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Evaluating Resonance Mitigation for Monopile-Supported Offshore Wind Turbine Considering Soil-Foundation-Structure Interaction Using a Passive Energy Dissipation Device

M. V. G. de Morais*
University of Brasilia, Faculty of Technology, Mechanical Engineering Dept., 70.910-900, Brasilia, Brazil
Ph. Alkhoury
Formerly Nantes Université, Ecole Centrale Nantes, CNRS, GeM, UMR 6183, F-44600 Saint-Nazaire, France
M. Aït-Ahmed
Nantes Université, IREENA, UR 4642, F-44600 Saint-Nazaire, France
A.-H. Soubra
Nantes Université, Ecole Centrale Nantes, CNRS, GeM, UMR 6183, F-44600 Saint-Nazaire, France
**mvmorais@unb.br (corresponding author)*

ABSTRACT: This paper evaluates the vibration reduction of a DTU 10MW monopile-supported offshore wind turbine (OWT) using a three-dimensional pendulum tuned mass damper (3D-PTMD). A three-dimensional (3D) finite element (FE) model considering the OWT superstructure, the monopile foundation and the surrounding soil together with a 3D-PTMD placed at the tower top was developed making use of FE code Abaqus/Standard. The soil-foundation interaction was modeled based on a recent p-y model that is suitable for large-diameter monopile. Optimal analytical formulas of the 3D-PTMD parameters were used to mitigate the risk of resonance of the OWT during operation including random excitation induced by turbulent wind and waves. Tower top displacement was analyzed in the presence of the 3D-PTMD to verify the efficiency of the 3D-PTMD parameters used.

Keywords: Offshore Wind Turbine (OWT); Vibration Reduction; Finite Element Analysis; Passive Control.

1 INTRODUCTION

Offshore wind turbines generally harness more wind energy than onshore turbines, mainly due to stronger and more consistent winds, along with typically larger turbine sizes. To optimize the utilization of wind resources, many monopile-supported offshore wind turbines are strategically located at water depths of 30m to 50m. In 2021, offshore wind power installations set a record with near to 21 GW of new capacity, bringing the total cumulative capacity to near to 55 GW (Global Wind Energy Council, 2023). These turbines typically consist of a wind rotor connected to a nacelle, which is supported by a tall, slender and flexible tower. It is worth noting that taller turbines have a higher energy harvesting capacity. However, increased tower height can lead to elevated levels of vibrations caused by rotor operating frequencies and environmental loads, which are further exacerbated by the tower size. Consequently, the introduction of structural control systems becomes imperative to avoid failure, minimize maintenance costs and limit excessive vibrations and risk of resonance.

Additionally, the interaction between the monopile foundation and the soil plays a crucial role in the dynamic behavior of the structure. A proper soil-structure interaction (SSI) modeling is essential, as it directly influences the performance of structural control systems desgined to mitigate excessive vibrations at resonance. A comprehensive understanding of SSI can improve the effectiveness of these control strategies, ensuring the reliability and longevity of offshore wind turbines. This paper focuses on the improvement brought by a passive energy dissipation through the reduction of the spectral peak of the Power Spectrum Density (PSD) response observed at resonance.

The Tuned Mass Damper (TMD) is a widely employed passive structural control device. It functions by transferring kinetic energy from the main structure to a secondary mass. In recent years, the integration of passive devices with wind turbines and offshore wind turbines (OWTs) has been the subject of extensive research. For instance, Sun & Jahangiri (2018) developed an analytical model for the National Renewable Energy Lab 5-MW monopile-supported OWT equipped with a 3D-Pendulum Tuned Mass Damper (3D-PTMD) to mitigate the effects of misaligned wind, wave, and seismic loads. The Pendulum Tuned Mass Damper (PTMD) serves as an alternative to the TMD, utilizing a pendulum as the passive device. Gerges & Vickery (2005) demonstrated the effectiveness of a PTMD in reducing the root mean square (RMS) displacement of a two-degree-of-freedom (2DoF) structures. Deraemaeker & Soltani (2017) presented an analytical procedure for the optimal design of a linear PTMD that was coupled with an undamped primary system. The Den Hartog equal peak method was applied to derive the optimal design parameters for the linear PTMD (Den Hartog, 1985). Tuning a PTMD involves optimizing the stiffness and damping properties of the pendulum mass and its length for a specific coupled system. However, there is limited research considering the soil-foundation-structure interaction when evaluating the vibration mitigation of monopile-supported offshore wind turbines subjected to combined wind and wave loads.

