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Inerter-based Passive Structural Control for Barge Floating Offshore Wind Turbines

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Abstract: Floating offshore wind turbines (FOWT) 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, the authors investigate passive structural control to mitigate the tower fatigue, in the form of a tuned mass damper (TMD) installed in the nacelle. The study focuses on evaluating the benefits of adding a parallel-connected inerter device to the TMD. Based on a reduced dynamics model for the barge-type offshore wind turbine identified using the FAST-SC synthetic reference data, an optimization of the TMD and the inerter parameters is carried out. To that end, genetic algorithms were used taking the tower fatigue as a fitness function, derived from the tower top displacement. The results confirm that the inerter has limitations when installed in a traditional TMD, but show significant benefits when the TMD stroke is constrained by stops. It is found that the improved performance including the inerter is dependent on the stroke limitation with respect to the ideal TMD stroke without stops. Therefore, the use of the inerter is especially useful to enhance performances for both mass and stroke constrained applications. The load reduction for the selected baseline model improved up to 6 % over the TMD with stops and 12 % over the TMD without stops.

Keywords: Barge Offshore Wind Turbine, Passive Structural Control, Tuned Mass Damper, Inerter, Genetic Algorithm Optimization, Fatigue.

1. INTRODUCTION

Wind energy production has experimented a huge expansion over the last few years. However, while some drawbacks like strong visual and noise impact remain unsolved for land-based turbines, the energy demand grows in parallel with the governments' commitment towards clean energy production (Mayorga et al., 2019).

It is well known that offshore wind resources are of higher quality than those on land, with stronger, steadier, and more frequent winds (Esteban et al., 2011). 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 as stated by Musial et al. (2004). Nevertheless, as Kaldellis and Kapsali (2013) claimed, the sea bed in these areas suffers a relatively large footprint from the turbine's foundations 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 depth. There are three main types of FOWT, depending on the restoring mechanism they rely on. The fundamental stabilizing methods are buoyancy, ballasting, and mooring. The derived floating foundation types are the barge, the spar buoy, and the tension leg platform. The present study focuses on the barge-type floating platforms, which stand out for their design, assembly, and maintenance benefits. The stability is achieved through its waterplane area moment and is moored by catenary lines.

Preliminary load analysis on barge-type FOWT carried out by Jonkman and Buhl (2007) has demonstrated that the wave- and wind-induced motions increase the displacements and loads on the structure due to an inverted pendulum effect. In these cases, the relative structural fatigue between the sea- and land-based turbines increases form the blade tip to the tower base, reaching unacceptable figures. 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 such as earthquakes, wind, or traffic (Saaed et al., 2015). In this context, structural control should be understood as an additional Degree Of Freedom (DOF) to the structure devoted to influence the structural behavior, instead of an intervention of the existing turbine power production control system. If sufficient, the main benefit of the structural control application is that it would not require any design modification of the baseline land-based wind turbine.

The application of structural control to offshore wind turbines has been a topic of interest the last years (Tomas-Rodriguez and Santos, 2019). One of the major contributions came from Lackner and Rotea (2011), who upgraded the software FAST (Fatigue, Aerodynamics, Structures, and Turbulence), developed by the U.S. National Renewable Energy Laboratory (NREL), to include structural control features creating FAST-SC. Then, Stewart and Lackner (2013) used FAST-SC to assess passive control solutions for both tension leg platforms and barge-type floating wind turbines.

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

However, while structural control has demonstrated to be capable of reducing FOWT loads, fatigue suppression rates achieved by means of traditional passive methods still result in excessive tower bending moments. Seeking an enhancement of the capabilities of the classical TMD, the inerter is presented as a potential solution. The inerter, introduced by Smith (2002), is a mechanical two-terminal one-port device with the property of producing a force proportional to the relative acceleration between its nodes.

