XLIV CILAMCE PORTO 2023

Using metamaterial to control offshore wind turbine vibrations

Marcela R. Machado[1,2], Maciej Dutkiewicz[1],

[1]*Faculty of Civil, Environmental Engineering and Architecture, Bydgoszcz University of Science and Technology*
Al. Prof. Sylwestra Kaliskiego 7, Bydgoszcz,Poland
marcelam@unb.br, macdut@pbs.edu.pl
[2]*University of Brasília - Campus Universitário Darcy Ribeiro, Faculdade de Tecnologia*
Asa Norte, 70910-900, Brasília - DF Brazil

Abstract. Wind energy is one of the renewable sources in fast development and implementation worldwide. Developing competitive renewable energies and energy supply networks, e.g. offshore wind turbines (OWT), is essential to guarantee a sustainable power supply in cities and megacities. In these scenarios, a reliable energy supply is crucial. These large and flexible structures are vulnerable to external vibration sources such as wind, sea waves and earthquake excitation. It is necessary to mitigate the dynamic responses of offshore wind turbines to ensure the safety of these structures. The OWT selected is a National Renewable Energy Lab (NREL) monopile 5 MW baseline wind turbine. This OWT is a conventional three-bladed variable-speed, pitch-to-pitch, upwind-controlled turbine. This paper explores using metamaterial to control vibrations from offshore wind turbine tower modes. The effectiveness of the proposed control is numerically investigated. The outcomes reveal the benefit of using the metamaterial compared to conventional tuned damped mass passive controls.

Keywords: Wind turbine dynamic analysis, Metastructure, Vibration control, Tuned mass damper.

1 Introduction

One of the renewable energy sources that is rising in development and use globally is wind energy. In the past ten years, worldwide countries have installed a remarkable amount of wind farms. Wind energy production depends on steady wind occurrences of the proper strength and free of hidden variations in speed or direction. In 2021, new WT installation reached 93.6 GW, with 72.5 GW generated onshore and 21.1 GW generated offshore. The global WT market expects to grow US$ 102.4 billion by 2030. Within the next five years, the Compound Annual Growth Rate (CAGR) predicts global output of 466 GW from new onshore WT installations and 90 GW from offshore WT capacity [1]. In May 2022, the European Union (EU) Commission proposed in the REPowerEU plan to increase renewable energy share and consumption to 45% to reduce reliance on fossil fuels further [2].

The selected wind turbine (WT) is a 5 MW baseline designed by the National Renewable Energy Laboratory (NREL) [3], used as a reference by research teams worldwide to standardise the specifications of baseline offshore wind turbines and quantify the benefits of advanced onshore and offshore wind energy technologies. The vibration of the WT is a complex multi-coupling phenomenon affected by several types of vibration features. Nevertheless, the important ones impact the blades, directly affecting the gearbox and nacelle. Multiple loads induce blade vibrations, such as wind turbulence, wind shear, gravity, mass and aerodynamic imbalances. Unsteady loads might lead to blade structural resonance, fatigue damage, and lifetime reduction, contributing to possible structural failure. The tower vibration originates from the coupled wind–rotor–tower system, mechanical transmission twist vibration, and rotor rotation, resulting from the loads, as mentioned above. Additionally, the effect of the waves on offshore wind turbines (OWT) should be considered. Wind turbine vibrations might threaten the environment, community business interests, and land itself [4], which must be monitored continuously.

This paper explores using metamaterial to control vibrations from offshore wind turbine tower modes. The effectiveness of the proposed control is numerically investigated. The outcomes reveal the benefit of using the metamaterial compared to conventional tuned damped mass passive controls.

2 Spectral wind turbine model

The spectral element method (SEM) is a mesh method similar to the finite element method with its shape function established from the exact solution of the wave equation formulated in the frequency domain [5]. The spectral model of the WT proposed in [6] has been modelled within the NREL 5-MW baseline monopile WT as represented in Fig. 1(a).

