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OPTIMUM VIBRATION CONTROL OF OFFSHORE WIND TURBINES USING MTMD UNDER SIMULTANEOUS EFFECT OF WIND AND WAVE LOADS

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ABSTRACT

Considering the depletion of fossil fuel resources and their environmental impacts, offshore wind energy has emerged as a promising renewable solution. However, floating offshore wind turbines (FOWTs) are exposed to complex aerodynamic and hydrodynamic loads, particularly under combined wind and wave excitation, which can lead to excessive vibrations and fatigue damage. Therefore, effective vibration control strategies are essential to enhance structural reliability and durability. This study investigates the dynamic behavior and vibration mitigation of a floating offshore wind turbine supported by a Tension Leg Platform (TLP) under moderate, high, and extreme wind-wave conditions. A coupled model was developed using FAST-SC, and Multi-Tuned Mass Damper (MTMD) systems were implemented as passive control devices. The optimal MTMD parameters and installation layouts were determined, and their effectiveness in reducing tower and platform responses was evaluated. The results demonstrate that the optimized MTMD systems significantly improve the dynamic performance of the FOWT, achieving maximum reductions of 34% in tower fore-aft displacement, 43% in platform roll motion, and 41% in tower-base bending moment compared with the uncontrolled case. These reductions indicate the capability of MTMD systems to suppress structural vibrations, mitigate fatigue accumulation, and enhance the long-term reliability of offshore wind turbines. Consequently, the proposed approach has the potential to extend the service life of critical structural components and reduce maintenance requirements and life-cycle costs. This study provides valuable insights for the design of reliable and durable floating offshore wind turbines operating in harsh marine environments.

Keywords: Floating offshore wind turbine; Tension Leg Platform; Multi-Tuned Mass Damper; Passive vibration control; Dynamic response mitigation.

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1. INTRODUCTION

The continued growth in global energy demand has emphasized the need to restructure energy systems and increase the share of renewable resources to ensure sustainable energy supply [1]. The development of clean energy technologies and the transition toward low-carbon systems are essential pathways for mitigating climate change and achieving net-zero emission targets [2]. Wind energy has become a key component of this transition due to its high potential, environmental benefits, and scalability [3]. The development of modern wind turbines accelerated in the 1970s, resulting in increased capacity and improved performance, with horizontal-axis onshore turbines becoming a major technology for renewable electricity [4, 5]. The concept of offshore wind energy was first introduced in the 1970s by William E. Heronemus as an early attempt to extend wind power development beyond onshore applications [6].

Growing limitations of onshore wind development, including land availability, site constraints, and social acceptance issues, accelerated the transition toward offshore resources [7]. Due to higher and more stable wind conditions, offshore regions enable the deployment of larger turbines with improved capacity factors and greater energy yield [8].

Since the 1990s, advances in construction, installation, and operation technologies, supported by industrial investments, have accelerated offshore wind development in deeper and more remote regions. These improvements have transformed offshore wind from an emerging concept into a reliable technology for large-scale renewable electricity generation [9]. Global offshore wind capacity is projected to reach approximately 1000 GW by 2050, highlighting its important role in future sustainable energy systems [10]. Figure 1 illustrates the technological evolution of offshore wind turbines, showing the continuous growth in turbine size, capacity, and performance.

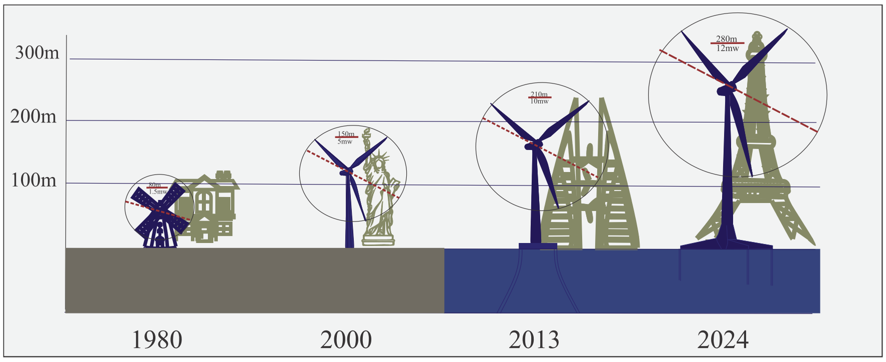

Figure1: Evolution of wind turbines

Offshore wind turbines are categorized into fixed-bottom and floating systems. Fixed-bottom foundations, including monopiles, jackets, and gravity-based structures, are mainly used in shallow waters [11]. In addition to the development of offshore wind technologies, structural optimization of supporting systems has received considerable attention. For fixed-bottom jacket structures, Kaveh and Sabeti showed that the CBO algorithm can significantly reduce structural weight while satisfying frequency constraints [۱۲]. Subsequently, CBO and ECBO algorithms were employed to optimize jacket structures under ULS and frequency

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limitations [13]. More recently, ECBO was applied to complex offshore platforms, successfully addressing buckling and stress constraints [14]. For deeper waters, floating offshore wind turbines provide a promising alternative where fixed-bottom systems face technical and economic limitations [15]. Floating concepts are mainly classified into spar, barge, and TLP systems [16]. TLP provide enhanced stability through vertical tension mooring, resulting in reduced wave-induced motions, structural loads, and lower pitch and roll responses compared with other floating concepts [17, 18].

Due to their large dimensions, structural flexibility, and exposure to combined wind, wave, and current loads, floating wind turbines represent highly complex dynamic systems. These environmental excitations can increase vibrations and accelerate fatigue damage, affecting structural reliability and service life [19]. The effects of dynamic responses on structural performance and fatigue behavior have been widely investigated [20], highlighting the need for advanced vibration analysis and control strategies [21]. To mitigate vibration effects, offshore wind turbines employ control strategies such as blade pitch control and structural control.

Although pitch control can regulate aerodynamic loads, power output, and rotor speed, its effectiveness in suppressing complex structural vibrations and resonance phenomena remains limited [22]. Therefore, structural control approaches have attracted increasing attention for improving the dynamic performance and long-term stability of offshore wind turbines under severe environmental conditions. Originally developed for civil engineering structures, these methods can be adapted to wind turbines to enhance structural response mitigation [23]. A 15% reduction in vibration amplitude of offshore structures has been reported to potentially double their service life, demonstrating the importance of vibration mitigation [20]. Structural vibration control methods are generally classified into passive, semi-active, active, and hybrid systems, each providing different advantages depending on structural characteristics, loading conditions, and design objectives [24]. Figure 2 presents the classification of vibration control strategies based on energy consumption and performance level.