This paper evaluates the vibration reduction at resonance of a DTU 10MW monopile-supported OWT using a 3D-PTMD while accounting for the soil-foundation structure interaction. A three-dimensional (3D) finite element (FE) model was developed using Abaqus/Standard, incorporating the OWT superstructure, the monopile foundation, the surrounding soil and a 3D-PTMD placed at the tower top. The soil-structure interaction was modeled based on Winkler approach (called also p-y method) making use of the recent model by Fuentes et al. (2021) that is suitable for large-diameter monopiles embedded in cohesionless soils and subjected to static or cyclic lateral loading. The optimal parameters for the 3D-PTMD were determined using design formulas from literature. These parameters allow one to mitigate the structural vibration at resonance of the monopile-supported OWT during operation including random excitations induced by turbulent wind and waves. The tower top displacement was analyzed to evaluate the effectiveness of the adopted optimal 3D-PTMD design parameters.

2 DTU 10MW WIND TURBINE

This study considers the DTU 10 MW reference three-bladed OWT (Alkhoury et al., 2022). This turbine is representative of the large-scale OWTs currently in production. It has a tower height of 115.63 meters and a hub height of 119 meters, with the tower gradually narrowing from a base outer diameter of 8.3 meters and a thickness of 0.038 meters to a top outer diameter of 5.5 meters and a thickness of 0.02 meters. The turbine is supported by an 8.3-meter outer diameter monopile foundation with a 9 cm thickness. The total length of the monopile is 80 meters, with 45 meters embedded in the seabed, 25 meters submerged in water, and the remaining 10 meters, known as the transition piece, extending above mean sea level (MSL). Detailed dimensions and properties of the DTU 10 MW turbine are presented in Figure 1 and Table 1.

The 3D structural model of DTU 10MW without PTMD (including the tower, transition piece, monopile, blades, hub and nacelle assembly) was developed by Alkhoury et al. (2022) using the Abaqus/Standard finite element code. As shown in Figure 2, the PTMD in this paper is modeled using a beam element of length l with a lumped mass (point mass in Abaqus) placed at one extremity. The other extremity of the pendulum is connected to the top of the wind turbine tower *via* a bidiretional torsional damper (Universal joint connector section in Abaqus).

Table 1 – Properties of reference offshore wind turbine DTU 10 MW.

Description	Maximum rated power	$10\ MW$
Blade	Rotor diameter (m)	178.332
	Hub height (m)	119
	Cut-in, rated, cut-off wind speed (m/s)	$4; 11.4; 25$
	Cut-in, rated rotor speed (rpm)	$6; 9.6$
	Length (m)	86.366
	Overall mass (kg)	$41{,}716$
Hub-Nacelle	Hub diameter (m)	5.6
	Hub, Nacelle mass (kg)	$105{,}520$; $446{,}036$
Tower	Height (m)	115.63
	Mass (kg)	$682{,}442$

A structural modal analysis of the parked OWT was carried out in Abaqus/Standard to calculate the first bending natural frequencies and the corresponding modal masses of the DTU 10 MW OWT (Table 2). For the tower first bending mode in fore-aft and side-to-side directions, the natural frequencies and the equivalent modal masses are almost equal (the difference is very small) because the tower and the foundation have axial symmetric shapes and properties.

Table 2 – Modal frequencies and equivalent masses for the modelled DTU 10 MW OWT.MW.

Mode	Description	Present study without gravity (Hz)	m_x (ton)	m_y (ton)	m_z (ton)
1	1st Bending tower, side-to-side	0.1937	---	1067.49	---
2	1st Bending tower, fore-aft	0.1949	1086.67	---	0.10