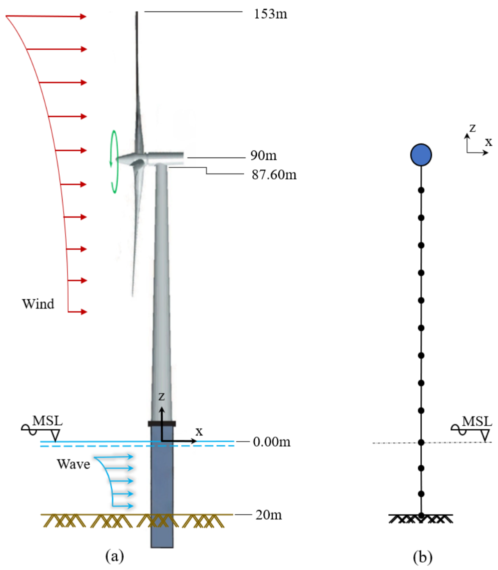


Figure 1. NREL 5 MW monopile offshore wind turbine schematic representation (a), and OWT spectral element model representation (b).

The spectral model consists of a beam element coupled to a lumped mass representing the slender tower and the rotor-nacelle, shown in Fig. 1(b). Only a spectral element can be assumed in the tower mesh for the model considering a continuous tower. In the case of the tapered shape of the tower, the element mesh is split by the number of reduced sections considered on the tapped tower model. The spectral representation of the OWT equation of motion in the frequency domain is obtained as

$$EI\frac{d^4\hat{v}}{dz^4} + \omega^2\left[\rho A + \tilde{m}_n\delta(z-L)\right]\hat{v} = \hat{q}$$

where E, I, ρ, and A are Young's modulus, inertia moment, mass density per unit length, and cross-section area, respectively; $\tilde{m}_n = m_n/EI\beta^3$, $\delta(z-L)$ is Dirac's delta at $z = L$. The hysteretic damping is introduced into the beam formulation by adding the damping factor (η) into Young's modulus (E) so that $E = E(1 + i\eta)$, where $i = \sqrt{-1}$; L is the OWT height, v and q are the transversal displacements and external load, respectively. The general solution of the spectral displacements follows the relationship

$$\hat{v}(z) = \sum_{i=1}^{4} a_j e^{-ik_j z} = \mathbf{s}(z,\omega)\mathbf{a} \tag{1}$$

where

$$\mathbf{s}(z,\omega) = [e^{-ik_1 z}, e^{-ik_2 z}, e^{-ik_3 z}, e^{-ik_4 z}], \qquad \mathbf{a} = [a_1, a_2, a_3, a_4]^T$$

the homogeneous differential equation with constant properties along the beam length, which is written in the spectral form as

$$\frac{d^4\hat{v}}{dz^4} - \beta^4\hat{v} = 0, \qquad \beta^2 = \omega\left(\frac{\rho A}{EI}\right)^{1/4} \tag{2}$$

the solutions of the form $e^{-i\beta z}$, the wavenumber β related to propagating and evanescent waves is $k_{1,3} = \pm\beta$ and $k_{2,4} = \pm i\beta$, respectively. By considering a finite structure with length l_e, the spectral nodal displacements in terms of a_j, which satisfy the boundary conditions of the system, where the spectral nodal displacements and slopes are obtained at the nodes so that at node 1 ($z = 0$) and node 2 ($z = l_e$). By applying the boundary conditions, the displacement in a matrix form is expresses as

$$\mathbf{d} = \begin{bmatrix} \hat{v}_1 \\ \hat{\phi}_1 \\ \hat{v}_2 \\ \hat{\phi}_2 \end{bmatrix} = \begin{bmatrix} \hat{v}(0) \\ \hat{v}'(0) \\ \hat{v}(l_e) \\ \hat{v}'(l_e) \end{bmatrix} = \begin{bmatrix} s(0,\omega) \\ s'(0,\omega) \\ s(l_e,\omega) \\ s'(l_e,\omega) \end{bmatrix} \mathbf{a} = \mathbf{G}(\omega)\mathbf{a} \tag{3}$$

where

$$\mathbf{G}(\omega) = \begin{bmatrix} 1 & 1 & e^{-ikl_e} & e^{-kl_e} \\ -ik & -k & ie^{-ikl_e}k & e^{-kl_e}k \\ e^{-ikl_e} & e^{-kl_e} & 1 & 1 \\ -ie^{-ikl_e}k & -e^{-kl_e}k & ik & k \end{bmatrix}$$