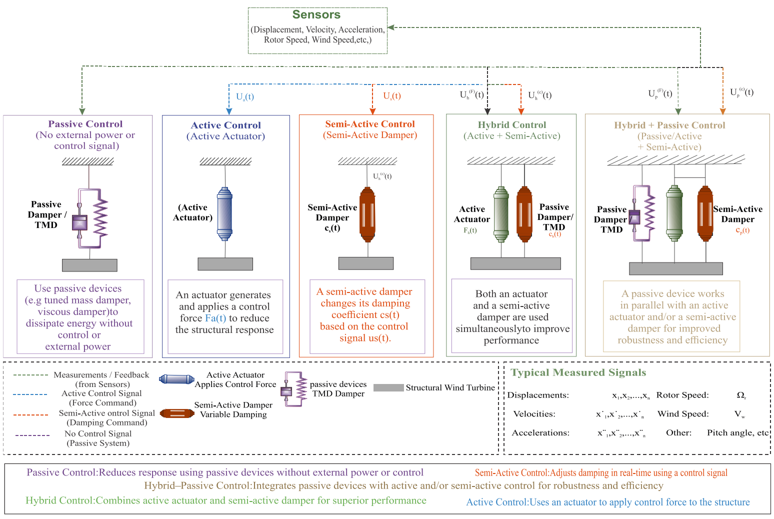

Figure 2: Classification of vibration control methods

However, offshore uncertainties can limit active and semi-active control performance due

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to their reliance on sensors, actuators, and external power. Passive control systems provide a reliable alternative by absorbing and dissipating vibration energy, thereby reducing structural responses under dynamic loading [25]. Several review studies have investigated passive vibration control and damper technologies for offshore structures and wind turbines. Sarkar et al. reviewed passive vibration control approaches for offshore structures under environmental loading [25]. Sarkar and Chakraborty summarized liquid damping technologies, including TLDs and TLCDs, for offshore structures and floating wind turbines [26]. Zhang and Huang reviewed damping technologies for offshore wind turbines, covering conventional and advanced damper configurations [2].

Furthermore, Fahimi-Farzam and Ziamehr reviewed passive vibration control strategies and highlighted the need for efficient vibration mitigation approaches for floating systems [27]. Among passive vibration control techniques, the TMD is one of the most widely applied solutions for structural vibration mitigation. First introduced by Frahm, the TMD consists of a secondary mass–spring–damper system tuned to the natural frequency of the primary structure, enabling vibration reduction through energy transfer and dissipation [28]. In offshore wind turbine applications, Stewart and Lackner investigated passive structural control approaches for floating wind turbines and highlighted the potential of TMD systems in reducing dynamic responses.

Tong et al. reported that optimized TMD configurations can significantly decrease tower vibrations [29], while Hussan et al. demonstrated improved mitigation using multiple TMDs compared with single-damper systems. Recent developments have focused on advanced TMD configurations. Laface et al. showed that a two-degree-of-freedom TMD installed on a spar-type floating wind turbine could reduce oscillations without retuning [30]. Ding et al. proposed a two-directional Tuned Liquid Column Damper (TTLCD) for floating wind turbines under combined wind and wave loading [31].

Fitzgerald et al. also reported enhanced vibration reduction using inertial damper configurations under critical dynamic conditions [32]. More recently, MTMD systems have attracted attention due to their robustness under complex environmental excitations. Du et al. demonstrated that optimized TMD systems can reduce structural loads and fatigue damage in offshore structures [33]. Liu et al. and Lu et al. confirmed the effectiveness of multi-TMD configurations in improving wind turbine dynamic performance and reducing low-frequency vibrations [34],[35]. Recent studies have further advanced passive vibration control strategies for floating offshore wind turbines.

Ziamehr and Fahimi-Farzam investigated a passive TMD system using FAST-SC and demonstrated significant reductions in structural responses under combined wind and wave loading [36]. Zhang et al. proposed hybrid damper configurations to enhance vibration suppression and structural stability [37], while Melo et al. showed that bidirectional TMD systems provide superior fatigue reduction and dynamic performance compared with conventional unidirectional dampers [38].

Despite these advances, comprehensive studies on MTMD applications in TLP based floating wind turbines remain limited. Although TLP platforms provide high stability through tensioned mooring systems and reduced pitch and roll motions, their coupled dynamics introduce challenges for vibration control under combined environmental loads. To accurately evaluate floating offshore wind turbine behavior, advanced aero-hydro-servo-elastic simulation tools are required. FAST, developed by the National Renewable Energy

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Laboratory (NREL), is widely used for offshore wind turbine simulations [39]. It enables coupled aerodynamic, hydrodynamic, structural, and control modeling through modules such as AeroDyn and HydroDyn. FAST-SC further extended this capability by enabling structural control analysis, including passive and active strategies [40].

The novelty of this study lies in applying an optimized MTMD system for vibration mitigation of a TLP-based floating offshore wind turbine using coupled FAST-SC simulations. Unlike previous studies focused mainly on fixed-bottom or other floating concepts, this research evaluates MTMD effectiveness in reducing tower and platform responses under combined wind and wave loading, aiming to enhance dynamic stability and fatigue performance for future deep-water offshore wind applications.

2. WIND TURBINE MODELING AND SOFTWARE

In this study, the 5-MW reference wind turbine developed by the NREL is adopted as the baseline model. This reference turbine has been extensively utilized in offshore wind energy research due to its representative aerodynamic, structural, and dynamic characteristics, providing a standardized framework for evaluating advanced control and vibration mitigation strategies.

For floating offshore wind turbines, the evaluation of tower-top responses is of particular importance, as these responses directly reflect the influence of environmental excitations on structural performance. The tower-top displacement is generally characterized by two dominant components: fore–aft motion, occurring along the wind direction, and side-to-side motion, perpendicular to the wind direction. The analysis of these displacement components provides essential information for assessing structural behavior and quantifying the effectiveness of vibration control systems. The schematic representation of tower-top displacement responses is illustrated in Figure 3.

