive control device. Section 4 discusses the effect of installing a TMD in different positions on the platform. Section 5 shows the results of installing two TMDs on the platform and varying their positions on it. Conclusions and future works finish the paper.

## 2. Related Works

Structural control devices have been lately applied to floating offshore wind turbines [12–14]. They are usually installed in the nacelle or, sometimes, in the tower. For instance, in spar type FOWTs, tuned mass dampers are sometimes installed in the tower, such as in [15], where the authors study a three-dimensional pendulum tuned mass damper and dual linear pounding tuned mass dampers to mitigate the three-dimensional vibrations of the wind turbine. Similarly, the authors in [12] propose a novel approach for optimizing the design parameters of the TMD (i.e., stiffness, damping, and installation location) to effectively reduce the vibrations of a spar-buoy turbine. Stewart and Lackner have used genetic algorithms to optimize the parameters of a TMD that is located in the nacelle for different types of floating turbines [16].

Nevertheless, the installation of TMDs in the platform of a FOWT is much less frequent. It may be due to the fact that the most widely used spar-type or TLG floating turbines do not have that surface, and there is not enough space in the nacelle or in the tower. Thus, the performance of structural control devices on the platform of a floating turbine has been studied little, and it is something quite recent.

Although the effect of platform-based TMDs may not be so relevant in terms of vibration suppression when compared to the installation of structural control devices in the nacelle, it has been shown that they do improve the stability of the system. For example, in [17], it is proposed to incorporate a tuned mass damper in a floating wind turbine platform. Based on a limited degree-of-freedom mathematical model of the barge-type offshore wind turbine, the authors use GA to obtain the TMD parameters that minimize the standard deviation of the tower top deflection. Numerical simulations that are based on FAST have been carried out to evaluate the effect of the passive control system. This work is mainly focused on the effects of the mass of a heavy TMD, where partial ballast is substituted for the equal mass of the tuned mass damper. The vibration mitigation is simulated in five typical load cases, and a significant reduction of the dynamic response is observed for the barge-type floating structure. In a more recent paper, the same authors show how platform-TMD effectively reduces the pitch movement and the low frequency vibration of the tower top fore-aft deflection, while the nacelle TMD is effective for the high frequency vibration of the tower top [18].

In [19], it is shown how the structural responses of the floating wind turbine are mitigated by using a single-degree of freedom tuned mass damper that was installed in the platform. Based on a new model that combines multi-body model and external control codes, the turbine model coupled with the TMD is simulated under wind and wave loads. The results demonstrate the effectiveness of the TMD designed after a parametric study of its configuration to mitigate the structural response of the barge-type floating wind turbine.

More recently, the authors in [20] have dealt with the same floating wind turbine with a tuned mass damper in the platform. In this case, they have designed a hierarchical sliding mode controller that regulates the states of the under-actuated nonlinear system. The external wave and wind loads are considered to be unknown disturbances and counteracted with two nonlinear disturbance observers.

The advantages of this proposal regarding the works that use control devices in the nacelle or in the tower of the WT, as most of the papers that are found in the literature do, is due to the fact that, as it has been proved, the heavier and more massive the TMD is, the better the reduction of vibrations. However, installing these devices in the nacelle or in the tower has strong size and weight limitations, whereas the platform of a barge-type floating turbine can afford larger TMD masses. In addition, other papers that work with TMDs in the platform use only one TMD, or they do not analyze the effects of placing the control devices at different positions and moving them to see how this influences the stability of the structure.

However, a drawback of this proposal is that the TMDs in the platform significantly reduce the oscillations of the barge, but this control configuration reduces, to a smaller degree, the vibrations of the tower and the nacelle, which are more important for the fatigue of the structure.

### 3. FOWT and TMD Models

#### 3.1. Barge Offshore Wind Turbine

In this work, a floating barge-type turbine is used for simulation purposes. Specifically, simulations have been carried out with the NREL Offshore 5 MW Baseline Wind Turbine model. This is a three-bladed, upwind, variable-speed, variable blade-pitch-to-feather-controlled multimewatt wind turbine model that was developed by the National Renewable Energy Laboratory to support concept studies aimed at assessing offshore wind technology [21]. The ITI Energy barge is a large, 40 m × 40 m × 10 m barge, with eight catenary mooring lines. Jonkman's PhD dissertation gives more details of this barge [22].

The simulation model of the floating wind turbine includes not only the model of the wind energy generation, but also its dynamics, which now depend on the support platform kinematics, kinetics, and hydrodynamics, as well as the mooring system responses. The main parameters of the wind turbine and the platform used for the simulation experiments are briefly described in Tables 1 and 2, respectively.

**Table 1.** Wind Turbine Parameters. Adapted from [21].

Parameter	Value
Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
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
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5°, 2.5°
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)

This model is available for simulation and analysis using the software FAST. This software, as developed by NREL, is a primary physics-based engineering tool for simulating the coupled dynamic response of wind turbines. With this tool, it is possible to simulate the floating wind turbine behaviour with different configurations and parameters. It allows for obtaining different output variables, such as the power and energy generated, the movement of the nacelle, the platform pitch, etc. In addition, hydrodynamic and aerodynamic forces can be included. Specifically, an extension, called FAST-SC, has been used in this paper, which allows for placing up to two TMDs both in the nacelle or in the platform of the floating turbine, and to simulate their action [23].

**Table 2.** Platform Parameters [22].

Parameter	Value
Roll Inertia about CM	$7269 \times 10^9 \text{ kg m}^2$
Pitch Inertia about CM	$7269 \times 10^9 \text{ kg m}^2$
Yaw Inertia about CM	$14,539 \times 10^5 \text{ kg m}^2$
Mass, including Ballast	$5452 \times 10^3 \text{ kg}$
Size ( $W \times L \times H$ )	40 m $\times$ 40 m $\times$ 10 m
Moonpool ( $W \times L \times H$ )	10 m $\times$ 10 m $\times$ 10 m
Water Displacement	6000 m <sup>3</sup>
Anchor (Water) Depth	150 m

Although, in this work, we use the embedded FAST floating WT model, which has different tools to represent all of the coupling forces that the floating device suffers, a reduced degree of freedom (DOF) model of wind turbine can be obtained using the Lagrange's equations. This model may help to understand the main variables of this complex and nonlinear system.

Two DOFs are usually considered for studying the dynamic behaviour of a FOWT, the platform pitch and the tower bending angle. The tower fore-aft bending is modeled with a spring and a damper with constant coefficients. The floating support platform is represented as a rigid body with three small rotational displacements. In the barge, the hydrodynamics forces and mooring coupling are also represented by a spring and a damper.

The Lagrange's equations of a non-conservative system with  $n$  DOFs are:

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

$$L = T - V \quad (2)$$

where  $T$  is the total kinetic energy,  $V$  is the total potential energy of the system,  $L$  is the Lagrange operator, and  $Q_i$  is the generalized non-potential force with respect to coordinate  $i$ . Except for the damping forces, the rest of the system is conservative.