The frequency-dependent displacement within an element is interpolated from the nodal displacement vector $\mathbf{d}$ by eliminating the constant vector $\mathbf{a}$ from equation (3) express the solution of the form $v(z,\omega) = \mathbf{g}(z,\omega)\mathbf{d}$, where $\mathbf{g}(z,\omega)$ is shape function described by

$$\mathbf{g}(z,\omega) = \mathbf{s}(z,\omega)\mathbf{G}^{-1}(\omega) = \mathbf{s}(z,\omega)\mathbf{\Gamma}(\omega) \tag{4}$$

By considering $\rho A\omega^2 = EIk^4$ and substituting in equation. 1, the weak form can be derived from weight-integral to obtain the dynamic stiffness matrix for the two-nodes beam element by,

$$\mathbf{S}(\omega) = EI\left[\int_0^L \mathbf{g}''(z)^T\mathbf{g}''(z)dx + k^4\int_0^L \mathbf{g}(z)^T\mathbf{g}(z)dz + \omega^2k^3m_n\right] \tag{5}$$

where $'$ expresses the spatial partial derivative.

2.1 Control system

The utilization of tuned mass dampers (TMD) or dynamic vibration absorbers (ADV) is a well-liked technique for passively managing wind turbine vibrations, owing to its simplicity and effectiveness. Generally, this approach works within two resonant frequencies and can be influenced by where it's positioned on the structure. Many structures have integrated metamaterials to enhance their characteristics and operational performance. This research explores the use of metamaterials to decrease the vibration levels of wind turbines. The turbine metastructure involves placing the resonators periodically along the wind turbine's tower. The resonator is engineered to control the wind turbine's first resonant frequency at 0.27 Hz. These resonators have been set up inside the wind turbine's tower, as demonstrated in the cross-sectional view of the tower in Fig.2(middle). The metaturbine is illustrated in Fig.2(left), and the spectral OWT representation containing thirteen elements and resonators is shown Fig.2(rigth).

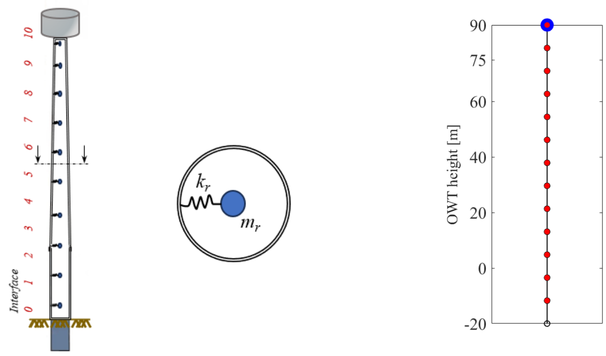


Figure 2. OWT metamaterial on the left, cross-sectional view of the tower in the middle, and spectral OWT representation containing thirteen elements and resonators(red dots) on the right.

The tuned frequency of the resonator is the relation of its stiffness (k_r) and mass (m_r) parameters and can be expressed as

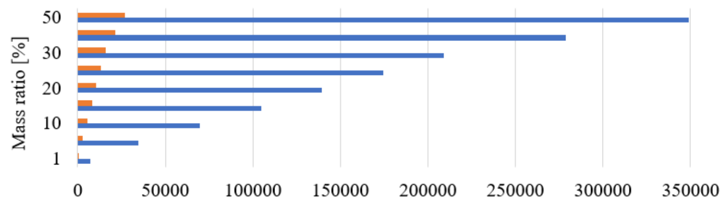
$$\omega_r = \sqrt{\frac{k_r}{m_r}} \quad r = 1, 2, ..., N \tag{6}$$

3 Numerical results

Based on the 5 MW baseline wind turbine monopile, the tower model is considered a continuous diameter beam coupled to a lumped mass as illustrated in Fig. 2. The mass of the rotor-nacelle assembly has 350 tons, a tower height of 107.6 m, an average tower diameter of 6.6 m, a tower wall thickness of 0.6 m, Young's modulus of 210 GPa, and a density of 8500 kg/m^3. It assumed a fixed base neglecting the soil-structure interaction. Thirteen elements and resonators were assumed in the spectral model mesh.