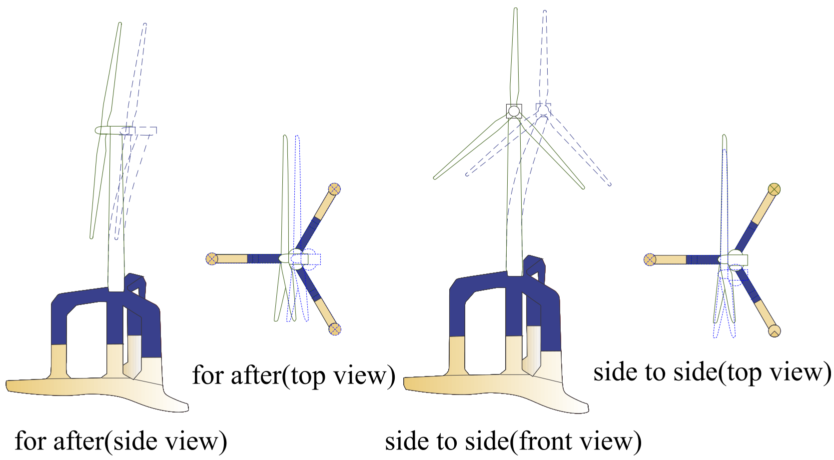

Figure 3: Tower-top displacement components under environmental loading

The selected floating support structure in this study is a TLP, which is recognized for its superior stability characteristics in deep-water offshore applications. The vertical tensioned

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tendon system provides strong constraints against heave and rotational motions, thereby reducing the overall dynamic response of the floating system. The six rigid-body degrees of freedom considered for the TLP platform include surge, representing longitudinal translational motion; sway, representing lateral translational motion; heave, representing vertical displacement; roll, pitch, and yaw, representing rotational motions about the longitudinal, transverse, and vertical axes, respectively. These platform motions are schematically presented in Figure 4.

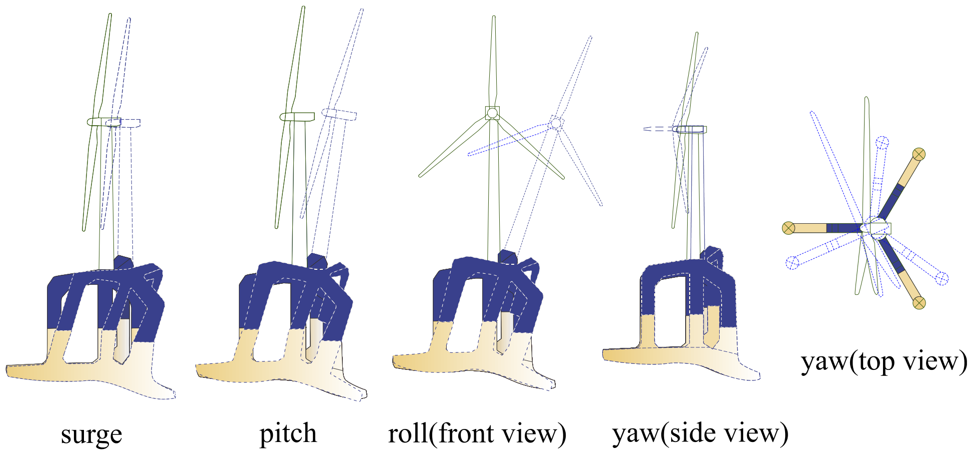

Figure 4: Schematic representation of TLP platform motions under environmental loading

The coupled dynamic response of the floating wind turbine under combined wind and wave loading is simulated using the FAST-SC software framework. FAST-SC is an extended version of the original FAST code, specifically developed to perform fully coupled aero-hydro-servo-elastic simulations of offshore wind turbines while incorporating structural control capabilities. This framework enables high-fidelity representation of the complex interactions among aerodynamic, hydrodynamic, structural, and control subsystems .The FAST-SC framework consists of several specialized modules, including AeroDyn and HydroDyn. AeroDyn calculates aerodynamic loads based on the Blade Element Momentum (BEM) theory, while HydroDyn evaluates hydrodynamic forces by considering the effects of buoyancy, added mass, radiation damping, and viscous drag. The equations of motion implemented in FAST-SC are formulated based on Kane's dynamics, which provides computational efficiency and effective handling of complex multibody dynamic systems. This capability makes FAST-SC a suitable tool for investigating the coupled dynamic behavior and control performance of floating offshore wind turbines.

A key capability of the FAST-SC framework is its ability to incorporate two independent TMDs simultaneously within the offshore wind turbine model. These dampers can be configured to operate independently along the X-axis (fore–aft direction) or Y-axis (side-to-side direction) and can be installed either inside the nacelle or on the floating platform. This flexibility enables targeted mitigation of critical vibration modes and provides various configurations for passive vibration control design. To facilitate control parameter optimization and post-processing analysis, MATLAB/Simulink was integrated with FAST-SC. This coupling provides an efficient environment for optimizing control parameters and processing the simulation outputs obtained from the aero-hydro-servo-elastic analyses. The

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governing equations implemented in FAST-SC are formulated based on Kane's method, which provides an efficient mathematical framework for analyzing complex multibody dynamic systems. These equations represent the fully coupled response of the offshore wind turbine by considering the interaction among aerodynamic, hydrodynamic, structural, and control forces. The general form of the equations of motion can be expressed as:

$$M\ddot{x} + C\dot{x} + Kx = F_{aero} + F_{hydro} + F_{TMD} \quad (1)$$

where M, C, and K represent the mass, damping, and stiffness matrices of the structural system, respectively, and x denotes the structural displacement vector. The external excitation terms include aerodynamic forces (**F_{aero}**), hydrodynamic forces (**F_{hydro}**), forces generated by the tuned mass dampers (**F_{TMD}**).

The aerodynamic loads acting on the turbine blades are calculated using the AeroDyn module based on the BEM theory. This approach considers aerodynamic effects such as axial and tangential induction factors, tip and root losses, and dynamic stall phenomena through appropriate aerodynamic models. The relative wind velocity at each blade element is determined as:

$$V_{rel} = \sqrt{(\Omega r(1 + a'))^2 + (V\infty(1 - a))^2} \quad (2)$$

where $V\infty$ represents the incoming wind velocity, Ω is the blade rotational velocity, r is the radial distance of the blade element from the rotation axis, and a and a′ are the axial and tangential induction factors, respectively.