The following equations express the kinetic energy  $T$ , the potential energy  $V$ , and the generalized non-potential forces  $Q_i$  of the FOWT system [17], respectively, where subindex  $t$  refers to tower and  $p$  to platform.

$$T = \frac{1}{2} I_t \dot{\theta}_t^2 + \frac{1}{2} I_p \dot{\theta}_p^2 \quad (3)$$

$$V = \frac{1}{2} k_t (\theta_t - \theta_p)^2 + \frac{1}{2} k_t (R_t \sin \theta_t)^2 + \frac{1}{2} k_p \theta_p^2 + m_t g R_t \cos \theta_t - m_p g R_p \cos \theta_p + m_t g [R_t \cos \theta_t + (R_t \sin \theta_t) \tan \theta_t] \quad (4)$$

$$\begin{cases} Q_{\theta_t} = -d_t(\dot{\theta}_t - \dot{\theta}_p) - \frac{d_t R_t (R_t \dot{\theta}_t \cos \theta_t)}{\cos \theta_t} \\ Q_{\theta_p} = -d_p \dot{\theta}_p + d_t(\dot{\theta}_t - \dot{\theta}_p) \\ Q_{x_t} = \frac{d_t (R_t \cos \theta_t \dot{\theta}_t)}{\cos \theta_t} \end{cases} \quad (5)$$

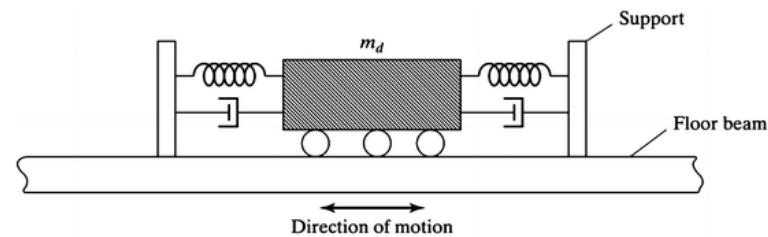
where  $I$  represents the rotational inertia, the  $k$  terms are rotational or linear restoration coefficients, the  $d$  terms are the linear or rotational damping constants, and  $R_t$  is the distance between the hinge and the center of mass of the tower. The mass of the tower is  $m_t$ , and  $g$  is the gravitational acceleration. Specifically, in these equations,  $k_t$  and  $k_p$  represent the spring stiffness of the tower and the platform, respectively, and, in the same way,  $d_t$  and  $d_p$  are the damping coefficients of both elements of the floating wind turbine. Finally, the state variables are the platform pitch angle ( $\theta_p$ ) and the tower rotation angle ( $\theta_t$ ).

The resulting nonlinear dynamic model of the barge floating wind turbine can be linearized for angles that are smaller than  $10^\circ$  [22], resulting:

$$\begin{cases} I_t \ddot{\theta}_t = m_t g R_t \theta_t - k_t (\theta_t - \theta_p) - d_t (\dot{\theta}_t - \dot{\theta}_p) - m_t g (R_t \theta_t) - k_t R_t (R_t \theta_t) - d_t R_t (R_t \dot{\theta}_t) \\ I_p \ddot{\theta}_p = -d_p \dot{\theta}_p - k_p \theta_p - m_p g R_p \theta_p + k_t (\theta_t - \theta_p) + d_t (\dot{\theta}_t - \dot{\theta}_p) \end{cases} \quad (6)$$

### 3.2. Tuned Mass Damper

Tuned Mass Dampers (TMD) are passive structural control devices. They are also called vibration absorbers or vibration dampers. These devices are mounted to a specific location in a structure, so as to reduce the amplitude of undesirable vibrations. They consist of a spring, a viscous damper, and a mass. Figure 1 shows a TMD that was mounted on the platform of the wind turbine.



**Figure 1.** A passive TMD mounted on the platform of the FOWT.

The values of the parameters associated to these components, i.e., the spring stiffness, the damping coefficient, and the mass, for optimal structural energy dissipation, can be obtained by different ways, although it is not a simple task. Even for an idealized one-degree-of-freedom structure, the optimal tuning of the spring and damper is dictated by a complex function. For structures with more degrees of freedom and non-linearities, such as an offshore wind turbine, there is no analytical solution for the optimal tuning, and numerical or heuristic approaches must be used [16].

At present, the methods to tune TMD parameters are frequency tuning, genetic algorithms (GA), and surface plot. The surface plot approach is computationally expensive, and it may take hours or days to finish one optimization process. Therefore, the frequency tuning and GA are the most common methods for tuning the TMD parameters [17].

The approach of frequency tuning is usually adopted in engineering projects. The mass and spring of TMD are turned to a system frequency by inputting different values, which satisfy the TMD mass vibrating near this frequency. For instance, in [17], those parameters are related to the natural frequency of the barge-type floating wind turbine. The TMD stiffness coefficient  $k_{TMD}$  is usually chosen applying equation:

$$k_{TMD} = 4\pi^2 f^2 m_{TMD} \quad (7)$$

where  $m_{TMD}$  is the TMD mass and  $f = 0.084$  hz is the first nature frequency of the platform. The tuning of the damping coefficient,  $d_{TMD}$ , is obtained by other methods, for instance, using genetic algorithms or any other optimization method.



However, according to [17], although the frequency tuning method is an effective approach to find the optimum TMD parameters, it has some limitations. That is why the application of GA to optimize TMD design has grown in recent years. Indeed, in that paper authors apply GA and frequency method to tune the TMD for the same wind turbine. They obtained similar values for the stiffness and damping coefficients for different masses, but the suppression rate of the vibration is better with the GA tuning. They use the suppression rate of the standard deviation of the tower top deflection, defined as Equation (8), as the function to be minimized, though in the other works the amplitude of the vibration, or other optimization criterion are proposed.

$$sr = \frac{\sigma_{without\ TMD} - \sigma_{with\ TMD}}{\sigma_{without\ TMD}} \quad (8)$$

where  $\sigma$  is the standard deviation of the variable considered, in our case, the standard deviation of the tower top displacement.

Regarding the mass parameter of the TMD, the platform can afford heavier TMDs than if the control device were placed in the nacelle or in the tower. In our case, based on the analysis that is presented in [17], where a TMD mass from 307,000 kg to 1,168,500 kg was considered, we decided to work with a mass of 500,000 kg. We know that, the more massive a TMD is, the greater its inertia and, therefore, the greater the kinetic energy that it can accumulate and the more vibration reduction it gets [16].

We have initially taken the values of the other TMD two parameters from [17], but interpolating the corresponding values to the mass we are using. Thus, the stiffness coefficient that we have used is 141,400 N/m and the damping parameter is 92,600 (Ns/m). The suppression rate of the standard deviation of the tower top deflection is used for the optimization.

It is worthy to remark that this work is oriented to the installation of wave converter devices in the platform, so this is a preliminary analysis and the mass is still a parameter to be determined.

