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INTEGRATED SIZING AND VIBRATION CONTROL OF MONOPILE IEA-15MW BENCHMARK OFFSHORE WIND TURBINE

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Abstract

This study advances offshore wind turbine (OWT) design through an integrated structural optimization and vibration control strategy, demonstrated on the IEA-15MW benchmark OWT with monopile foundation. The proposed strategy aims to reduce the constructional steel use in the OWT supporting tower and monopile by leveraging the structural motion control achieved by tuned mass dampers (TMDs). First, minimum weight optimal sizing of OWT tower and monopile is undertaken for a target natural frequency. Next, optimal tuning of an omnidirectional TMD located at the top of the tower is carried, followed by performance assessment of the TMD-equipped OWT. The assessment utilizes high-fidelity, time domain, fully coupled aero-hydro-servo-elastic code OpenFAST models, while low-order dynamic OWT model is considered for TMD tuning. The redesigned support structure has 19.42 % less mass as compared to the benchmark 15 MW OWT. Time domain numerical simulations reveal the TMD's efficacy in suppressing structural vibrations of redesigned OWT for a TMD with a mass ratio of 3% without exceeding stroke constraints.

Keywords: Optimal Sizing, Offshore Wind Turbines, Tuned Mass Damper, Structural Motion Control.

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1 INTRODUCTION

Achieving global targets for carbon neutrality by 2050 hinges on the rapid deployment of renewable energy technologies, with wind power being a cornerstone of this transition. To address the increasing demands for renewable energy generation, the wind energy sector is pushing for higher power capacity offshore wind turbines (OWTs) with evermore taller and slenderer supporting towers and larger rotors. A representative example is the recent benchmark IEA-15MW-RWT developed by NREL with 150 m hub height and 240 m rotor diameter [1]. The design and fabrication of such large-scale OWTs require thicker steel sections in their support structures which increase material demands and embodied carbon emissions. For example, the support structure of the IEA-15MW-RWT weighs 2200 t, representing a 149 % increase compared to the support structure weight of the previous NREL 5 MW benchmark [1,2]. At the same time, OWT support structures represent a substantial, 20–25 %, fraction of the OWT total cost [3]. Therefore, sizing optimization of the OWT support structures can help with reducing the overall offshore wind costs including savings in material usage [4], which thus lowers embodied carbon emissions thereby contributing to more sustainable energy.

Apart from considerable material demands, large-scale OWTs (>12 MW capacity) are slender which makes them vulnerable to dynamic loads due to wind and waves, leading to excessive oscillations of OWT towers. Such oscillations reduce the fatigue life of structural components and the OWT power generation, while they might lead to collapse under extreme loading conditions [5]. Thus, the use of dynamic vibration absorbers, such as translational tuned mass dampers (TMDs) [6,7], pendulum-tuned mass dampers (PTMDs) [8,9], and inerter-based absorbers [10], widely considered for mitigating tower oscillations in smaller scale wind turbines (i.e. <10MW), seems to be a viable way forward to mitigate tower oscillations in large scale OWTs.

To this end, this paper presents the implementation of integrated redesign and TMD-based motion control approach on the benchmark IEA-15MW-RWT wherein, first, minimal weight structural optimization is carried out on the support structure of IEA-15MW-RWT to achieve a target first natural frequency, followed by employing a two degree of freedom (2DOF) system (optimally sized OWT + TMD) to obtain optimal stiffness and damping ratios of TMD. Dynamic performance assessment is carried out using a high-fidelity multi-physics model of the TMD-equipped redesigned OWT in OpenFAST simulation platform.

2 BENCHMARK 15 MW OFFSHORE WIND TURBINE AND REDESIGN CONSIDERATIONS

The IEA-15MW RWT specified in [1] is considered as the case study benchmark structure, representative of the large-scale OWTs currently under development by several manufacturers. It incorporates a 3-bladed, upwind, horizontal-axis rotor mounted on a monopile foundation with its base fixed at the mudline. The rotor spans 240 m in diameter, and each blade measures 117 m in length. The hub height is 150 m, while the tower height is approximately 130 m above mean sea level. The tower's outer diameter transitions from 10 m at its base to 6.5 m at its apex. The monopile foundation extends to a total length of 75 m with a constant outer diameter of 10 m; of this length, 45 m is embedded within the seabed and 30 m is submerged. The support structure of the benchmark OWT is designed such that the first natural frequency of the OWT is 0.17 Hz.