The local angle of attack (α) is obtained from the difference between the inflow angle (ϕ) and the blade pitch angle (θ) as:

$$\theta - \emptyset = \alpha \quad (3)$$

To generate realistic turbulent wind conditions, TurbSim software was employed to produce three-dimensional stochastic wind fields. The generated wind data were subsequently transferred to AeroDyn to provide realistic aerodynamic excitation during the dynamic simulations. The hydrodynamic loads acting on the floating platform are calculated using the HydroDyn module. The total hydrodynamic force is expressed as:

$$\mathrm{F_{hydro}} = F_{\mathrm{buoyancy}} + F_{\mathrm{wave}} + F_{\mathrm{added\ mass}} + F_{\mathrm{drag}} + F_{radiation\ damping} \quad (4)$$

where F_{hydro} represents the total hydrodynamic force, $F_{buoyancy}$ is the restoring force caused by hydrostatic pressure, F_{wave} represents wave-induced excitation forces, $F_{added\ mass}$ accounts for the additional inertia resulting from fluid interaction with the structure, F_{drag} denotes viscous drag forces, and $F_{radiation}$ damping represents the damping force associated with wave radiation generated by structural oscillations. The complete simulation workflow of the floating offshore wind turbine system, including aerodynamic, hydrodynamic, structural, and vibration control components within the FAST-SC environment, is illustrated schematically in Figure 5.

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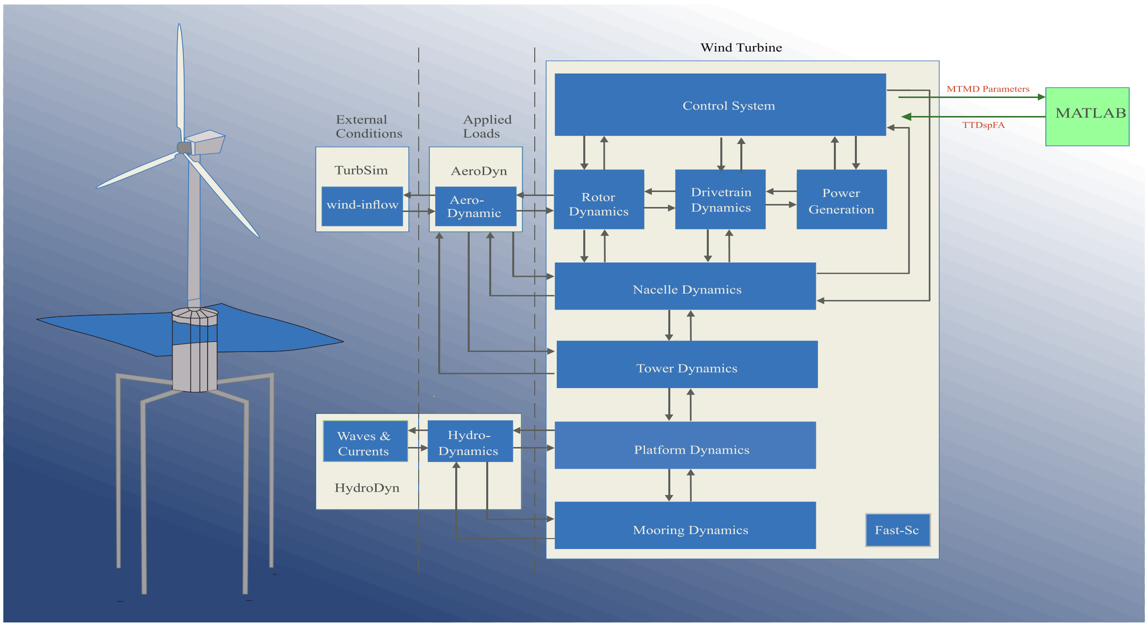

Figure 5: Overview of the FAST-SC framework simulations

3. WIND TURBINE AND TLP PLATFORM SPECIFICATIONS

For the numerical simulations conducted in this study, the NREL 5-MW reference wind turbine mounted on a floating Tension Leg Platform (TLP) was adopted as the baseline model. Owing to its well-established structural and aerodynamic characteristics, this reference model has been widely employed in offshore wind energy research.
The main technical specifications of the wind turbine, including its structural and aerodynamic characteristics, are summarized in Table 1. These parameters define the numerical model of the turbine used throughout the simulations.

Table 1: Technical specifications of the NREL 5-MW reference wind turbine [19]

Turbine Property	Specification
Rating power	5 MW
configuration	3 Blades
Hub height	90 m
Rotor diameter	126 m
Rotor mass	110000 kg
Tower mass	347460 kg
Nacelle mass	240000 kg
Turbine mass	697460 kg

The geometric and physical properties of the TLP support platform are presented in Table 2. These characteristics determine the floating platform configuration and mooring system,

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which significantly influence the hydrodynamic behavior and dynamic response of the offshore wind turbine under combined wind and wave loading.

Table 2: Properties of the TLP platform [41]

Platform Properties	Specifications
Platform mass	8600 ton
Platform draft	89.47 m
Number of mooring lines	8 (4 pairs)
Mooring line length	151.73 m
Water depth	200 m

4. WIND AND WAVE LOADING SCENARIOS

To evaluate the dynamic performance of the floating offshore wind turbine, three environmental loading scenarios corresponding to moderate, high, and very high wind conditions were considered. Realistic turbulent wind fields were generated using TurbSim, which produces three-dimensional stochastic wind profiles with appropriate spatial and temporal turbulence characteristics. The generated wind fields were subsequently imported into FAST-SC as aerodynamic input. Wave loads were modeled using the JONSWAP wave spectrum implemented in FAST-SC, enabling realistic simulation of offshore wave conditions by automatically determining the corresponding wave height and peak period for each wind scenario. Each simulation was performed for 300 s to ensure stable dynamic responses and adequate statistical convergence. Moreover, the wind and wave propagation directions were assumed to be aligned (fore–aft) to represent the most critical loading condition. The environmental loading parameters adopted in the numerical simulations are summarized in Table 3.