### 3.3. Simulation Scenario and Performance Metrics

In this work, one and two TMD control devices are placed on the platform, moving them in perpendicular directions, fore-aft, and side-side, to test how the position of the TMDs influences the dynamics response of the wind turbine (Figure 2).

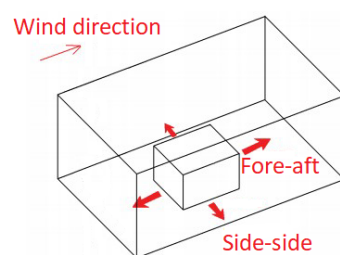


Figure 2. TMD movements.

The most significant vibrations occur in the fore-aft direction of the tower, i.e., in the direction of the wind. They have a direct effect on the fatigue of the structure, which is usually measured by the variable Tower Top Displacement in the fore-aft direction (TTDspFA), or its deviation. The coupling between side-side and fore-aft motion is not considered as, according to Lackner [24], for this floating wind turbine model the fore-aft fatigue loads are substantially larger (approximately 3×) than the side-side loads.

Different simulations have been carried out moving the TMDs along the horizontal and vertical axes of the platform (Figure 2). To test the different locations of the TMDs, the surface of the platform has been discretized every 3 m. The simulation time is 100 s and the sample time is  $T_s = 0.01$  s.

It is a common approach to consider free decay simulations to test the floating turbine [25,26]. The simulation of the hydrodynamics forces is complex, and so is the aerodynamics. Hence, a simple way to introduce those effects in the simulation, mainly the waves, is to separate the WT a small angle from its equilibrium position. The initial angle of the support platform is assumed to be smaller than  $10^\circ$ , due to the fact that higher waves are not likely to occur. Indeed, an initial displacement of  $5^\circ$  platform pitch has been considered, and then allowing the system to come to the rest.

Regarding the criteria to measure the effectiveness of the TMD, the tower top displacement, TTDspFa, is the variable strongest that is linked to the fatigue of the floating structure, as already said [27]. Thus, the sum of the absolute value of the oscillations and standard deviation,  $\sigma(\text{TTDspFa})$ , have been calculated for the simulation experiments. The standard deviation also helps to measure the amplitude of the oscillation. A low standard deviation indicates that the values tend to be close to the mean, while a high standard deviation indicates that the values are spread out over a wider range. A small deviation is a good result, even if the mean is not 0, as is the case. The WT may be leaning due to the mass added on the platform front or behind the tower. The suppression rate of the TTDspFa has also been obtained to show the reduction of the vibrations.

In addition, the pitch angle of the platform, PtfmPitch, has been also analyzed, since it gives information regarding the motion of the platform and, so, on the stability of the floating system. The same three criteria have been calculated for this variable, namely: absolute value of the oscillation, standard deviation, and suppression rate.

The formulas of the absolute value (9), (11) and the standard deviation (10), (12) are given by the following equations for the variables, TTDspFa and PtfmPitch. In these expressions,  $N$  is the total number of discrete samples.

$$|\text{TTDspFa}| = \sum_{i=1}^N |\text{TTDspFa}_i| \quad (9)$$

$$\sigma(\text{TTDspFa}) = \sqrt{\frac{1}{N} \sum_{i=1}^N (\text{TTDspFa}_i - \mu(\text{TTDspFa}))^2} \quad (10)$$

$$|\text{PtfmPitch}| = \sum_{i=1}^N |\text{PtfmPitch}_i| \quad (11)$$

$$\sigma(\text{PtfmPitch}) = \sqrt{\frac{1}{N} \sum_{i=1}^N (\text{PtfmPitch}_i - \mu(\text{PtfmPitch}))^2} \quad (12)$$

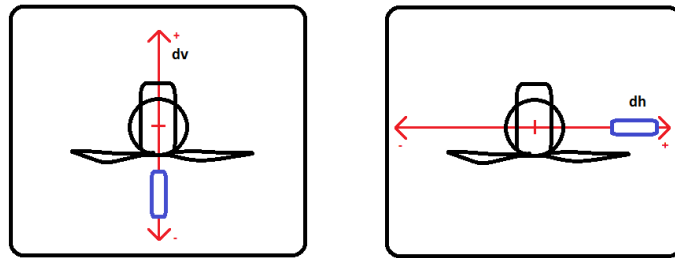
#### 4. Effects of the Different Platform-TMD Positions on the FOWT Stability

##### 4.1. Variation of the TMD Position in the Downwind Direction

First, the effect of only installing one TMD on the FOWT platform has been studied. This passive control device is moved in the fore–aft and side–side directions to test different positions.

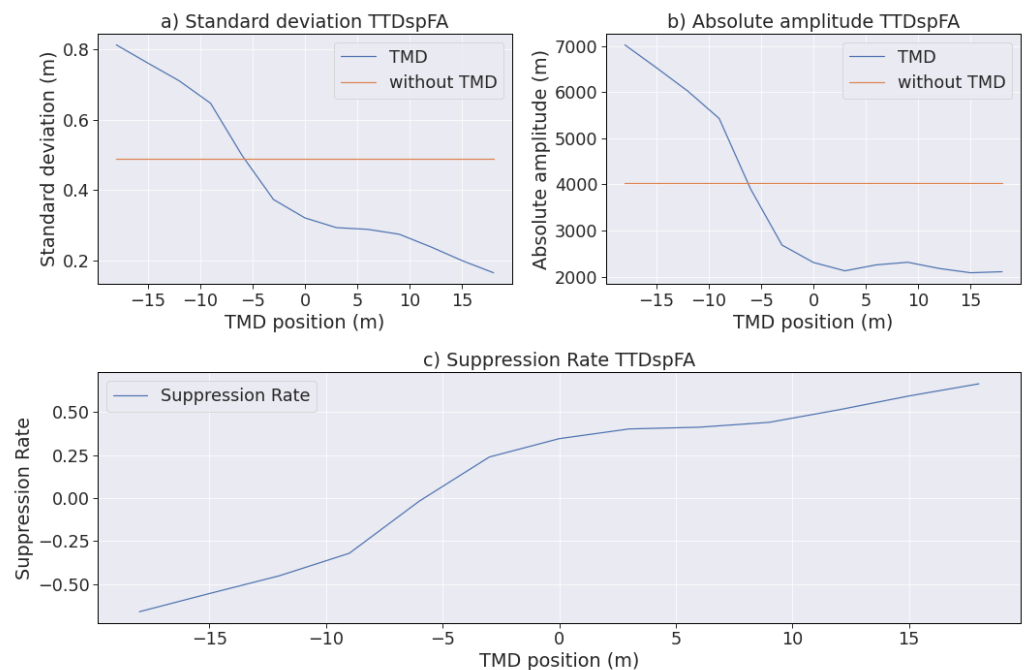
Figure 3 shows a view from above of the wind turbine (blades, tower, and platform), in black. The TMD device is represented by a blue rectangle. The center of the tower that is projected on the platform is considered to be the origin of the displacements (small red segment). In Figure 3, left, the displacement of the TMD with respect to the origin in the wind direction (dv axis) is shown and, in Figure 3, right, in the side-side direction (dh axis).