The design of the support structure of OWTs is based on a limit state design (LSD) philosophy. As per the design codes of practice for fixed bottom OWTs [11,12], the critical design requirements for monopile supported OWTs typically include (i) Ultimate Limit State: Checks for yielding and buckling (ii) Fatigue Limit State: Checks for fatigue damage under operational conditions (iii) Serviceability Limit State: Checks for vibrations and deflections and (iv) Resonance criterion: Natural frequency of OWT does not overlap with frequencies of environmental loads or rotor loads.

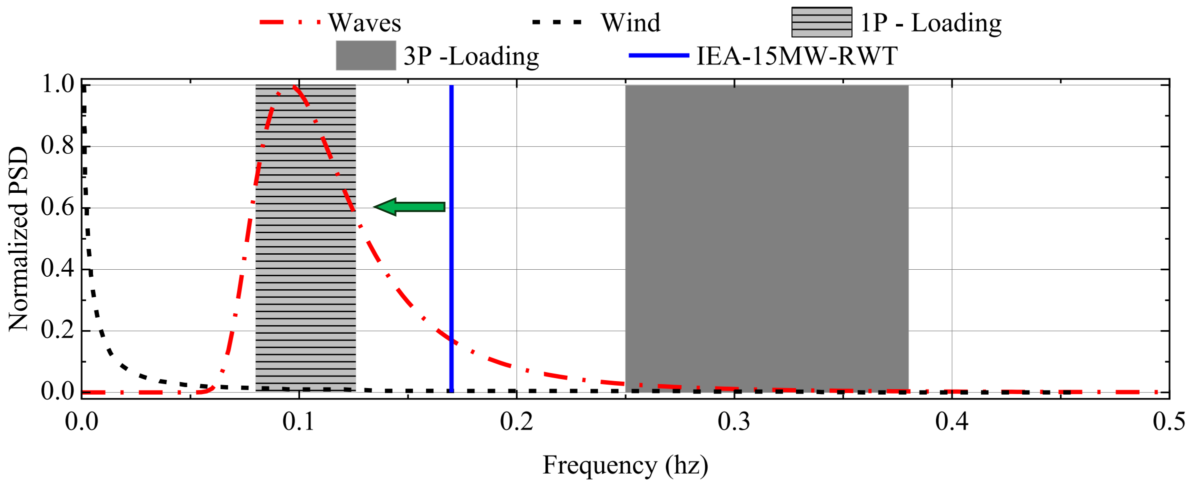

Figure 1: Normalized power spectral densities PSDs of various excitations and first fundamental natural frequency of the support structure (represented by vertical line) of IEA-15MW-RWT

The resonance criterion identifies the first fundamental natural frequency f_1 as a critical factor in designing OWT support structures. **Figure 1** shows the normalized power spectral density functions for the environmental and mechanical loads acting on the IEA-15MW-RWT. The rated wind speed of IEA-15MW-RWT is 10.59 m/s and wind loading spectra is represented by Kaimal spectrum. JONSWAP spectrum is used to characterize ocean waves, and it takes three key parameters as the input: (i) Significant wave height H_S (m) (ii) Peak period T_p (sec) and (iii) Wave Peak Shape γ. For severe sea state (SSS) typical of Northern Europe's waters, these parameters are quantified as $H_s = 9.25$ m, $T_p = 15.728$ sec and $\gamma = 1.708$ [13]. To address frequency constraints, the soft-stiff design approach is adopted in which f_1 lies between $1P$ and $3P$ loading frequency ranges, where $1P$ is rotor frequency and $3P$ is blade passing frequency. This approach requires that the natural frequency of the OWT should be sufficiently away from $1P$ frequency. Specifically, DNV standards [14] mandate that f_1 be at least 10 % above $1P$ upper limit. This mandate requires $f_1 \geq f_{thres} = 0.1386$ Hz for IEA-15MW-RWT. Notably, aiming for a low natural frequency design close to f_{thres} increases susceptibility to wave loading frequencies (see **Figure 1**), which can cause large oscillations and consequently accelerate fatigue damage accumulation. This is the reason why a relatively stiff design with $f_1 = 0.17$ Hz is chosen for the benchmark structure. Such considerations justify the integration of an omnidirectional TMD to suppress large support structure motions to enable safe design of a more flexible OWT support structure compared to the original benchmark IEA-15MW-RWT (see green arrow in **Figure 1**).