Table 3: Wind and Wave Loading Parameters Used in the Simulations

Wind category	Wind speed (m/s)	Wave height (m)	Wave period (s)
Moderate	10	1.3	4.5
High	25	8	9.5
Very high	30	8	11

5. MTMD DESIGN AND IMPLEMENTATION

In this study, an MTMD system is designed and implemented to mitigate the dynamic responses of the floating offshore wind turbine supported by a TLP. The MTMD configuration is developed to target the dominant vibration modes of the coupled turbine–platform system and to improve the overall dynamic performance under combined environmental loading. To investigate the influence of damper placement on vibration mitigation efficiency, two independent TMD units are

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incorporated into the system with different installation locations. In the proposed configuration, one TMD is installed inside the nacelle to control the fore–aft (X-direction) tower vibrations, while the second TMD is mounted on the TLP platform to reduce side-to-side (Y-direction) platform-induced responses. The adopted MTMD arrangement is illustrated in Figure 6. A total mass ratio of 4% of the structural mass is assigned to the MTMD system, with the mass equally distributed between the two dampers. Accordingly, each TMD is designed with a mass ratio of 2% of the total structural mass. This configuration enables simultaneous mitigation of tower and platform vibrations while maintaining a practical implementation strategy for floating offshore wind turbines.

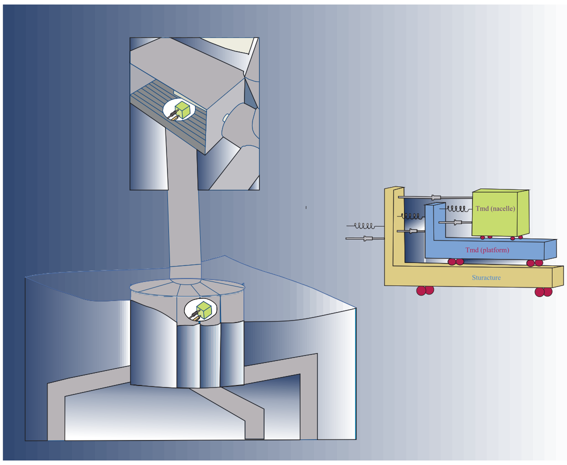

Figure 6: MTMD setup with TMD-X in the nacelle and TMD-Y on the TLP platform

In the second configuration, both TMD units are integrated within the nacelle and configured to target the dominant vibration modes of the tower in the fore–aft (X) and side-to-side (Y) directions, respectively in Figure 7. The corresponding TMD mass ratios are defined as 4% of the nacelle mass and 4% of the platform mass, enabling effective mitigation of coupled tower–platform dynamic responses.

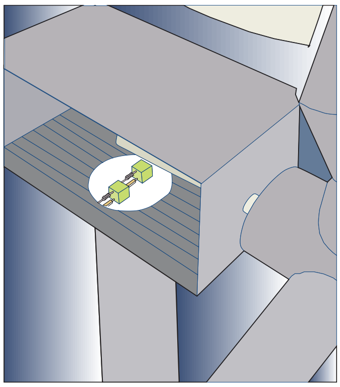
Figure 7: MTMD setup with TMD-X and TMD-Y on the nacelle

In both configurations, the TMD parameters, including mass, stiffness, and damping ratio, are optimized based on the dominant natural frequencies of the tower and platform in the corresponding directions. Fully coupled nonlinear simulations were conducted within the FAST-

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SC framework, enabling the simultaneous implementation of passive dampers along multiple vibration directions. The influence of damper placement on vibration mitigation performance is evaluated in the following results section. The obtained findings provide valuable insights into the selection of an effective MTMD configuration for improving the dynamic stability and fatigue performance of floating offshore wind turbines.

6. MTMD PARAMETER OPTIMIZATION

To improve the vibration control performance of the MTMD system, the principal design parameters of the TMD units, namely mass, stiffness, and damping, were optimized using a genetic algorithm (GA) implemented in MATLAB. The optimization process aimed to minimize the tower-top fore–aft displacement, which was selected as the primary objective function due to its significance in representing the dynamic behavior of the offshore wind turbine. The optimal TMD frequencies were determined by tuning them to the dominant structural frequencies through iterative nonlinear time-domain simulations performed in the FAST-SC environment.

In the proposed MTMD system, the individual TMD units were tuned to the dominant structural frequencies with slightly different tuning frequencies to provide a wider effective bandwidth for vibration suppression under combined wind and wave excitations. This tuning strategy improves the system's ability to mitigate multi-directional dynamic responses, including tower fore–aft and side-to-side vibrations, as well as platform motions such as pitch and roll. The optimal mass, stiffness, and damping parameters of each TMD unit were determined through an iterative optimization process integrated with nonlinear time-domain simulations in the FAST-SC environment.

Tables 4 and 5 present the optimized design parameters for the two MTMD configurations investigated in this study. Table 4 summarizes the optimized parameters for the configuration with both TMD units installed inside the nacelle, while Table 5 presents the corresponding parameters for the configuration consisting of one TMD installed in the nacelle and the other mounted on the TLP platform. These optimized parameters were subsequently used to evaluate the effectiveness of the proposed MTMD configurations in reducing the dynamic responses of the tower and floating platform under simultaneous wind and wave loading.

Table 4: Optimized MTMD Parameters – Nacelle Configuration

Parameters	**TMD-X (Nacelle)**	**TMD-Y (Nacelle)**
Mass (kg)	13900	13900
Stiffness (kN/m)	20.8	21.8
Damping (kN·s/m)	3.40	4.57

Table 5: Optimized MTMD Parameters – Nacelle and TLP Configuration

Parameters	**TMD-X (Nacelle)**	**TMD-Y (Nacelle)**
Mass (kg)	27900	344000
Stiffness (kN/m)	44.6	361.0
Damping (kN·s/m)	6.35	61.6

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7. RESULTS AND DISCUSSION

The effectiveness of the proposed MTMD system in mitigating the dynamic responses of the floating offshore wind turbine and its supporting TLP platform was evaluated through coupled FAST-SC simulations. Table 6 summarizes the percentage reduction in critical structural responses compared with the uncontrolled case for the two investigated MTMD configurations. The evaluated responses include tower-top displacements, tower base moment responses, and platform rotational motions, providing a comprehensive assessment of the vibration mitigation capability of the proposed control strategy.