**Figure 3.** Displacement of the TMD along the fore–aft (**left**) and side–side (**right**) axis.

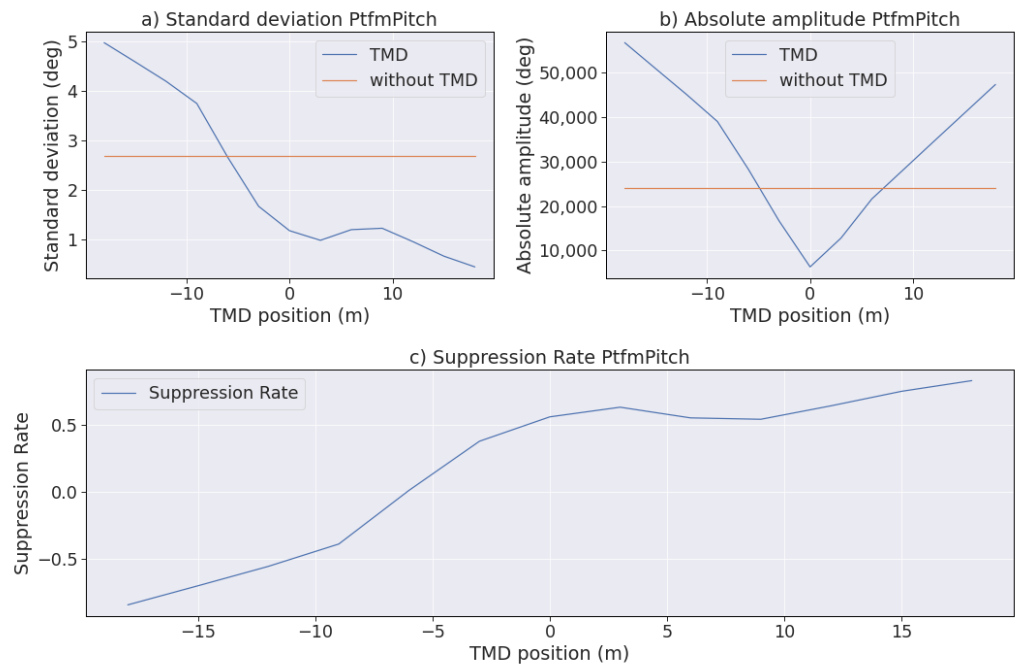
The results of moving a single TMD from  $dv = -18$  m to  $dv = +18$  m, every 3 m, in the fore–aft or downwind direction, which is, in the direction in which the turbine is oriented ( $dv$  axis), are shown in Figure 4. In all of the images, the orange line represents the response of the wind system without TMD and, in blue, the wind turbine with the TMD in different positions.



**Figure 4.** The results when moving the TMD along the fore–aft direction. **(a)** Sum of TTDspFA standard deviation; **(b)** Sum of TTDspFA amplitude; **(c)** TTDspFA suppression rate.

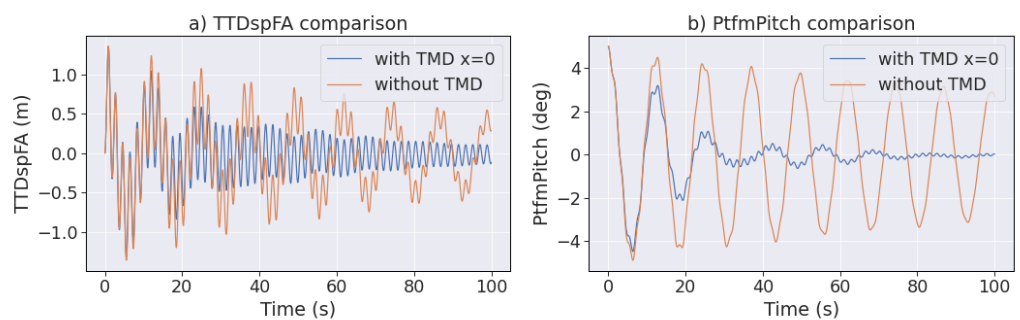
Figure 4a shows the standard deviation of TTDspFa (m) and Figure 4b shows the absolute value of the oscillation (m). They both have the same trend. There are positions of the TMD that reduce the oscillations and, on the contrary, other control device locations worsen it, regarding the system without TMD. The response of the turbine according to these variables is better than without TMD when the control device is placed in front of the tower, which is, in front of the center. Specifically, it is possible to see that the standard deviation is higher with respect to the deviation without TMD when placing the control device from  $-5$  m to  $-18$  m, even above the values obtained without TMD. Symmetrically, placing it at the front of the tower makes these metrics better. Indeed, for positive positions, it is possible to observe how the standard deviation is reduced a lot. The suppression rate confirms these results (Figure 4c). To summarize, negative positions from  $-5$  m on gives a negative suppression rate, increasing the oscillations; on the contrary, placing the TMD in front of the tower produces a high positive suppression rate.

The same happens with the motion of the platform of the floating wind turbine (Figure 5). The variable platform pitch (blue line) is shown in this figure when the TMD has been moved from  $dv = -18$  m to  $dv = +18$  m (every 3 m) in the downwind direction. As it can be seen, its effect is similar to that produced in the tower top displacement of the turbine, at least regarding the standard deviation (Figure 5a). Nevertheless, the absolute amplitude of the pitch angle of the platform has a minimum around 0 cm (Figure 5b), which is, under the tower. The suppression rate (Figure 5c) is also similar to the TTDspFA one, i.e., positive from  $dv = -5$  m on.



**Figure 5.** Platform pitch when moving the TMD on the platform in the fore-aft direction. (a) Sum of PTFmPitch standard deviation; (b) Sum of PTFmPitch amplitude; and, (c) PTFmPitch suppression rate.

In Figure 6, the action of a TMD located under the tower is shown. As it is possible to see, the amplitude of the oscillations of the wind turbine (TTDspFA) are reduced (left). The same effect happens with the platform pitch, where the vibration and frequency are significantly decreased (right). Therefore, the impact of the vibrations can be reduced installing a TMD in the platform.