3 ADOPTED OPTIMIZATION DRIVEN DESIGN APPROACH

3.1 Optimal sizing of support structure (tower + monopile) of IEA-15MW-RWT

The optimal sizing of the support structure of the OWT is carried out using the Wind-plant Integrated System Design and Engineering Model (WISDEM), an open-source software package developed by NREL. A simplified finite element model of IEA-15MW is developed and 'pyFrame3DD' is employed to carry out modal analysis and static finite element analysis. The tower and monopile are discretized using frame elements, whereas the rotor nacelle assembly

(RNA) is modelled as a rigid body (mass at the top with eccentricity). These elements are assumed to be tapered, with linearly varying outer diameter and constant thickness throughout the element. The design variables, stored in vector **a**, are the outer diameters and thickness of the elements. The objective function seeks to minimize the total mass of the OWT tower and monopile, M, and it can be mathematically written as

$$\min_{\mathbf{a}} \left\{ M(\mathbf{a}) \right\}. \tag{1}$$

The minimum weight sizing of the support structure is constrained by a frequency constraint, and it is sized to a target natural frequency of 0.14 Hz, considering the design principles and criteria outlined in Section **2**. Furthermore, constraints for checking ultimate stress, global and shell buckling as specified by Eurocode Standards [15] are also imposed in the optimization process. Partial Safety Factors for material γ_M, loads γ_N and consequences of failures γ_F are assumed to be 1.3, 1.35 and 1.0, respectively (taken from [16]). The loads acting at the top of the tower in the design phase are summarized in **Table 1**.

Parameter (units)	Value
Tower top force along fore-aft direction (kN)	2.86×10^3
Tower top force along side-side direction (kN)	-4.40×10^2
Tower top force along vertical direction (kN)	-1.37×10^4
Tower top moment about fore-aft direction (kNm)	2.20×10^4
Tower top moment about side-side direction (kNm)	-9.85×10^4
Tower top moment about vertical direction (kNm)	-3.62×10^4

Table 1: Tower top loads for IEA-15MW-RWT considered in the optimal sizing [17]

3.2 Optimal tuning of tuned mass damper (TMD)

A simplified 2-DOF system is used to facilitate the calculation of tuning parameters of TMD, wherein the support structure of OWT is modelled as a generalized single degree of freedom system. Optimal tuning is pursued, aiming to minimize the tower top displacement variance under white noise excitation, given the mass ratio μ of the TMD (percentage of the total OWT mass), see e.g. [18]. Mathematically, the optimization problem for TMD tuning is formulated as

$$\min_{\mathbf{y}} \left\{ \int_0^{\omega_c} \left| H(\omega) \right|^2 d\omega \right\} \text{ with } \mathbf{y}^{min} \leq \mathbf{y} \leq \mathbf{y}^{max}. \tag{2}$$

where ω_c is the cut-off frequency above which the frequency response function of tower top displacement, $H(\omega)$, takes on negligible values. The vector **y** stores the design variables of the problem, namely TMD frequency ratio, ν, and TMD critical damping ratio ξ_d. The frequency response function of the 2-DOF system is given as

$$H(\omega) = \frac{(\nu^2 - g^2 + 2ig\nu\xi_d)\mu}{\left\{1 - g^2 + 2ig\xi\right\}\left(\nu^2 - g^2 + 2ig\nu\xi_d\right) - \left[\left(\nu^2 + 2ig\nu\xi_d\right)\mu\right]g^2}. \tag{3}$$

where $i = \sqrt{-1}$ and $g = \omega/\omega_n$, while ω_n and ξ, are the natural frequency and critical damping ratio of the generalized single degree of freedom system, respectively. The solution of the problem in Eq. (2) is obtained by an in-house pattern search routine to iteratively localize the optimal solution within the design domain [19]. The process continues until convergence is reached, in accordance with a specified tolerance value of 10^{-2}.