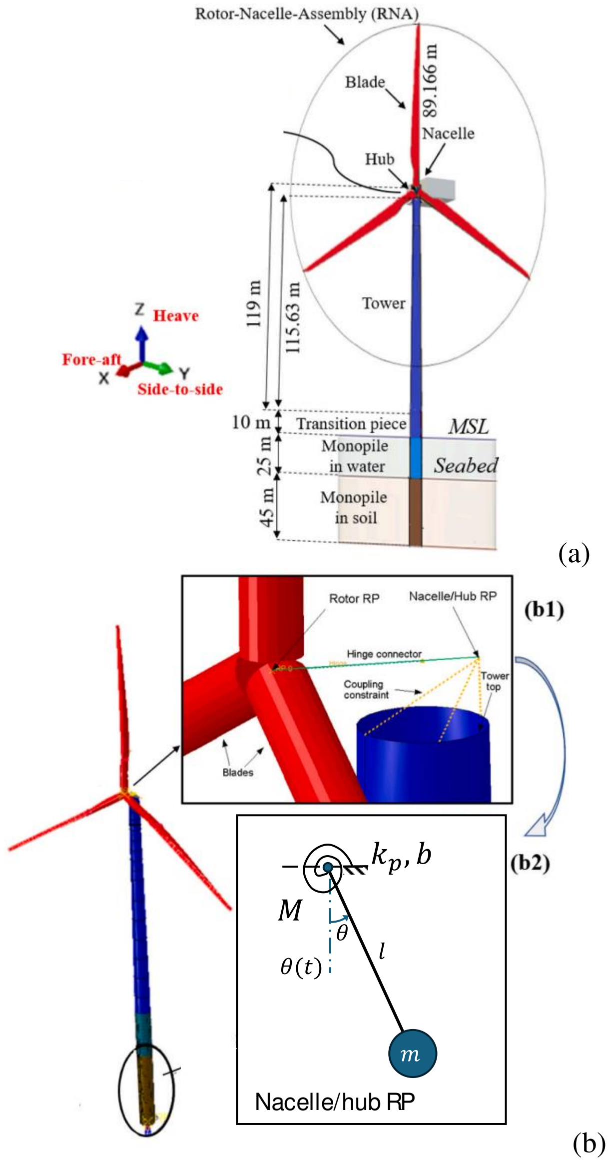

Figure 1 – Schematic representation of the DTU 10MW OWT(a), main view with the geometric dimensions (b) 3D structural FE modelling considering the soil-monopile interaction (b1) nacelle/hub interconnection with the tower top and rotor and (b2) a detailed modelling of the 3D PTMD connection to the nacelle/hub RP located at tower top.

3 REDUCED PRIMARY SYSTEM COUPLED TO PTMD

To implement a Pendulum Tuned Mass Damper (PTMD) structural control system within the OWT, the finite element model of DTU 10MW OWT was simplified to a single degree-of-freedom (1DOF) system in fore-aft direction, using the effective mass m_x and the first bending tower modal frequency. Figure 2 presents a schematic representation of the main dynamic system (primary system) coupled with a PTMD, where the primary system is subjected to an external excitation force $f(t)$. The equation of motion of this two Degree of Freedom (DoF) dynamic system (u, θ), where u is the spring-mass horizontal displacement and θ is the pendulum's rotational angle, is given by:

$$\begin{bmatrix} M+m & ml \\ ml & ml^2 \end{bmatrix} \begin{bmatrix} \ddot{u} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} C & 0 \\ 0 & b \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & k_p + mlg \end{bmatrix} \begin{bmatrix} u \\ \theta \end{bmatrix} = \begin{bmatrix} f(t) \\ 0 \end{bmatrix} \quad (1)$$

where M, C and K are respectively the mass, damping and stiffness coefficients of the primary system, while the pendulum parameters include the bob mass m, pendulum length l,rotational stiffness k_p and damping coefficient b.

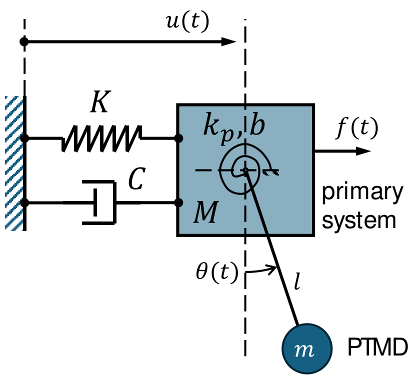

Figure 2 – Main structure coupled to a Pendulum Tuned Mass Damper with external Force $f(t)$.

In matrix form, the equation of motion (1) can be rewritten, as:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{f} \quad (2)$$

where, $\boldsymbol{x} = [u \quad \theta]^T$ is the displacement vector; $\boldsymbol{f} = [f(t) \quad 0]^T$ is the excitation vector; $\boldsymbol{M}$, $\boldsymbol{C}$, and $\boldsymbol{K}$ are respectively the mass, damping and stiffness matrices.