The use of inerters in structural control has been studied along with network synthesis since its discovery. Chen and Hu (2019) demonstrated that adding one inerter alone to the traditional TMD provides no benefits in terms of H_∞ and H_2 performance, regardless of being added in parallel or series connection. Instead, the device should be introduced along with an inerter-based mechanical network, which confers an additional DOF to the system. There exist several contributions presenting FOWT load mitigation with this approach, as in Hu and Chen (2017b), Hu and Chen (2017a), or Hu et al. (2018). All of them optimize a passive network consisting of a finite interconnection of springs, dampers, and inerters. Although the inerter helped to slightly improve the performance, that came at the cost of a significant increase in complexity of the DVA configuration. Moreover, the studies did not take into account the constraints derived from the turbine nacelle dimensions.

This work explores the addition of the inerter device to a traditional TMD installed in the nacelle of a barge-type floating offshore wind turbine. This approach has been previously explored by the authors in Tomas-Rodriguez et al. (2018) and Tomas-Rodriguez et al. (2019). The main contribution of this paper is to re-think the use of parallel-connected inerters in TMDs, taking into account the additional dynamics provided by the stops used for limiting the stroke. To that end, a reduced DOF FOWT model is formulated based on Euler-Lagrange's equations and validated using FAST-SC reference simulation data. The optimization of the TMD parameters is then performed using genetic algorithms (GA) to reduce the tower fatigue in the fore-aft direction. Different optimization cases have been considered, yielding results that confirm previously stated theories and potential new directions of research.

The article is structured as follows. Section 2 describes the selected baseline system and presents the reduced dynamic model used for its simulations. Section 3 formulates the optimization problem along with the optimization cases. In Section 4 the results are presented. Section 5 discusses the obtained results and provides some hints for future research.

2. FOWT MODEL

The wind turbine selected for the analysis is the NREL 5-MW wind turbine defined by Jonkman et al. (2009). 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 parameters are summarized in Table 1. This model is considered to be a benchmark.

Table 1. Parameters of the NREL 5-MW Wind Turbine. Jonkman et al. (2009)

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	40,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)

The 5-MW wind turbine is mounted on the ITI Energy barge, designed by Vijfhuizen (2006). 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 moor the platform preventing its drift. The barge properties can be found in Table 2.

Table 2. Parameters of the ITI Energy Barge. Vijfhuizen (2006)

Size (WxLxH)	40 m x 40 m x 10 m
Moonpool (WxLxH)	10 m x 10 m x 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

Considering that the proposed FOWT is a benchmark, there are no real data available, so it is essential to simulate its behavior. To that end, an aeroelastic computer-aided engineering tool called FAST (Fatigue, Aerodynamics, Structures, and Turbulence) developed by the NREL, will be used. Moreover, there is an advanced version of FAST developed by Lackner and Rotea (2011), called FAST-SC, which includes structural control capabilities.

Although it can provide high fidelity data, FAST-SC software is overkill in terms of computational time for this particular problem, especially if included in an optimization loop. Instead, a reduced DOF model was formulated based on the fundamental dynamics that governs the turbine response.

The FOWT model consists of three rigid bodies: the barge platform, the TMD and the turbine, the latter composed of the tower and the rotor-nacelle assembly. Three DOFs are considered in the model; TMD translation, platform pitch and tower bending. The two latter ones were selected according to Jonkman and Buhl (2007), which proved that the first collective platform pitch-tower bending mode conforms the largest contribution to fatigue loading. The turbine is modelled as 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 $\mathrm{k_t}$ and $\mathrm{d_t}$ respectively. The barge pitch is modelled by a rotational second order linear equation containing a spring force representing the overall contribution of the hydrostatic restoring moment and mooring lines stiffness. A damping force is also included to simulate hydrodynamic damping, wave radiation and viscous damping. The coefficients of the spring and damper forces are $\mathrm{k_b}$ and $\mathrm{d_b}$, respectively. The model includes a TMD with a parallel-connected inerter, whose parameters are the spring stiffness, damper coefficient and inertance ($\mathrm{k_T}$, $\mathrm{d_T}$, and $\mathrm{b_T}$). The TMD is installed inside the nacelle, acting in the fore-aft direction. The rest of dynamics and external loads from wind and waves have not been considered, as the model will be only used for free decay tests.