The metamaterial wind turbine control performance is compared with the classical TMD control configuration installed at the WT's tower top. A hysteretic damping of $\eta = 0.03$ is imposed in the resonator's spring, and they are attached periodically along the OWT (fig.2). For instance, no external loads e.g. waves, wind and blade rotation, are considered. The total mass ratio varies from 1 to 50%, a unitary excitation force is located at the free end (interface point-10), and the receptance responses estimated along the turbine's tower interface are guided by the points from 0 to 10 of Fig. 2(left).

Previous research has focused on placing TMDs at the top of offshore wind turbines, where the first frequency mode shape experiences significant displacement. While this solution effectively controls the target frequency and bandwidth, it requires adding a significant amount of mass and stiffness to the turbine, typically ranging from 5% to 28% of the turbine's mass. Constructing, installing, and repairing these TMDs remains challenging due to their associated mass and space requirements in the nacelle or inside the turbines. In contrast, using metamaterials to mitigate offshore wind turbine vibration presents a novel design solution that reduces the complexity of control operations by significantly reducing the mass of the resonators while maintaining their effectiveness. By varying the mass ratio from 1% to 50% of the WT mass, each mass resonator is displayed in Figure 3. It shows the relation of TMD and metamaterial control solution in the single resonator mass ratio function. Both control has similar mass ratio, but the mass of each resonator is drastically reduced. However, for the metamaterial control, 13 resonators are used.



	1	5	10	15	20	25	30	40	50
Metamaterial	537	2683	5365	8048	10730	13413	16095	21461	26826
TMD	6975	34873	69746	104619	139492	174365	209238	278984	348730

Resonator weight [Kg]

Figure 3. TMD and metamaterial control solution varying the mass ratio from 1% to 50% of the OWT mass. The mass of a single resonator is displayed in the figure and table as the mass ratio of the control changes. Both control has similar mass ratio. TMD assumed only one resonator, while the metamaterial 13 resonator is periodically placed along the tower.

Usually, the TMD or resonator operates at a certain frequency. The dynamic coupling between the resonators and the main structure divides the controlled resonance mode shape, creating more degrees of freedom around the target mode shape. As a result, other resonance frequencies emerge on either side of the primary system's operating frequency, which the resonators manage. This passive vibration control works within a specific range, and when it goes beyond this range, it can lead to undesirable outcomes, such as an increase in the amplitude of neighbouring modes. Figure 4 compares the TMD (LHS) and metastructure (RHS) controlling the first resonant frequency with mass ratio (ϵ) varying from 1 to 50%. The concept of acoustic metamaterial relies on the notion of infinite resonators, wherein the simple expression for the bandgap occurs precisely when the number of resonators (n) approaches infinity. However, in practical scenarios, the number of resonators (n) takes on a finite value, as observed in [7]. The mass ratio directly influences the attenuation bandwidth, but this effect saturates and cannot be expanded further by increasing the mass. As a result, all control efforts induce a division in the target mode shape, creating a localized bandgap. The Tuned Mass Damper (TMD) displays a wider frequency bandwidth split among