4 PTMD OPTIMUM PARAMETERS

In this paper, the chosen optimum parameters of the 3D-PTMD are only the length of the pendulum l and the omnidiretional rotational damping coefficient b (Figure 2). To determine the optimum value of the pendulum length (i.e. l_{opt}) and the optimal value of the omnidirectional rotational damping (i.e. b_{opt}), the following expressions proposed by Soltani & Deraemaeker (2022) were used in this paper:

$$l_{\text{opt}} = \frac{\mu M g + \sqrt{(\mu M g)^2 + 4 K k_p \mu \gamma_{opt}^2}}{2\mu K \gamma_{opt}^2} \quad (3)$$

$$b_{\text{opt}} = 2\xi_{opt} l_{opt} \sqrt{m} \sqrt{m g l_{opt} + k_p} \quad (4)$$

where, $\mu = m/M$ is the mass ratio, $\gamma_{opt} = \omega_p/\omega$ is the optimal frequency ratio, where $\omega_p^2 = \left(k_p + m g l_{opt}\right)/\left(m l_{opt}^2\right)$ and $\xi_{opt} = b_{opt}/\left(2 m l_{opt} \omega_p\right)$ is the optimal damping ratio of PTMD.

For the computation of the tuning ratio γ_{opt} and the damping ratio ξ_{opt} that appear in equations (3)-(4), the optimal analytical expressions proposed by Sun & Jahangiri (2018) for an offshore wind turbine equiped with a bidiretional PTMD and subjected to combined wind and wave loadings were adopted and are given as follows:

$$\gamma_{\text{opt}} = 7.6\mu^2 - 2.5\mu + 1 \quad (5)$$

$$\xi_{\text{p,opt}} = -2.7\mu^2 + \mu + 0.062 \quad (6)$$

It should be noted that the rotational stiffness k_p in equations (5)-(6) was assumed in this paper to be equal to zero as it was found that this parameter has negligible effect on the vibration reduction and bob pendulum displacement. The optimal parameters of the PTMD together with the corresponding tuning and damping ratios and the resulting pendulum frequency for two different mass ratios (1% and 2%) as adopted in the analysis are listed in Table 3.

5 RESULTS AND DISCUSSION

The numerical results presented in this section correspond to load case 10 (LC10) of the reference project UpWind. LC10 is characterized by a mean wind speed at hub height of $20\, m/s$, a significant wave height of $2.76\, m$ and a peak period of $6.99\, s$. Further details on the modelling and generation of load case LC10 can be found in Alkhoury et al (2022).

Table 3 – Optimum tuning and damping ratios as well as the resulting frequency of the pendulum together with the parameters of pendulum (m, l_{opt}, b_{opt}) for two different values of the mass ratio μ, when $k_p = 0.0$ and $f_s = 0{,}193 Hz$.

μ	1%	2%
γ_{opt} [eq. 5]	0.99	0.98
ξ_{opt} (%) [eq. 6]	6.09	6.94
$f_p = \omega_p/2\pi\,(Hz)$	0.1911	0.1892
$m\ (kg)$	10,675	21,349
$l_{opt}(m)$ [eq. 3]	7.01	7.34
$b_{opt}\ (kNm.s/rad)$ [eq. 4]	88.9	215.0

Figures 3 and 4 show respectively the relative fore-aft and side-to-side displacement time histories (with respect to the nacelle frame) of the bob pendulum. For a mass ratio of $\mu = 2\%$, the pendulum's motion in the fore-aft direction is within the limits (denoted by the max (+2m) and min (-2m) displacements in figures 3 and 4) imposed by the wind tower geometry at top (i.e. the tower top inner diameter).

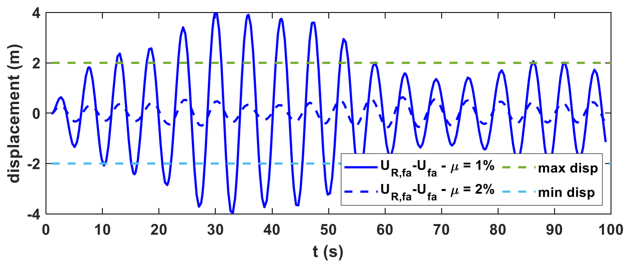

Figure 3 – Relative fore-aft displacement of bob pendulum with respect to nacelle frame.