Table 6: Percentage Reduction of Tower Responses Using MTMD

Response	Configuration(Location of TMD)	Wind Speed (m/s)		
		10	**25**	**30**
For-After Displacement	Nacelle-Nacelle	20%	13%	5%
	Nacelle-Platform	**34%**	**21%**	7%
Side to Side Displacement	Nacelle-Nacelle	23%	3%	3%
	Nacelle-Platform	22%	4%	3%
Tower Base Moment(X)	Nacelle-Nacelle	**41%**	11%	15%
	Nacelle-Platform	**38%**	12%	10%
Tower Base Moment(Y)	Nacelle-Nacelle	21%	13%	6%
	Nacelle-Platform	**35%**	**20%**	8%
Platform Roll	Nacelle-Nacelle	**43%**	5%	5%
	Nacelle-Platform	**39%**	8%	3%
PlatForm Pitch	Nacelle-Nacelle	21%	7%	4%
	Nacelle-Platform	31%	10%	7%

The results demonstrate that the MTMD system can effectively reduce both tower and platform responses; however, its performance is strongly influenced by the damper placement and environmental loading intensity. Under the moderate wind condition (10 m/s), which is close to the rated operating speed of the NREL 5-MW reference turbine (11.4 m/s), the highest control efficiency was achieved. The Nacelle–Platform configuration provided the most significant reduction in tower-top fore–aft displacement, reaching 34%, while the Nacelle–Nacelle configuration achieved a reduction of 20%. This superior performance indicates that distributing the dampers between the nacelle and the floating platform enables more effective interaction with the coupled tower–platform dynamic behavior.

In addition to translational responses, the MTMD system showed considerable effectiveness in controlling platform rotational motions. The maximum reduction in platform roll response reached 43% for the Nacelle–Nacelle configuration, while the Nacelle–Platform arrangement resulted in a 39% reduction. Similarly, platform pitch motion was reduced by up to 31% using the Nacelle–Platform configuration. These results highlight the capability of MTMD systems to mitigate not only tower vibrations but also the low-frequency rotational responses that significantly affect the dynamic stability of floating offshore wind turbines.

The tower-base bending moments were also considerably reduced. Under the moderate wind condition, the maximum reduction in tower base moment response reached 41% in the X-direction and 35% in the Y-direction, demonstrating the potential of MTMD systems to

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alleviate long-term structural damage caused by cyclic environmental loading. As the wind intensity increased to 25 and 30 m/s, the vibration mitigation efficiency decreased for both configurations. This behavior can be attributed to the increasing contribution of nonlinear aerodynamic and hydrodynamic effects, which alter the dominant response characteristics of the floating wind turbine system and reduce the effectiveness of fixed-parameter passive dampers. Nevertheless, the MTMD configurations continued to provide measurable reductions in structural responses, confirming their robustness under severe environmental conditions. A detailed comparison of the two MTMD arrangements and their influence on the overall dynamic performance of the floating wind turbine system is presented in Figure 8.

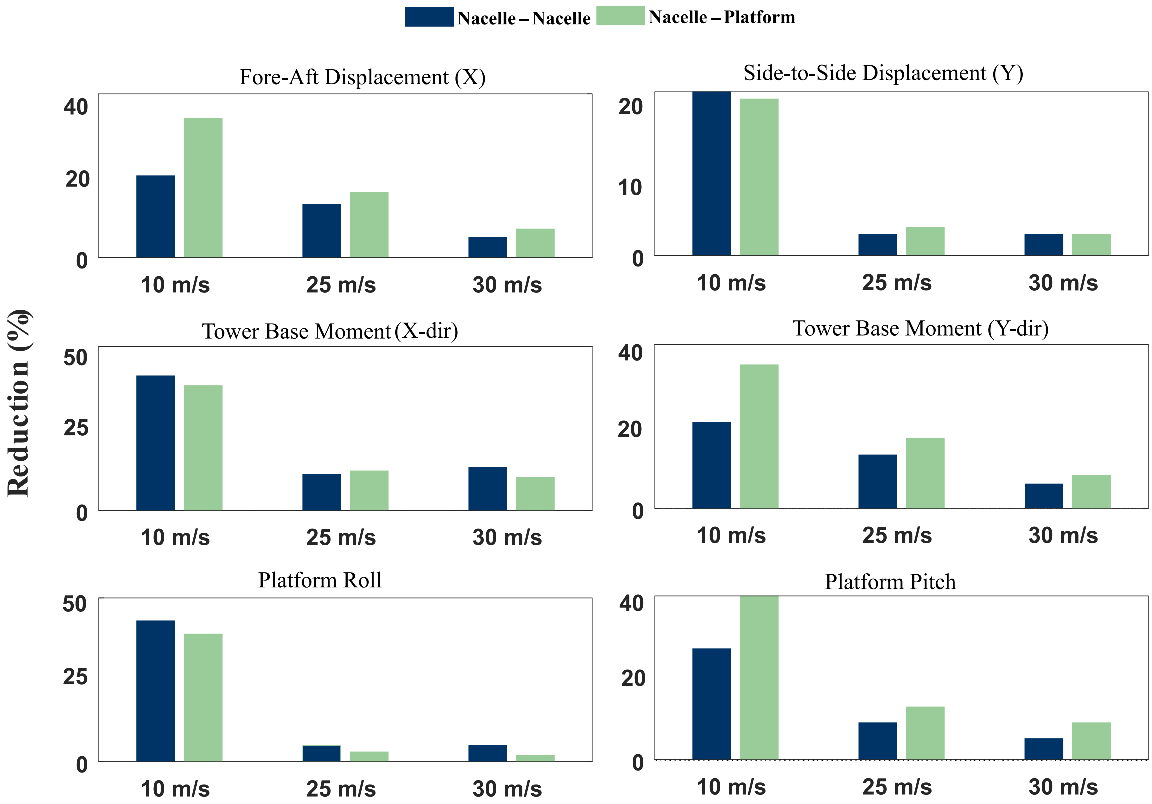

Figure 8: Comparison of responses for different TMD placements

The effectiveness of the proposed MTMD system in reducing the dynamic responses of the floating offshore wind turbine and TLP platform was evaluated through FAST-SC simulations. Table 6 summarizes the percentage reductions in tower-top displacement, tower base bending moment, and platform rotational responses compared with the uncontrolled case for both MTMD configurations. The results indicate that MTMD performance is strongly influenced by damper placement and loading intensity. Under the moderate wind condition (10 m/s), close to the rated speed of the NREL 5-MW turbine, the highest control efficiency was achieved. The Nacelle–Platform configuration reduced the tower-top fore–aft displacement by 34%, compared with 20% for the Nacelle–Nacelle arrangement, demonstrating the advantage of distributed damper placement in controlling coupled tower–platform dynamic behavior.