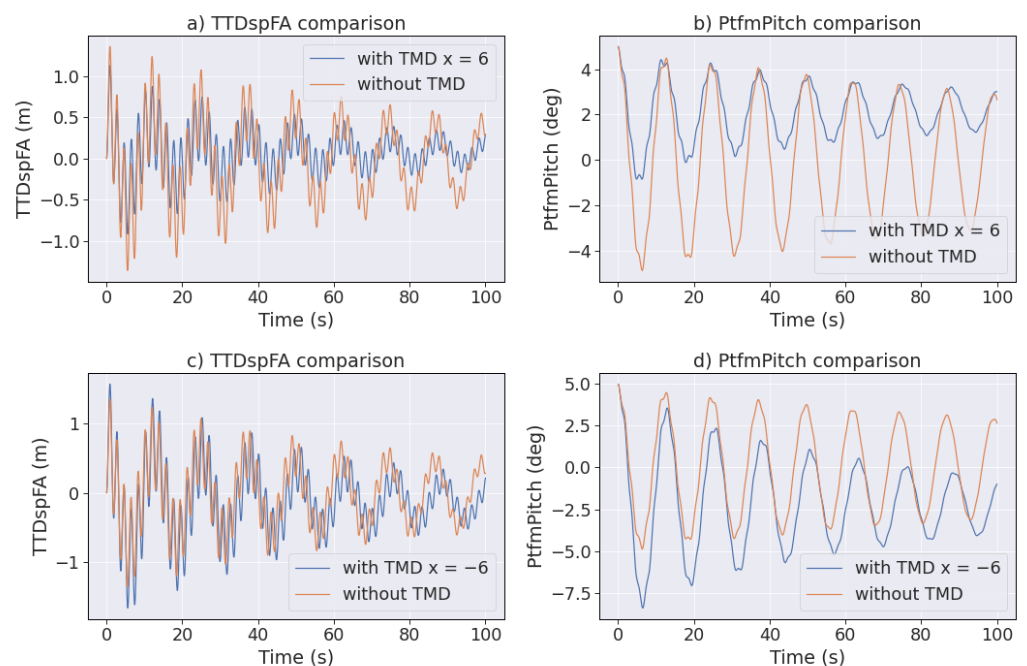


**Figure 6.** Comparison of the TTDspFA (a) and PtfmPitch (b) without TMD (orange) and with a TMD located under the tower (blue).

To better understand the behavior of the floating wind turbine, Figure 7 shows the wind turbine variables under study, TTDspFA and PtfmPitch, with a TMD being located

at +6 m and at −6 m in the dv axis (top and bottom figures, respectively, blue lines). It is compared with the movement of the turbine without TMD (orange line). First, it is possible to see how with a TMD the vibrations are more drastically reduced over time than without TMD, which confirms the effectiveness of using a TMD.

However, the platform pitch (Figure 7, right, top), that, without TMD, is stabilized at  $0^\circ$  (orange line), with the TMD being positioned at +6 m tends to stabilize around  $2^\circ$  (blue line). This means that the tower is leaning. With the TMD located at −6 m, in front of the tower, the oscillation tends to stabilize around  $-2^\circ$  (Figure 7, right, bottom). This effect produced when placing the TMD on the platform is due to the fact that the TMD adds a heavy mass, causing the WT to be inclined towards the direction in which the new mass has been placed.



**Figure 7.** Comparison of the PtfmPitch (a) and TTDspFA (b) without TMD (orange) and with TMD located at 6 m (a) and (b) and −6 m (c) and (d) in the fore–aft direction (blue).

In addition to this effect, it is possible to see in those figures how, when the TMD is at +6 m in front of the tower, the oscillation is much smaller than without TMD. The mean angle of the oscillation is around  $3^\circ$ , since the first oscillation goes from  $5^\circ$  to  $-1^\circ$ . On the contrary, placing the control device at −6 m makes the oscillation of the barge initially greater than without TMD, although, eventually, the TMD reduces it. In this case, the mean angle of the oscillation is around  $7^\circ$ .

This is due to the fact that placing the new mass on the platform has the effect of diverting the center of mass towards the load. Accordingly, the initial free-decay platform angle, in this case  $5^\circ$ , is measured regarding the center of the platform, and not with respect to the new center of masses. That is why the platform oscillates around the new center of mass (Figure 7). This means that, now, the angle is higher or lower, depending on to where the center of mass has been deviated by the TMD.

In any case, these results make us rule out any position of the TMD, but  $dv = 0$  m, under the tower or quite near the center (Figure 5b). Otherwise, the tower will lean towards the mass, out of its equilibrium position and with the center of mass deflected from the center of the platform, which can lead to destabilization of the WT, as it has not been designed for that asymmetric situation.

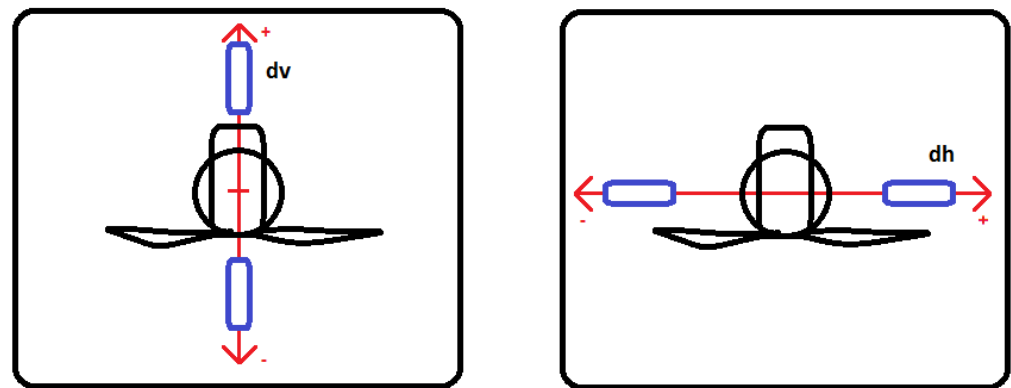
#### 4.2. Variation of the TMD Position in the Side-Side Direction

The influence of moving a TMD, oriented in the fore-aft direction, along the side-side axis of the platform (as shown in Figure 3, right), has been also analyzed, from  $dh = -18$  m to  $dh = +18$  m (every 3 m). The results are the same when moving it in the downwind direction. That is, any asymmetry in the platform mass regarding its center makes it more unstable.

#### 5. Simulation of Two TMDs on the FOWT Platform at Different Positions

According to the results that were obtained with a TMD, it is clear that, when using two TMDs on the barge, they must be symmetrically located in order to not move the center of mass of the wind turbine from the center of the platform. Therefore, although installing two TMDs on the floating platform gives rise to a wider range of combinations in their positioning, it is possible to rule out certain configurations due to the required symmetry.