3.3 Time Domain Assessment in OpenFAST

For design assessment, the OpenFAST simulation environment is used to analyze TMD equipped 15 MW OWT with redesigned tower and monopile based on the IEA Wind Task 37 reference model, which is publicly available on Github (https://github.com/IEAWindTask37/IEA-15-240-RWT). Here, the benchmark OpenFAST model is modified to include the redesigned support structure and an omnidirectional TMD mounted at the top of the tower. Five different values of TMD mass ratio μ are considered varying from 1 % to 5 % of the total mass of the OWT and the secondary mass is allowed to undergo motion without any constraints on its displacement. Numerical simulations spanning 700 seconds are conducted under different metocean conditions, with the initial 100-second transient phase discarded to eliminate start-up artifacts from the generator and blade pitch control systems.

D LC	Wind velocity at hub height	Wave conditions
1.2	V_{hub} = 5, 8, 14 and 20 m/s	H_s = 0.75 m; T_p = 10.500 sec; γ = 1.000
1.6	V_{hub} = 5 m/s	H_s = 9.25 m; T_p = 15.789 sec; γ = 1.708
1.6	V_{hub} = 20 m/s	H_s = 9.25 m; T_p = 15.789 sec; γ = 1.708
6.1	V_{hub} = 29.63 m/s	H_s = 5.93 m; Tp = 13.024 sec; γ = 1.394
6.1	V_{hub} = 40.55 m/s	H_s = 9.25 m; T_p = 15.789 sec; γ = 1.708

Table 2: Metocean conditions for assessment of redesigned 15 MW OWT in OpenFAST.

The performance evaluation of the redesigned 15 MW OWT incorporates three critical Design Load Cases (DLCs: 1.2, 1.6, and 6.1) as specified in [12], which were shown to be most critical for the assessment of OWTs in previous studies [20,21]. DLC 1.2 corresponds to baseline power production under normal environmental conditions, representing the turbine's standard operational regime. DLC 1.6 pertains to power generation under extreme sea states, whereas DLC 6.1 simulates storm conditions when the turbine is idling with feathered blades. The relevant wind and wave loading parameters for these cases are summarized in **Table 2** taking values for a representative site from North Europe [13]. The worst-case response for each DLC is assumed to be representative of that particular DLC, and only this scenario is reported in the results for the sake of conciseness.

4 NUMERICAL APPLICATION

4.1 Optimally sized support structure of IEA-15 MW OWT

Following the optimal sizing methodology outlined in Section **3.1**, the first natural frequencies of the IEA-15MW OWT with the redesigned support structure are determined to be 0.1399 Hz in the side-side (SS) direction and 0.1408 Hz in the fore-aft (FA) direction. **Figure 2** plots the outer diameter and thickness distributions between the benchmark IEA-15MW-RWT design and the optimized redesigned configuration. The redesigned monopile exhibits a reduced diameter of 8.85 m compared to the benchmark's 10 m, consistently remaining smaller across its length. Its thickness profile is also reduced relative to the benchmark design. In this regard, the optimization process yields significant reductions in mass. The total mass of the optimized support structure is calculated at 1773 t: a 19.4% decrease from the original benchmark. A breakdown of these savings for both tower and monopile components is provided in **Table 3**. The total mass reductions achieved by various configurations of redesigned OWTs equipped with TMDs are presented in **Table 4**. When compared to the benchmark IEA-15MW-RWT, the findings reveal that a redesigned 15 MW OWT incorporating a TMD with a mass ratio of 5% exhibits a total mass reduction of 286 tonnes, equivalent to an 8.81% reduction.