$$\begin{cases} I_t\ddot{\theta}_t = m_t g R_t \theta_t - k_t(\theta_t - \theta_b) - d_t(\dot{\theta}_t - \dot{\theta}_b) \\ -m_T g(R_T\theta_t - x_T) - k_T R_T(R_T\theta_t - x_T) \\ -d_T R_T(R_T\dot{\theta}_t - \dot{x}_T) \\ \\ I_b\ddot{\theta}_b = -m_b g R_b \theta_b - d_b\dot{\theta}_b - k_b\theta_b \\ +k_t(\theta_t - \theta_b) + d_t(\dot{\theta}_t - \dot{\theta}_b) \\ \\ m_T\ddot{x}_T = m_T g\theta_t + k_T(R_T\theta_t - x_T) \\ +d_T(R_T\dot{\theta}_t - \dot{x}_T) \end{cases} \tag{1}$$

The model equations (1) were obtained using the Euler-Lagrange approach as in He et al. (2017). An identification process was carried out to determine the following parameters of the model: the spring stiffness, the damping coefficient, and the inertia moment of both the barge platform (subindex b) and the tower (subindex t), i.e., $\mathrm{k_b}$, $\mathrm{k_t}$, $\mathrm{d_b}$, $\mathrm{d_t}$, $\mathrm{I_b}$, and $\mathrm{I_t}$. The model was then validated by comparing the response for free decay tests to the simulation of FAST-SC. The TMD was activated in the validation to diversify the simulation scenario, which helps to avoid overfitting to the identification data set (Villoslada et al., 2019).

3. INERTER-BASED STRUCTURAL CONTROL OPTIMIZATION

The wind turbine is equipped with a TMD, 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, more specifically its spring stiffness ($\mathrm{k_T}$) and damper coefficient ($\mathrm{d_T}$). In addition, the TMD is fitted with an inerter, in parallel to the spring and the damper. The inertance, $\mathrm{b_T}$, which is the inerter proportional constant coefficient (kilograms) has to be optimized as well. The complete vibration absorber device is depicted in Fig. 1.

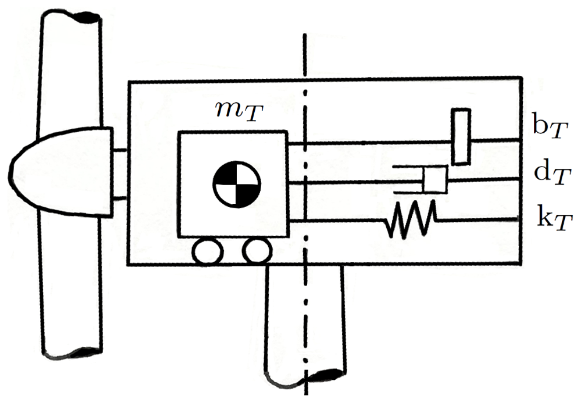

Fig. 1. TMD and inerter installed in the nacelle.

In order for the nacelle to be capable of accommodating the TMD, its dimensions must be considered as a constraint for the TMD stroke. This can be done by introducing TMD stops, each of it composed of a spring and a damper of large coefficients, located at both ends of the TMD mass track. This adds new dynamics to the model and three new variables to the problem: the distance from which the stop starts to act ($\mathrm{x_s}$) and its spring and damper coefficients ($\mathrm{k_s}$, $\mathrm{d_s}$).

The fitness variable for the optimization is σ(TTD), the standard deviation of the translational deflection of the tower measured at the top, i.e., Tower Top Displacement (TTD). As the TTD is proportional to the tower bending moment, its standard deviation is correlated with the tower fatigue loads.