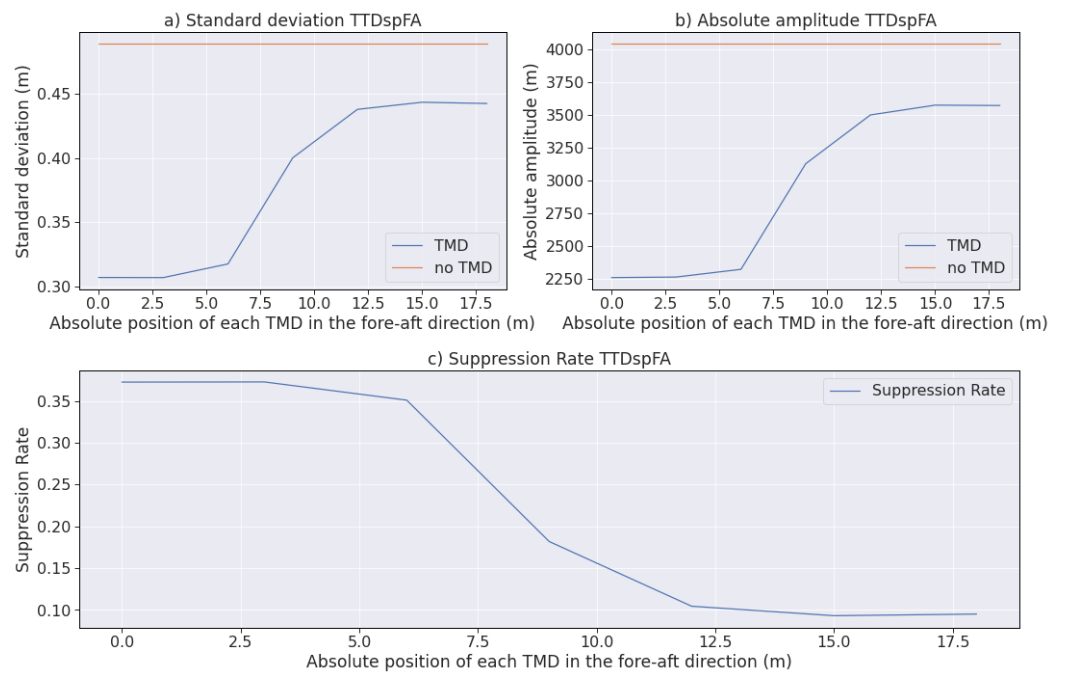
Figure 8 shows two of the configurations tested. On the left, moving the TMDs along the fore-aft direction ( $dv$  axis) and, on the right, moving the two TMDs horizontally ( $dh$  axis).



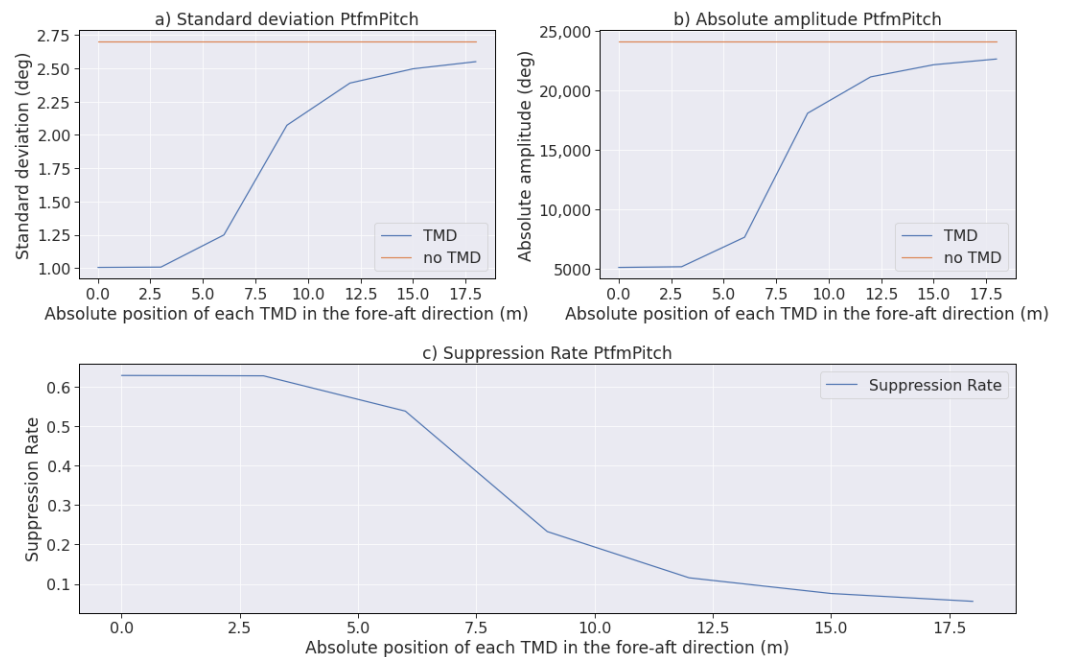
**Figure 8.** Displacement of both TMDs along the fore-aft (left) and side-side (right) axis keeping the symmetry.

First, the two TMDs are placed on the platform, on each side of the tower, and they are moved in the downwind direction,  $dv$ , always keeping both at the same distance from the tower. Simulations have been carried out moving them every 3 m. Figure 9 shows the variable  $TTD_{spFA}$  and Figure 10 the pitch of the platform when moving both of the TMDs this way. They both present the same trend.

In any of the positions, this configuration improves the three criteria evaluated, namely: standard deviation of the  $TTD_{spFA}$ , absolute amplitude, and suppression rate, in comparison with not applying any TMD (orange line). The best situation is to keep the TMDs as close to the center as possible, at least less than 3 m away from the center, as we can see in these figures. Once the 3 m distance is exceeded, the stability gets slightly worse, although, as it has been said, it is always better than without TMD (suppression rate always positive).

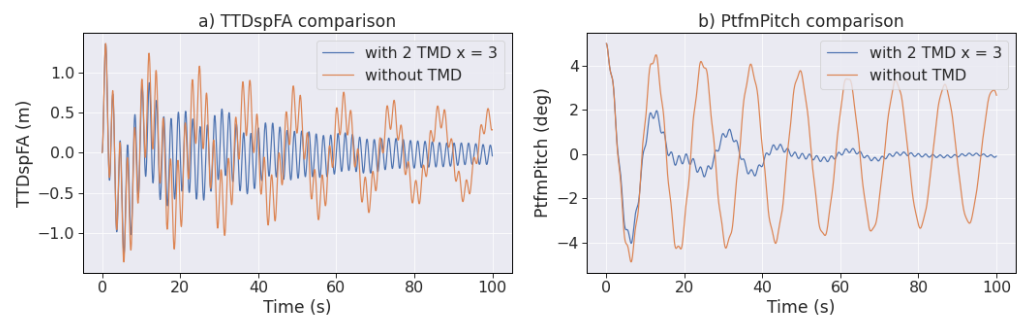


**Figure 9.** Results when moving two TMDs in the fore-aft direction keeping the same distance to the center. (a) Sum of TTDspFA standard deviation; (b) Sum of TTDspFA amplitude; and, (c) TTDspFA suppression rate.



**Figure 10.** The results when moving two TMDs in the fore-aft direction keeping the same distance to the center. (a) Sum of PtfmPitch standard deviation; (b) Sum of PtfmPitch amplitude; and, (c) PtfmPitch suppression rate.

Figure 11 shows the TTDspFA (left) and the variable PtfmPitch (right) with two TMDs placed at 3 m from the tower in the fore-aft direction (blue lines) and without TMD (orange line). These results confirm the suppression rate obtained before. That is, the oscillation is greatly reduced.