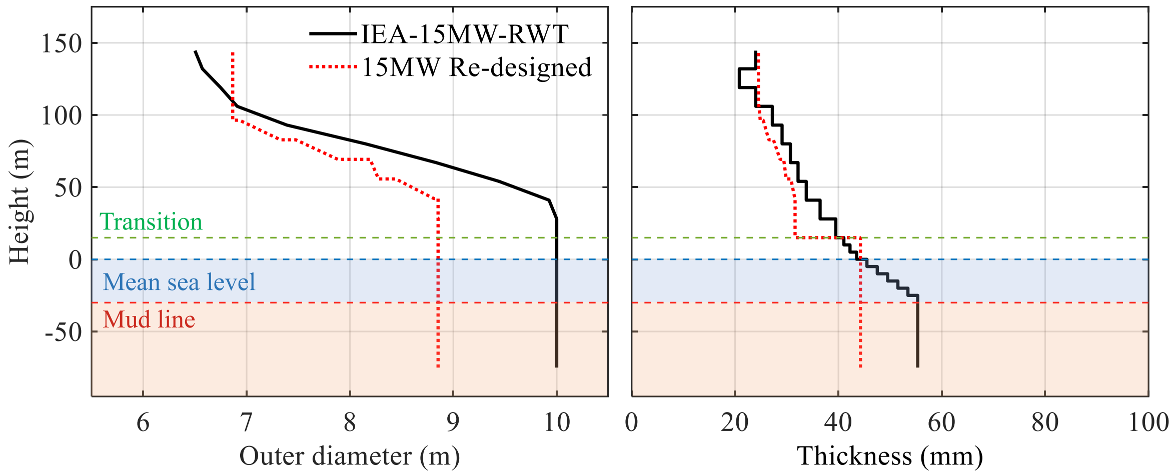

Figure 2: Comparison of outer diameter and thickness of monopile and tower of IEA-15MW-RWT and optimally sized 15 MW OWT.

Parameter	Initial	Optimal	Reduction (%)
Tower mass (t)	890.50	753.13	15.43
Monopile mass (t)	1309.95	1019.95	22.14
Total support structure (t)	2200.45	1773.08	19.42

Table 3: Mass and cost savings between original benchmark design and optimized design.

OWT configuration	Support structure mass (t)	TMD mass (t)	OWT mass (t)	Reduction (%)
IEA-15MW-RWT	2200.45	0	3250.23	-
15MW-OWT R-0	1773.08	0	2822.86	13.15
15MW-OWT R-1	1773.08	28.22	2851.08	12.28
15MW-OWT R-2	1773.08	56.46	2879.32	11.41
15MW-OWT R-3	1773.08	84.69	2907.55	10.54
15MW-OWT R-4	1773.08	112.91	2935.77	9.67
15MW-OWT R-5	1773.08	141.14	2964.00	8.81

Table 4: Mass of support structure, total OWT mass and mass reduction with respect to benchmark IEA-15MW-RWT for all the structural configurations considered.

4.2 Assessment of TMD-equipped redesigned 15 MW OWT

The structural performance of the redesigned OWT is investigated using time-domain simulations, as explained in Section **3.3**. **Figure 3** presents the standard deviation and peak values of the tower top displacement in SS direction of redesigned 15 MW OWT in comparison with the uncontrolled benchmark IEA-15MW-RWT. The reduced stiffness of the redesigned OWT manifests greater tower oscillations under uncontrolled conditions compared to the benchmark configuration. However, the addition of TMD demonstrates tower top motion suppression in the redesigned configuration depending on the DLC.