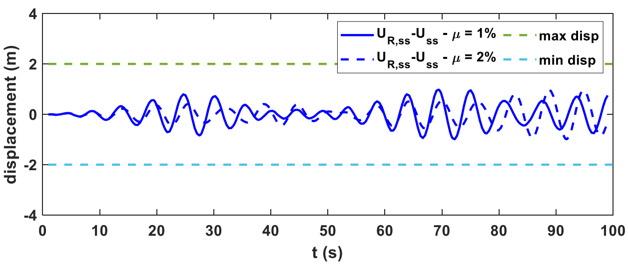

Figure 4 – Relative side-to-side displacement of bob pendulum with respect to nacelle frame.

Figure 5 and Figure 6 present the frequency contents (i.e. PSDs) of fore-aft and side-to-side nacelle displacements for both the controlled OWT (with mass ratios $\mu = 1\%$ and $\mu = 2\%$) and the uncontrolled OWT. In the fore-aft direction (see Figure 5), a reduction of 8.2dB and 10.8dB was observed at 0.188 Hz for mass ratios of 1% and 2%, respectively. In the side-to-side direction (see Figure 6), the reduction observed at 0.188Hz (resonance) was 6.4dB and 12.1dB for a mass ratio of 1% and 2%, respectively.

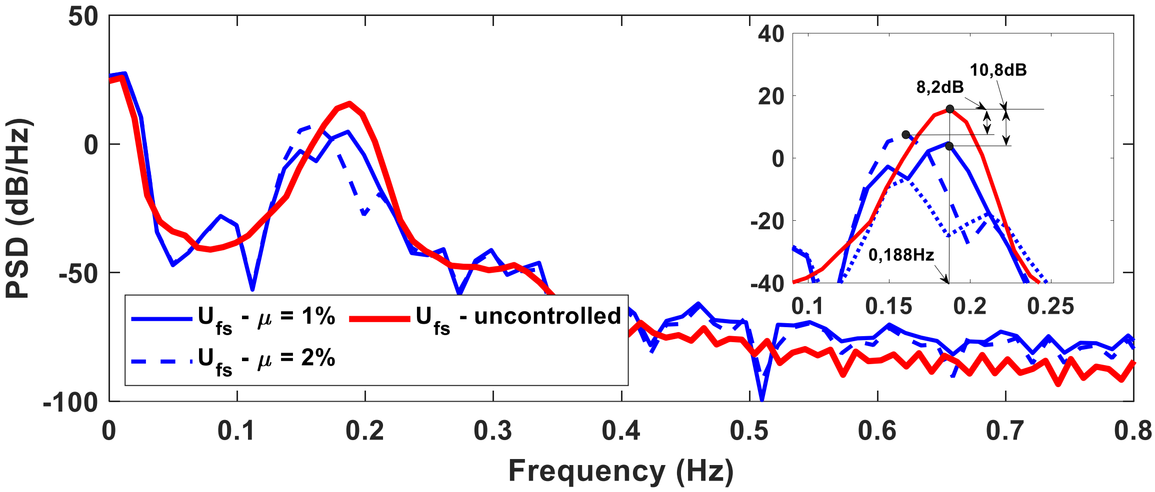

Figure 5 – PSDs of fore-aft nacelle displacement for controlled (with $\mu = [1\%; 2\%]$) and uncontrolled OWTs.