The FOWT model was included in the optimization loop, and evaluated for free decay tests with an initial platform pitch of 5 degrees over 100 seconds, to compare it with previous results. Genetic algorithms (GA) were used to find the optimum configurations of the TMD and the inerter. The GA had an initial population size was 50 individuals, rank scaling, and stochastic uniform selection with a crossover probability of 0.8 and a mutation probability of 0.01. To address the space limitations constraints, a TMD stroke penalty was added to the fitness function (F) for those solutions exceeding the defined stroke limitation ($\mathrm{stroke_{max}}$), laying (2). Note that the best solution is that with the lowest value of F, so any configuration having a stroke higher than $\mathrm{stroke_{max}}$ will be penalized proportionally to the exceeded stroke. To ensure the final solution is within the limits, it was empirically found that the penalty had to be increased by a factor of 10. All the optimization was done with Matlab.

$$F = \sigma(TTD) \cdot \left(\frac{10 \cdot stroke}{stroke_{max}}\right) if stroke > stroke_{max} \tag{2}$$

In order to explore the benefits of including an inerter into the existing structural control device, different scenarios were considered combining the TMD optimization and the stops. The optimization cases that will be presented in the next subsections are the following:

(1) Optimization of the inerter, added to an already optimized TMD without stops.
(2) Optimization of the inerter, added to an already optimized TMD with stops.
(3) Optimization of the inerter together with a TMD without stops.
(4) Optimization of the inerter together with a TMD with stops.

Regarding the TMD mass optimization, it always tends to its maximum possible value if optimized (Villoslada et al., 2019). Two constant values were selected for the experiments, according to the mass ratios used in civil engineering: 20,000 kg and 40,000 kg. These masses represent 2.8 and 5.7 % of the wind turbine mass and 0.33 and 0.65 % of the total mass including the barge platform.

3.1 Case 1: Inertance optimization on an optimized TMD without stops

The first case covers the addition of an inerter to an already optimized TMD without stops. This case requires two optimizations in sequence, one for the conventional TMD alone and the other for the inerter added afterwards. The first optimization was run with a fixed inertance set to zero and obtained the conventional TMD parameters k_T and d_T. Those parameters were then held constant to run the second optimization with the inertance as the problem variable.

This optimization case resulted in an inertance value near to zero, which means that the inerter addition cannot enhance the performance of a traditional TMD without stops. The results are shown in Table 3 and the achieved performance can be found on Table 6, where case 1 corresponds to the configuration denoted as TMD.

Table 3. Optimization results for case 1 and 3.

m_T kg	k_T N/m	d_T N·s/m	b_T kg
20,000	4,568	2,636	0
40,000	8,292	9,766	0

3.2 Case 2: Inertance optimization on an optimized TMD with stops

This second case was similar to case 1, but with the addition of stops in the first optimization. Nevertheless, the results were the same, i.e., the inertance tends to zero. The solution is shown in Table 4 and the achieved performance can be found on Table 6, where case 2 corresponds to the configuration denoted as TMD_S.

Table 4. Optimization results for case 2.

m_T kg	k_T N/m	d_T N·s/m	X_s m	k_s N/m	d_s N·s/m	b_T kg
20,000	1,877	6,174	8.09	502,900	893,400	0
40,000	2,197	11,614	8.00	499,600	315,200	0

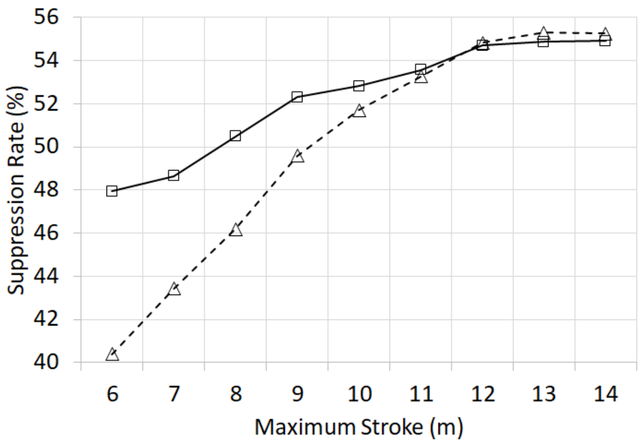

Fig. 2. TMD performance as a function of the stroke limitation: (□) with inerter and (△) without inerter.