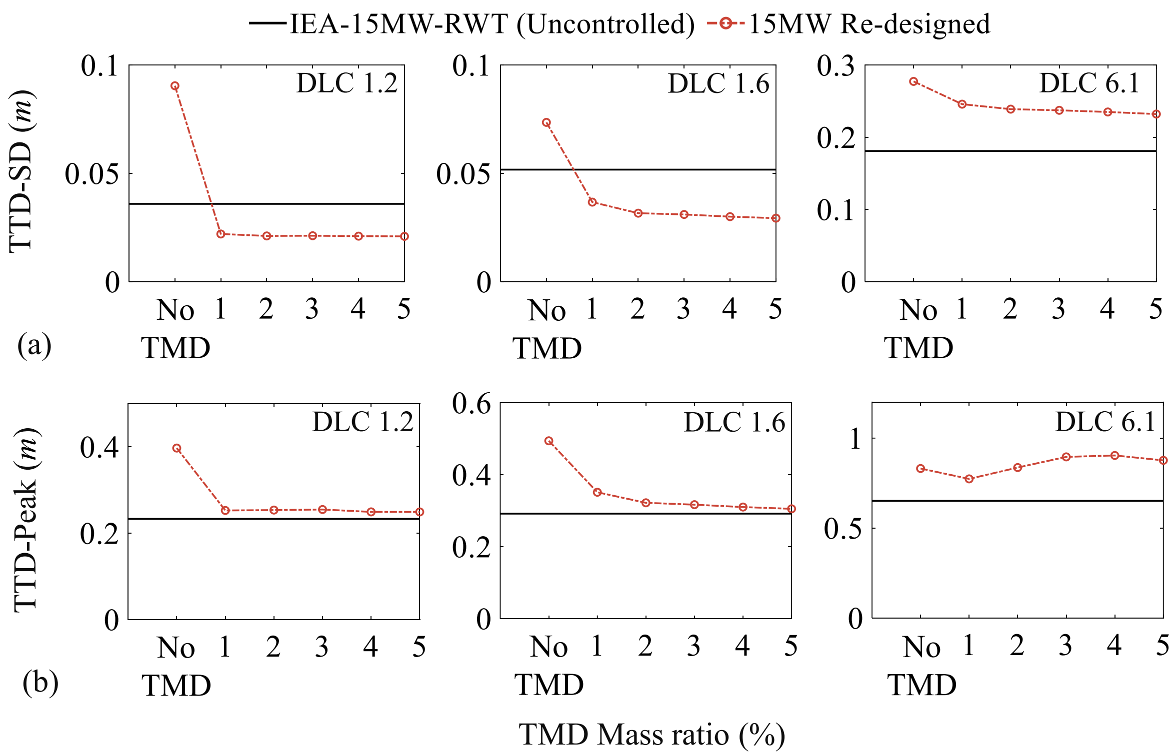

Figure 3: A comparison of tower top displacement (TTD) in SS direction between benchmark 15MW OWT and TMD equipped redesigned 15 MW OWT for three different DLCs. (a) Standard deviation (b) Peak

For DLCs 1.2 and 1.6, the addition of TMD demonstrates a substantial reduction in both standard deviation and peak tower-top displacement. Remarkably, even a minimal TMD mass ratio (μ = 1%) integrated into the redesigned 15 MW OWT reduces the standard deviation below the original benchmark design, while peak values are only slightly above the benchmark. For DLC 6.1, while the TMD contributes to reducing the standard deviation of SS displacement, it does not outperform the uncontrolled benchmark design. Additionally, under idling conditions, no reduction in peak values is observed with the implementation of a TMD. Instead, a TMD mass ratio μ = 4 %, show the highest value of peak TTD-SS equal to 0.90 m, representing an increase of 8.71 % compared to uncontrolled redesigned OWT.