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The MTMD system also effectively mitigated platform motions, achieving maximum reductions of 43% in roll and 31% in pitch responses. Furthermore, the tower-base bending moment was reduced by up to 41% in the X-direction and 35% in the Y-direction. Since the tower-base bending moment is one of the primary indicators of fatigue loading, these reductions are expected to significantly mitigate fatigue accumulation caused by cyclic environmental loading. As wind intensity increased to 25 and 30 m/s, the mitigation efficiency decreased due to stronger nonlinear aerodynamic and hydrodynamic effects and variations in the dominant dynamic characteristics of the system. Nevertheless, both MTMD configurations maintained effective vibration reduction under severe conditions.

Overall, the Nacelle–Platform configuration provided superior performance, offering greater reductions in tower responses and platform motions due to improved interaction with the coupled structural modes and enhanced vibration energy dissipation. Figure 9 presents the time histories of tower-top fore–aft displacement and tower base bending moment, comparing the uncontrolled case with the optimized MTMD configuration under different wind conditions.

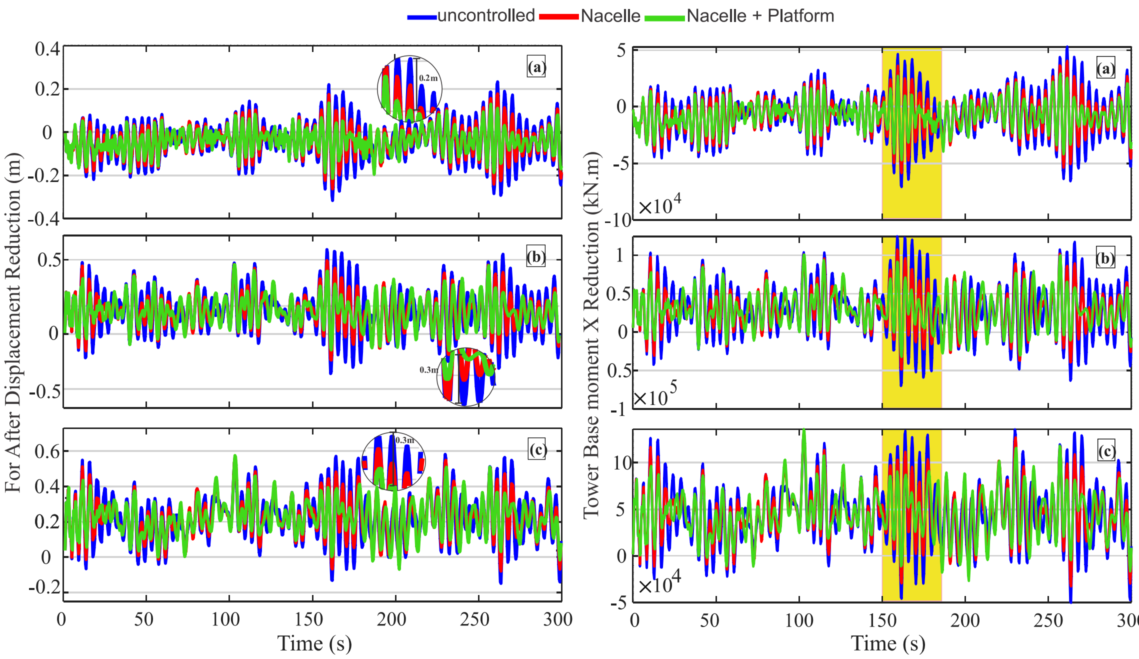

Figure 9: Comparison of responses for uncontrolled and MTMD-controlled cases under different wind speeds: (a) 10 m/s, (b) 25 m/s, and (c) 30 m/s

8. SENSITIVITY ANALYSIS

To evaluate the robustness of the optimized MTMD design and quantify the influence of parameter uncertainties, a sensitivity analysis was performed on the optimal Nacelle–Platform MTMD configuration. The analysis was conducted under three representative wind conditions of 10, 25, and 30 m/s, considering variations in the two critical design parameters of the MTMD system: tuning frequency and damping ratio. The selected parameters directly govern

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the effective stiffness and energy dissipation capability of the dampers and therefore have a significant influence on vibration control performance. The objective of this analysis was to investigate the sensitivity of the structural responses to deviations from the optimized MTMD parameters, particularly in terms of tower-top fore–aft displacement and tower base bending moment, which is a primary indicator of fatigue damage accumulation.

The sensitivity analysis was carried out by applying positive and negative variations around the optimized frequency and damping values. This approach enables evaluation of the robustness of the MTMD system against possible design uncertainties, modeling inaccuracies, and variations in environmental loading conditions. Since excessive tower-top displacement increases cyclic loading and bending demands at the tower base, effective vibration suppression can directly contribute to reducing fatigue accumulation and improving structural durability. Table 7 summarizes the variation of tower-top fore–aft displacement and tower base bending moment under different MTMD frequency and damping ratio values.

The results indicate that the system performance is highly dependent on accurate frequency tuning. A deviation from the optimal frequency reduces the interaction between the damper and the dominant structural modes, resulting in lower vibration mitigation efficiency. In contrast, variations in damping ratio show a comparatively smaller influence, indicating that the optimized system maintains relatively stable performance within a practical damping range.

The optimized frequency of 0.2 Hz provides the minimum structural responses under different wind conditions. At this frequency, the tower-top displacement and tower base bending moment reach their lowest values, confirming the importance of frequency matching between the MTMD and the dominant vibration modes of the floating wind turbine system. The sensitivity results also demonstrate that excessively low or high tuning frequencies cause detuning effects, which reduce the energy transfer efficiency between the primary structure and the secondary damping system.