3.3 Case 3: TMD and inerter optimization without stops

This third case considers the optimization of both the TMD (without stops) and the inerter in the same loop. However, as the inertance of the solution was practically zero, the results were exactly the same as those from case 1. This means that in case 3, like in case 1 and 2, the inclusion of an inerter can never improve the system response characteristics. This is in tune with the previous existing studies (Chen and Hu, 2019) and could justify the use of the inerter along with an additional mechanical network.

The results are shown in Table 3 and the achieved performance can be found on Table 6, where again case 3 corresponds to the configuration denoted as TMD.

3.4 Case 4: TMD and inerter optimization with stops

The optimization of an inerter together with a TMD with stops gives promising results in terms of vibration reduction. A parametric study was done for stroke limitations ($stroke_{max}$) ranging from 6 m to 14 m. In this case, the stops spring and damper coefficients, k_s and d_s, were held constant to $5 \cdot 10^5 N/m$ and $5 \cdot 10^5 N \cdot$s/m, respectively, for simplicity, being the stop distance (x_s) the only variable optimized from the stops.

The results are shown in Fig. 2, where the performance is measured in terms of Suppression Rate, which is the ratio of σ(TTD) reduction with respect to the baseline system without structural control in the same conditions. The horizontal axis represents the maximum stroke achieved by each of the solutions, which matches case by case with the respective stroke limitation.

Analyzing Fig. 2, it is clear that the more restricted is the TMD stroke, the better is the performance gained by including an inerter in the structural control scheme. It is worth noting that an ideal TMD without stops and 40,000 kg of mass would require a stroke of 14.27 m (to each side). The nacelle length is 18 m, so a feasible TMD should have 8 m of stroke at most. Unfeasible solutions with greater stroke values were evaluated just to identify the trends.

The results show that the stops presence modifies the TMD dynamics making the use of the inerter favourable

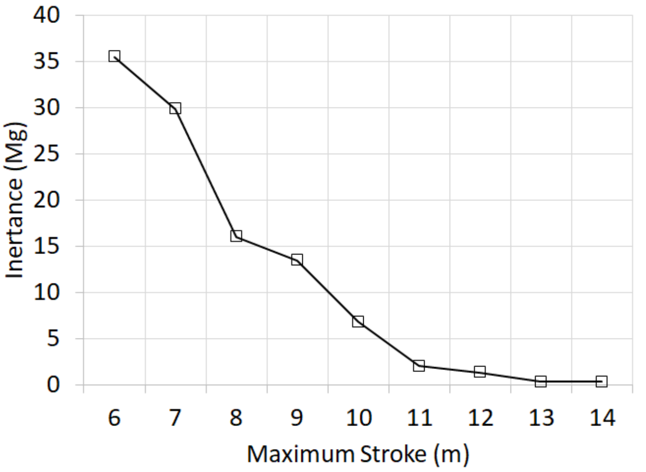

Fig. 3. Inertance as a function of the stroke limitation.

when the stroke is limited. The improvement of the performance caused by the inerter grows with the stroke limitation with respect to the ideal TMD stroke without stops. This means that less massive TMDs, which require more stroke, will benefit more from the presence of the inerter device. Regarding the value of the inertance, the optimum value increases with the stroke limitation, as shown in Fig. 3.

Once the benefits of adding the inerter have been proved, a more accurate optimization process was carried out in order to find the best possible solution. To that end, the range of the variables were narrowed and their resolutions were extended. The stroke constraint was set to a maximum value of 8 m. The optimal solutions for the two masses considered are presented in Table 5, where k_T refers to the TMD spring stiffness, d_T to the damper coefficient, X_s to the stops distance, k_s to the stops springs stiffness, d_s to the stops dampers coefficients and b_T to the inertance.