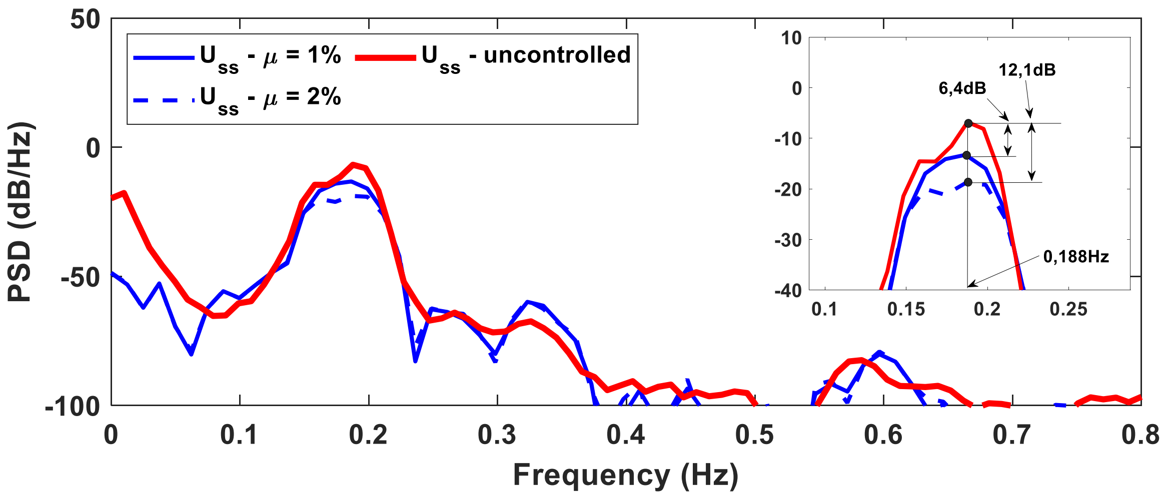

Figure 6 – PSDs of side-to-side nacelle displacement for controlled (with $\mu = [1\%; 2\%]$) and uncontrolled OWTs.

6 CONCLUSIONS

A three-dimensional structural numerical model of a DTU 10MW monopile-supported OWT equipped with a 3D-PTMD was developed using Abaqus finite element software to evaluate the vibration mitigation at resonance of the OWT when using a 3D-PTMD. The 3D finite element model incorporated soil-foundation-structure interaction through the Winkler approach, utilizing a recent p-y model suitable for large-diameter monopiles. The analysis of the spectral peak reductions (observed at resonance) in the lateral displacements of the OWT tower top was conducted to evaluate the effectiveness of the optimal parameters adopted for the 3D-PTMD. With a relatively small mass ratio of $\mu = 2\%$, the results indicated a relatively slight reduction in the vibrations at resonance, accompanied with an acceptable bob displacement within the inner diameter limits of the tower. Further research is needed to evaluate the relevance of the selected optimal parameters of the 3D-PTMD. For this purpose, a procedure to determine the optimal pendulum parameters through vibration minimization is required.

AUTHOR CONTRIBUTION STATEMENT

First Author: FE Modeling, Simulation, Formal Analysis, Writing Original draft. **Second Author**.: FE Modeling, Conceptualization, Supervision, Reviewing. **Third Author**: Conceptualization, Supervision, Reviewing. **Last Author**: Supervision, Reviewing.

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REFERENCES

Alkhoury, P., Aït-Ahmed, M., Soubra, A.-H., & Rey, V. (2022). Vibration reduction of monopile-supported offshore wind turbines based on finite element structural analysis and active control. *Ocean Engineering*, *263*, 112234. https://doi.org/10.1016/j.oceaneng.2022.112234

Den Hartog, J. P. (1985). *Mechanical Vibrations*. DOVER PUBLICATIONS.

Deraemaeker, A., & Soltani, P. (2017). A short note on equal peak design for the pendulum tuned mass dampers. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-Body Dynamics*, *231*(1), 285–291. https://doi.org/10.1177/1464419316652558

Fuentes, W., Gil, M., & Rivillas, G. (2021). A p–y Model for Large Diameter Monopiles in Sands Subjected to Lateral Loading under Static and Long-Term Cyclic Conditions. *Journal of Geotechnical and Geoenvironmental Engineering*, *147*(2). https://doi.org/10.1061/(asce)gt.1943-5606.0002448

Gerges, R. R., & Vickery, B. J. (2005). Optimum design of pendulum-type tuned mass dampers. *The Structural Design of Tall and Special Buildings*, *14*(4), 353–368. https://doi.org/10.1002/tal.273

Global Wind Energy Council. (2023). *GWEC Global Wind Report 2023*.

Soltani, P., & Deraemaeker, A. (2022). Pendulum tuned mass dampers and tuned mass dampers: Analogy and optimum parameters for various combinations of response and excitation parameters. *Journal of Vibration and Control*, *28*(15–16), 2004–2019. https://doi.org/10.1177/10775463211003414

Sun, C., & Jahangiri, V. (2018). Bi-directional vibration control of offshore wind turbines using a 3D pendulum tuned mass damper. *Mechanical Systems and Signal Processing*, *105*, 338–360. https://doi.org/10.1016/j.ymssp.2017.12.011