**Figure 11.** Comparison of TTDspFA (a) and PtfmPitch (b) without TMD (orange) and with two TMDs located in the fore-aft axis at 3 m from the center (blue).

Now, the two TMDs are moved in the side-side direction, every 3 m, always keeping both at the same distance from the center. Figure 12 shows the variable TTDspFA and Figure 13 the PtfmPitch. It can be seen that neither the standard deviation nor the sum of the vibration amplitude varies. The same happens with the suppression rate of the tower top displacement, which is almost constant around the value of 0.37. That is, the suppression rate remains constant getting a reduction of the oscillation of approximately 37.26%, while the PtfmPitch suppression rate is around 0.62, which is, 62.82%, whatever the position of the TMDs.

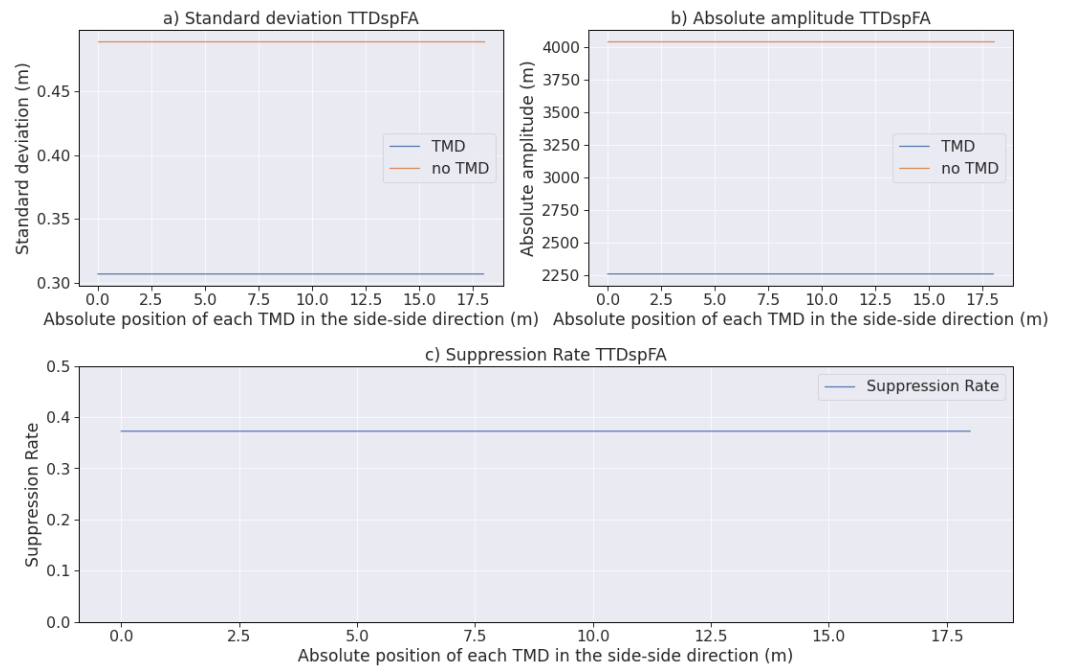
These results mean that no matter how far the TMDs are from the center, moving both of them at the same distance from the tower in the side-side direction, it does not affect the metrics of the variables that are being evaluated. In any case, the stability of the WT is much better than without TMD, independently of the distance to the center.

In order to show an example of how the vibrations are reduced, both of the TMDs have been placed 18 m from the center in the side-side (dh) axis. Figure 14 shows the WT response.

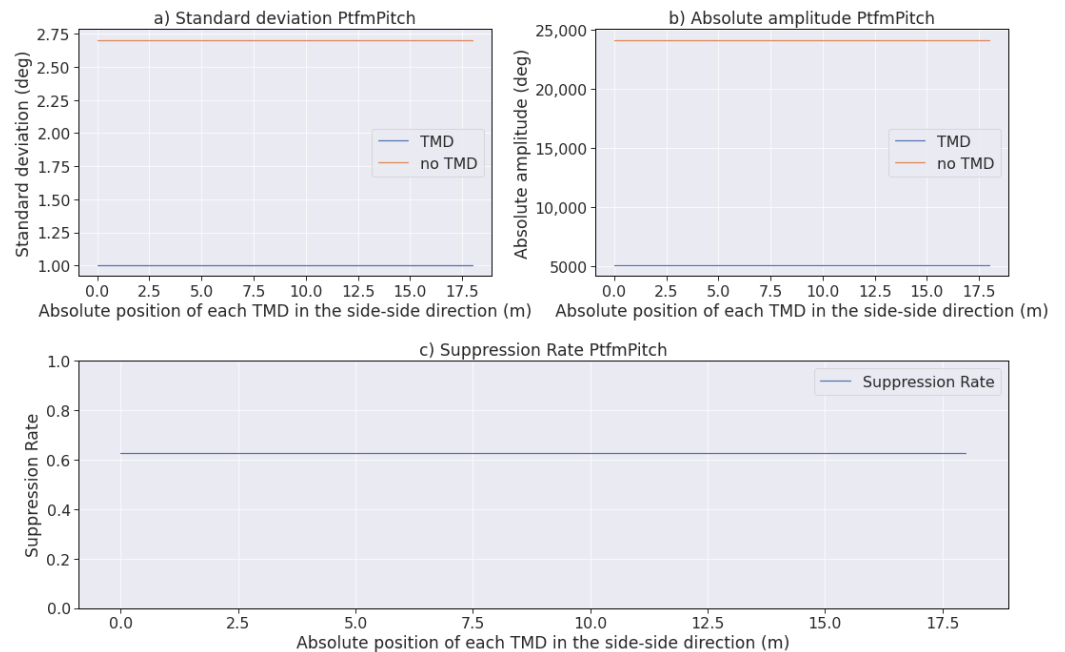
Some conclusions can be drawn from these two cases. In addition to always keeping the symmetry, the TMDs must be as close to the center as possible if they are on the downwind axis, while the distance at which they are placed with respect to the side-side axis is irrelevant. The improvement that was obtained by the TMDs in any position of the side-side axis is comparable to the improvement when both of the TMDs are near the center in the fore-aft axis.

Finally, experiments placing the two TMDs with diagonal symmetry on the platform have been performed (Figure 15). Because it seems that 3 m from the center was an optimal distance in the fore-aft direction, simulations have been carried out with TMD1 at ( $dh = 3, dv = 3$ ) and TMD2 at ( $dh = -3, dv = -3$ ). Another simulation was tested with the two TMDs at ( $dh = 3, dv = -3$ ) and ( $dh = -3, dv = 3$ ). In both cases, the metrics give the same values, reducing the vibrations. Figure 16 shows the vibrations (TTDspFA on the left and PtfmPitch on the right) with the first symmetrical positioning of the two TMDs.