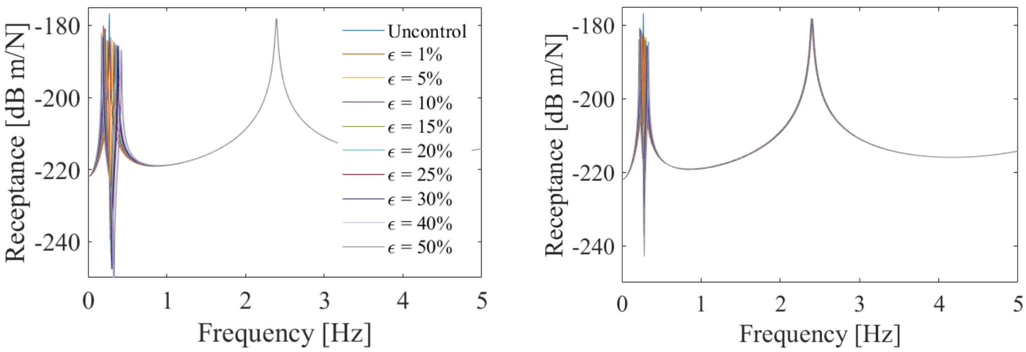


Figure 4. Receptance response of the OWT controlled by the TMD (LHS) and metamaterial (RHS), both assuming mass ratio varying from 1% to 50%.

these properties. This characteristic is observed most prominently when the device is placed at the top section of the turbine, which is mostly impossible because of other components already installed in the OWT nacelle. The proposed control based on the metamaterial shows a good performance in controlling the target resonant frequency, with the advantage of the resonators being displaced along the tower and the reduced mass and stiffness associated with each one.

4 Conclusions

This work investigated vibration mitigation employing a metamaterial in the OWT design. We calculated the dynamic response of the turbine with and without control using the Spectral element method. For an application study case, we considered the NREL 5 MW monopile OWT assuming all functional features and links with the working system present in [4]. The WT metamaterial has shown to be an efficient solution to mitigate vibration and the traditional TMD with an advance of reducing the resonator size in comparison with the TMD without losing efficiency in the vibration mitigation.

Acknowledgements. The authors would like to acknowledge the research support of the POLONEZ BIS project SWinT, reg.no. 2022/45/P/ST8/02123 co-funded by the National Science Centre and the European Union Framework Programme for Research and Innovation Horizon 2020 under the Marie Skłodowska-Curie grant agreement no.945339. M.R. Machado would like to acknowledge the support from the FAPDF and CNPq(Grants no.00193-00000766/2021-71 and no. 404013/2021-0).

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors or has the permission of the owners to be included here.

References

[1] GWEC. Global wind report annual market update 2019. Technical report, Global Wind Energy Council, 2020.
[2] J. Jonkman, T. Larsen, A. Hansen, T. Nygaard, K. Maus, M. Karimirad, Z. Gao, T. Moan, I. Fylling, J. Nichols, M. Kohlmeier, J. Vergara, D. Merino, W. Shi, and H. Park. Offshore code comparison collaboration within iea wind task 23:phase iv results regarding floating wind turbine modeling: 2010 european wind energy conference (ewec) 20-23 april 2010, warsaw, poland, april 2010. European Wind Energy Conference : EWEC2010, EWEC2010 ; Conference date: 20-04-2010 Through 23-04-2010, 2010.
[3] J. Jonkman, S. Butterfield, P. Passon, T. Larsen, T. Camp, J. Nichols, J. Azcona, and A. Martinez. *Offshore code comparison collaboration within IEA wind annex XXIII: Phase II results regarding monopile foundation modeling*. National Renewable Energy Laboratory (NREL), 2008.
[4] J. M. Jonkman, S. Butterfield, W. Musial, and G. Scott. *Definition of a 5-MW reference Wind Turbine for Offshore System Development [electronic resource]*. National Renewable Energy Laboratory, 2009.
[5] U. Lee. *Spectral Element Method in Structural Dynamics*. John Wiley & Sons, Ltd, 2009.

[6] G. B. Colherinhas, Girao de M. V. Morais, and M. R. Machado. Spectral model of offshore wind turbines and vibration control by pendulum tuned mass dampers. *INTERNATIONAL JOURNAL OF STRUCTURAL STABILITY AND DYNAMICS*, vol. 22, n. 05, 2022.
[7] C. Sugino, S. Leadenham, M. Ruzzene, and A. Erturk. On the mechanism of bandgap formation in locally resonant finite elastic metamaterials. *JOURNAL OF APPLIED PHYSICS*, vol. 120, n. 13, 2016.