The stroke of the tuned mass damper (TMD) is a critical parameter to ensure its safe integration and operation within the tower of the OWT. For the redesigned 15 MW OWT, the top diameter of the tower measures 6.865 m. To maintain adequate clearance for cables on either side of the tower, a maximum allowable TMD stroke of 3 m is specified, leaving approximately 0.4 m of clearance on each side. A TMD stroke exceeding 3 m is deemed impractical for integration at the tower's apex. **Figure 4** shows peak TMD strokes in SS direction for redesigned 15 MW OWT as μ varies from 1 % to 5 %. During DLCs representing operational power production scenarios (DLCs 1.2 and 1.6), TMD strokes remain well below the critical threshold, with higher μ yielding significant reductions in damper strokes. Under extreme loading conditions during idling state (DLC 6.1), strokes exceed permissible limits, reaching as high as 5.37 m and 3.6 m for μ = 1 % and μ = 2 %, respectively. Increasing mass ratio beyond these values effectively reduces the stroke to acceptable levels and at μ = 5%, the peak stroke decreases to 2.68 m. Therefore, a TMD with mass ratio of no less than 3% is recommended for achieving operational feasibility and optimal vibration control in the redesigned OWT for the herein considered site-specific metocean conditions and DLCs.

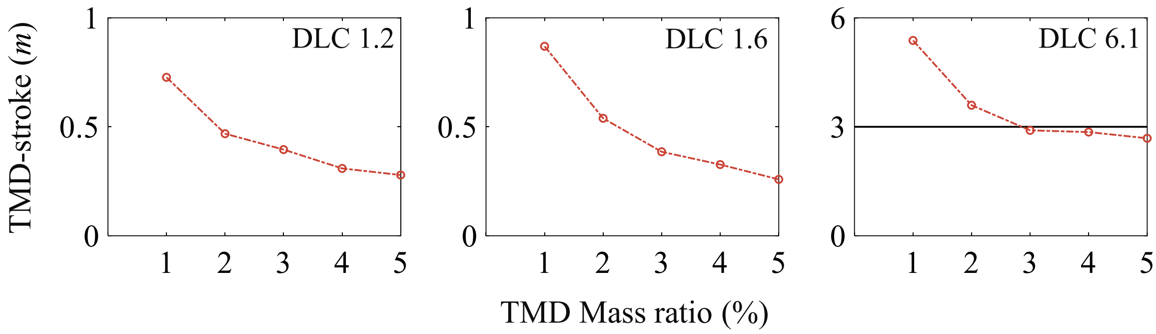

Figure 4: Peak values of TMD stroke (in SS direction) vs TMD mass ratio for optimally redesigned 15 MW OWT considering three different DLCs. The horizontal solid line in DLC 6.1 represents the threshold of 3 m for TMD stroke.

5 CONCLUSIONS

This study, based on the recent benchmark IEA-5MW-RWT, investigated the application of an integrated redesign and vibration control approach to achieve minimal structural mass for the support structure. The redesign approach involved minimal weight structural optimization of the support structure of IEA-15MW-RWT for a target natural frequency, which is 17.6 % lower than that of the benchmark design. Subsequently, an omni-directional TMD was considered to be installed at the apex of the tower to mitigate the vibrations of the redesigned support structure. Finally, the assessment of the structural performance of the TMD equipped redesigned OWT was carried out. The optimal tuning of the TMD was performed using a simplified 2-DOF dynamic model, in which the primary structure i.e., the OWT was represented as a generalized single-degree-of-freedom system. The variance of tower-top displacement under white noise excitation was minimized to determine the optimal stiffness and damping properties of the TMD. For the assessment of the re-designed OWT, time domain simulations were performed in OpenFAST against 3 critical DLCs representing different operational conditions of the OWT. Performance metrics included the standard deviation and peak values of tower-top displacement in SS direction. Additionally, TMD stroke amplitudes were analyzed to check for operational feasibility within practical constraints.

The presented numerical results indicate that optimizing the support structure for minimum weight with a target natural frequency of 0.14 Hz yields substantial benefits, including a 19.42% reduction in structural mass. The retrofitting of the redesigned OWT with a TMD highlighted its effectiveness in mitigating structural vibrations, especially during power generation phase. Under extreme environmental conditions, TMD strokes along the SS direction exceeded the operational limit of 3 m when secondary mass ratios were below 3 %. Increasing this ratio to 3 % or higher successfully relaxed the TMD strokes within acceptable limits. These findings position the integrated redesign and control strategy of support structure as a viable pathway for safe and sustainable development of next generation wind farms.

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