Table 7: Sensitivity analysis of tower displacement and base moment with respect to frequency and damping ratio

Damping Ratio%	**Wind Speed(m/s)**					
	10		25		30	
	For After (m)	MomentX (ton.m)	For After (m)	MomentX (ton.m)	For After (m)	MomentX (ton.m)
5	0.08	168.5	0.21	258.9	0.29	392.6
9	0.8	157.8	0.2	255.3	0.29	388.7
13	0.8	158.8	0.2	256.3	0.29	388.7
Frequency (HZ)	**Wind Speed(m/s)**					
	10				10	
	For After (m)	MomentX (ton.m)	For After (m)	MomentX (ton.m)	For After (m)	MomentX (ton.m)
0.1	0.11	340	0.23	315.4	0.3	436.5
0.2	0.08	157.8	0.2	255.8	0.29	388.7
0.3	0.11	295	0.25	289.8	0.31	432.3

Similarly, the damping sensitivity results show that increasing or decreasing the damping ratio around the optimum value produces limited changes in the structural responses. This behavior indicates that the proposed MTMD configuration is less sensitive to moderate damping variations, providing a more robust passive control solution for offshore wind turbine applications.

To further illustrate the coupled effects of MTMD parameters on structural responses, surface plots for tower-top fore–aft displacement and tower base bending moment are presented in Figures 10 and 11. These plots provide a comprehensive visualization of the response variation under simultaneous changes in frequency and damping ratio, allowing identification of sensitive regions and optimal parameter ranges. Together with the numerical results in Table 7, these analyses confirm the reliability and robustness of the optimized MTMD system under different environmental loading scenarios.

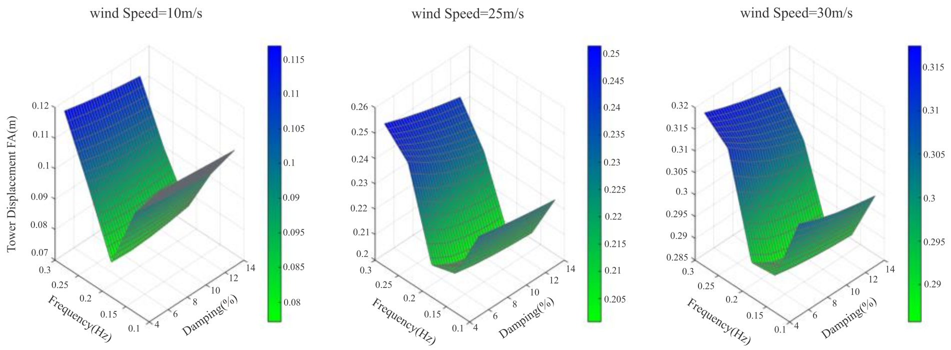

Figure 10: Surface plots of FA displacement for three wind speeds

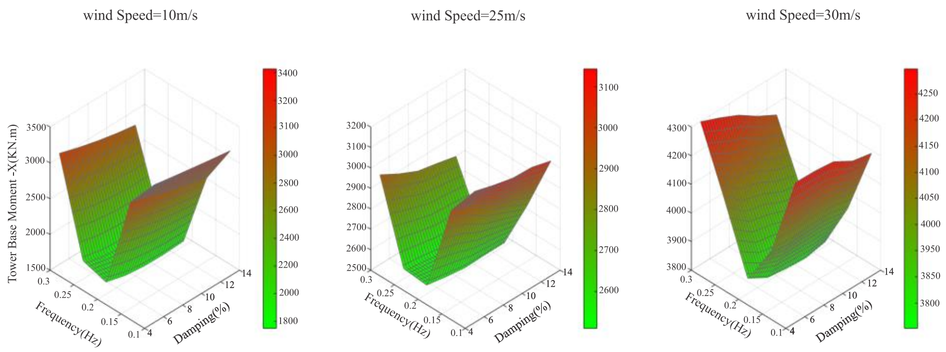

Figure 11: Surface plots of tower base moment (X) for three wind speeds

9. CONCLUSION

This study investigated the effectiveness of a Multiple Tuned Mass Damper (MTMD) system as a passive vibration control strategy for a floating offshore wind turbine supported by a Tension Leg Platform (TLP) under combined wind and wave loading. Two MTMD layouts, namely Nacelle–Nacelle and Nacelle–Platform, were evaluated under three representative wind speeds of 10, 25, and 30 m/s. The numerical results demonstrated that both MTMD layouts significantly improved the dynamic performance of the floating offshore wind turbine compared with the uncontrolled case by reducing tower displacements, platform motions, and

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tower-base moment responses.

Under the moderate wind condition (10 m/s), the Nacelle–Platform layout achieved maximum reductions of 34% in tower fore–aft displacement, 35% in lateral tower-base moment, and 31% in platform pitch motion, while the Nacelle–Nacelle layout provided better mitigation of platform roll motion (43%) and fore–aft tower-base moment (41%). Under higher wind speeds (25 and 30 m/s), both configurations remained effective, although the mitigation efficiency decreased due to increased environmental loading complexity. These findings highlight the importance of optimizing both MTMD parameters and installation location for effective vibration control.

The reduction in control efficiency under severe conditions is mainly attributed to the high axial stiffness of TLP tendons, stronger nonlinear aerodynamic and hydrodynamic interactions, variations in turbine dynamic characteristics caused by blade pitch control, partial detuning between MTMD frequencies and dominant structural modes, and simultaneous excitation of multiple vibration modes.

The comparison between the two layouts indicates that no single configuration provides optimum performance for all response quantities. While the Nacelle–Platform arrangement is more effective for global coupled responses, the Nacelle–Nacelle configuration performs better for specific responses such as platform roll and fore–aft tower-base bending moment. Therefore, simultaneous optimization of damper placement and mechanical properties, including mass, stiffness, and damping ratio, is essential for maximizing MTMD effectiveness. From an engineering perspective, the proposed MTMD system provides a practical and cost-effective passive control solution for floating offshore wind turbines operating in harsh marine environments.

By reducing structural vibrations and fatigue damage, the proposed system has the potential to extend the service life of critical components, enhance structural reliability, and improve the long-term economic performance of floating offshore wind energy systems. Overall, this study provides a framework for the design and optimization of passive vibration control systems for floating offshore wind turbines. Future research should consider other floating platform concepts, long-term environmental uncertainties, reliability-based optimization, and experimental validation to further improve the applicability of MTMD systems.

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