Table 5. TMD optimized with stops and inerter.

m_T kg	k_T N/m	d_T N·s/m	X_s m	k_s N/m	d_s N·s/m	b_T kg
20,000	4,769	15	7.95	256,900	936,100	28,904
40,000	3,340	426	7.96	243,800	828,800	17,364

The performances reached by the inerter solutions (denoted as I-TMD$_S$) are summarized in Table 6. For comparison purposes, the table also includes other two solutions without inerter: with stops (denoted as TMD$_S$) and without them (denoted as TMD). For the two masses considered, the I-TMD$_S$ solution always provides the best load reduction, improving the TMD$_S$ up to 6 % and the TMD up to 12 %.

Eventually, a power spectral density (PSD) analysis allows to compare the solutions in the frequency domain. Fig. 4 provides the PSD of the TTD variable for the three different solutions with 40,000 kg of mass. As a reference value, the FOWT without structural control experiences up to 800 and 250 m^2/Hz of power on the first and second TTD fundamental modes. Although the unrestricted TMD achieves a higher reduction on the first mode, the stroke limited optimizations (TMD$_S$ and I-TMD$_S$) can also lower the second mode response. The inerter addition to the TMD with stops clearly enhances the vibration absorption capabilities on both natural frequencies.

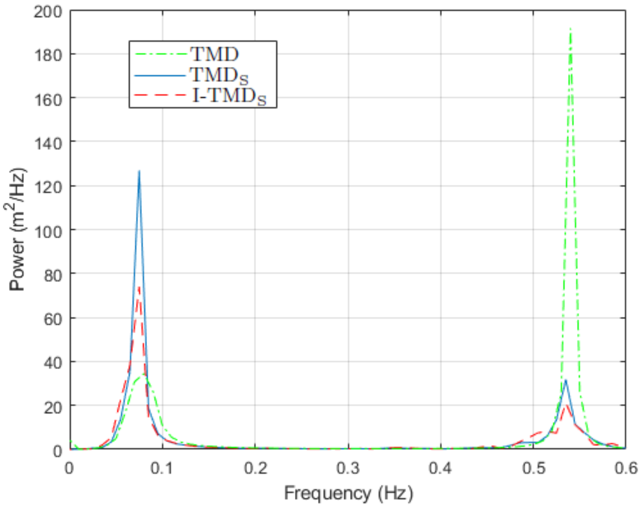

Fig. 4. PSD of TTD variable (m_T = 40,000 kg).

Table 6. Performance comparison.

Config.	m_T kg	Suppression Rate %	Stroke m	σ(TTD) m
TMD	20,000	34.73	23.57	0.3204
TMD$_S$	20,000	34.81	8.189	0.3200
I-TMD$_S$	20,000	40.75	8.171	0.2908
TMD	40,000	40.06	14.27	0.2942
TMD$_S$	40,000	47.99	8.369	0.2553
I-TMD$_S$	40,000	52.22	8.369	0.2345

4. CONCLUSIONS AND FUTURE WORKS

This study shows under which scenarios an inerter device parallel-connected to a standard TMD passive structural control system reduces the vibrations in a floating offshore wind turbine.

First, it was proved that the inerter does not provide any performance improvement if it is added to a TMD without stops or to a previously optimized TMD (with or without stops). However, the tower displacement can be significantly reduced if an inerter is added in parallel to a standard TMD with stops and optimized altogether. Indeed, this is the opposite of what could be expected with unlimited TMD stroke.

Even more, the lower the stroke of a TMD, the greater the improvement obtained by the inerter presence. This makes the inerter especially useful to enhance conventional passive structural control for both mass and stroke constrained applications. The load reduction regarding the selected baseline FOWT model was up to 6 % over the TMD with stops and 12 % over the TMD without stops.

As future works, other structural control methods including inerter can be studied, even combining semi-active and passive inerter-based control devices.

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