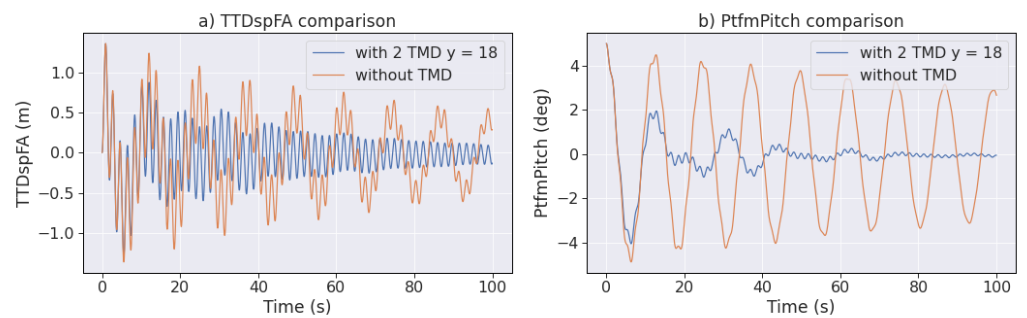




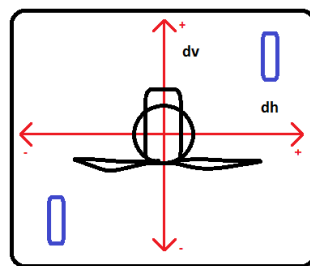
**Figure 12.** The results when moving two TMDs in the side-side direction keeping the same distance to the center. (a) Sum of TTDspFA standard deviation; (b) Sum of TTDspFA amplitude; and, (c) TTDspFA suppression rate.



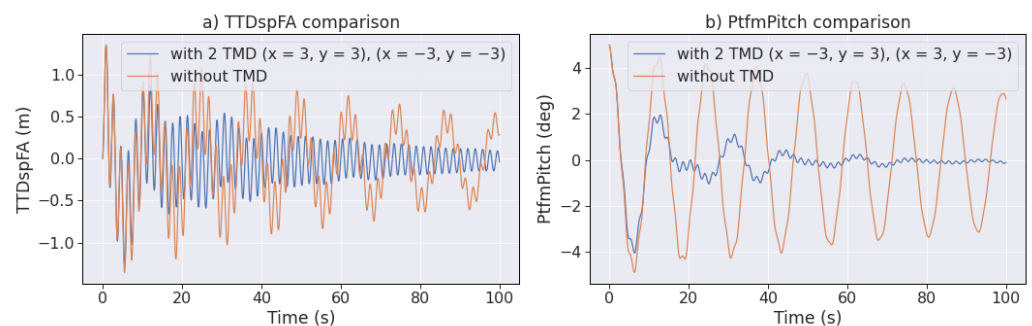
**Figure 13.** Results when moving two TMDs in the side-side direction keeping the same distance to the center. (a) Sum of PtfmPitch standard deviation; (b) Sum of PtfmPitch amplitude; (c) PtfmPitch suppression rate.



**Figure 14.** Comparison of TTDspFA (a) and PtfmPitch (b) without TMD (orange) and with two TMDs located in the side-side axis at 18 m from the center (blue).



**Figure 15.** Two TMDs located on the platform with diagonal symmetry.



**Figure 16.** TTDspFA (a) and PtfmPitch (b) without TMD (orange line) and with two TMDs in the diagonal (blue line).

To summarize, when considering this analysis, the best option is to place the two TMDs symmetrically at each side of the tower, regardless of the distance.

#### Discussion and Analysis of the Results

From the analysis of the position of the TMDs, it is possible to say that, although using an optimized TMD on the platform reduces the vibrations, placing two TMDs at the optimal positions obtains the greatest reduction of the tower top deviation and of the platform pitch (Table 3).

The best option to lower the oscillations is to place both TMDs the closest possible to the center of the platform ( $dh = 0$ ,  $dv = 0$ ), where the tower is. Moreover, it has been proved that it is better to use two TMDs than only one with double mass, due to the damping and stiffness actions.

However, because of the dimensions of the TMDs, both of the devices cannot be under the tower. Still, positioning the two TMDs symmetrically at a distance that is smaller than 3 m in the fore-aft axis improves the results regarding a TMD under the tower, and much more than not using any. The suppression rate results are really good, especially with

respect to the platform pitch, as expected. The same results are obtained with the TMDs on the diagonal axis of the tower as long as they are at the same distance from the center and closer than 3 m.

As said before, the displacement in the side–side direction hardly varies the metrics studied, and the high reduction of the vibrations is obtained with this configuration.

**Table 3.** Comparison of different positioning of the TMDs and the suppression rate of TTDspFA and of PltfPitch.

Number of TMDs	Distribution	Position (m)	TTDsp FA Suppression Rate	PltfPitch Suppression Rate
1		dh = 0, dv = 0	0.3455	0.5609
2	Fore-aft axis	(3, 0) and (−3, 0)	0.3728	0.6273
2	Side-side axis	(0, −18) and (0, 18)	0.3726	0.6282
2	Diagonal	(3, 3) and (−3, −3)	0.3728	0.6273

These conclusions are of great interest for the design of the planned hybrid marine energy system, where various marine energy devices will be placed on the floating wind turbine platform.

## 6. Conclusions and Future Work

In this work, the effect of installing passive control TMD devices at different positions on the platform of a floating wind turbine has been analyzed. The final aim is to find the best position for these structural control systems in order to better stabilize the structure and reduce vibrations.

To do it, a 5 MW NREL barge-type floating turbine model has been simulated using the FAST software. One and two TMDs have been placed on the platform, and the turbine dynamics and its vibrations have been analysed for free-decay tests. A detailed study of the influence on the WT response of moving the TMDs in the fore–aft and side–side directions, with different orientations, has been carried out.

Several conclusions can be drawn from this analysis. First, installing these control devices on the platform of the FOWT significantly reduce the oscillations of the platform pitch and, in a smaller degree, of the tower of the wind turbine. On the contrary, installing a TMD in the nacelle lessens the vibrations of the tower to a greater extent. An advantage of this configuration is that the platform of the wind turbine allows more massive TMDs and, hence, a greater reduction of the vibrations.

However, adding some masses on the platform of the floating device may cause asymmetry in its dynamics, changing the center of mass of the wind turbine. Thus, finding the right position of the TMDs is important.

As expected, the FOWT is more stable when two TMDs are used in comparison with applying only one or none. With more control devices is easier to find symmetrical configurations. Accordingly, we think that exploring the option of installing several devices on the platform of a FOWT has interesting practical advantages. Even more, if those devices are active energy absorbers, then they may further increase the reduction of the fatigue of the floating wind turbine and, at the same time, increase the energy generation forming a hybrid wind and marine energy system.

The main results of this work can be extrapolated to other wind energy converters, as far as they have enough surface to install control devices. In any case, it can be said that, in general, any device attached to a wind energy turbine will create an asymmetry in its dynamics that must be considered.

As future work, it is proposed to expand the number of TMDs on the platform, within realistic limits, and, above all, to replace these passive structural control devices with the model of the marine energy systems to study the dynamics of the whole.

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