

Article

Comparative Performance Assessment of Tuned Mass Dampers for Vibration Suppression in Monopile Offshore Wind Turbines Under Different Operational Conditions

Yingna Li ^{1,2} , Jingcai Zhang ^{1,*} , Hao Yang ¹ , Shuhang Wang ¹, Siyu Liu ¹ and Lingxi Gu ¹ ¹ School of Transportation and Civil Engineering, Nantong University, Nantong 226019, China² School of Marine Science and Engineering, South China University of Technology, Guangzhou 511442, China

* Correspondence: zhangjingcai@ntu.edu.cn

Abstract

A tuned mass damper (TMD) is one of the dominant technologies for vibration control in offshore wind turbines (OWT). However, the variation in their vibration mitigation performance across a range of typical load cases throughout the full service life of wind turbines remains to be comprehensively assessed. This paper investigates the vibration mitigation patterns of TMDs on the dynamic responses of OWTs across five typical operational and extreme load cases, namely cut-in wind speed, rated power operation, cut-out wind speed, and two categories of extreme wind conditions. The results demonstrate that TMDs do not exert significant control effects across all load cases and response indicators. Their vibration mitigation effect on nacelle acceleration is the most stable and prominent, with optimal performance achieved under the cut-out wind speed shutdown load case, where the peak fore-aft vibration mitigation rate can reach 60.0%. However, the vibration mitigation rate of tower top displacement under normal operating load cases is significantly lower than that under shutdown conditions; the peak fore-aft displacement mitigation rate under the rated wind speed load case is merely 7.8%. The fore-aft foundation reaction forces achieve limited mitigation from TMD control, with a slight negative vibration mitigation effect even observed under extreme wind conditions. The effect of frequency detuning exhibits pronounced directional heterogeneity. For the side-to-side direction, −20% detuning reduces the mitigation rate from 45.0% to 29.2%, while for the fore-aft direction, +10% detuning increases it from 58.2% to 72.6% under rated operating conditions.

Keywords: offshore wind turbine; structural vibration; tuned mass damper; vibration control

Academic Editor: Jianhua Zhang

Received: 27 June 2026

Revised: 23 July 2026

Accepted: 29 July 2026

Published: 31 July 2026

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1. Introduction

Monopile offshore wind turbines (MOWTs) are the most widely applied structural form in shallow and medium water depths. Throughout their service life, MOWT structures are persistently subjected to coupled wind and wave loads, and effective vibration control is critical to ensuring their structural safety.

Tuned mass dampers (TMDs) represent a class of effective damping devices widely employed for vibration mitigation [1–3]. As the first-order bending mode dominates the structural response with peak displacement at the tower top, the nacelle is the optimal position for a single TMD. The devices are usually installed inside the nacelle of the MOWT.

Numerous scholars have investigated the vibration control performance and key influencing factors of TMDs for OWTs under multi-hazard coupled excitations. Lin et al. [4]

tested a TMD-OWT system. Lu et al. [5] demonstrated that TMDs show outstanding performance on OWT considering the RNA. Zhang et al. [6] found TMD show limited performance for normal operation. Elias [7] found that TMDs are preferred to OWT with a flexible base. Ju et al. [8] optimized the structural parameters of TMD. Robinson et al. [9] revealed the influence of SSI on the mitigation effect of the TMD. Jiang et al. [10] found that higher aerodynamic damping reduces TMD's vibration control capacity in turbine operation. Zhang et al. [11] and Dong et al. [12] proposed optimization methods for enhancing the performance of TMD.

Nevertheless, conventional single TMDs are inherently limited to narrowband vibration suppression tuned to a single structural frequency. Multi-tuned mass damper (MTMD) systems, composed of multiple individual TMD units with staggered tuning frequencies, can achieve effective multi-mode vibration control for OWTs. MTMDs present superior structural control robustness to a single TMD [13]. McNamara et al. [14] proposed an optimized multi-TMD layout scheme based on the modal displacement characteristics. Colherinhas et al. [15] proposed and studied the device with a pendulum mass block. Lu et al. [16] reported that the MTMD system outperforms a single TMD for low-frequency vibrations. Wang et al. [17] reported that ice-induced vibration can be mitigated by TMD. Lai et al. [18] assessed the improvement in the fatigue life of OWTs equipped with TMDs.

On this basis, various enhanced TMDs have been proposed and tested to further improve control performance. Leng et al. [19] proposed a novel TMD that can adjust the frequency of the device for superior performance. Liu et al. [20] proposed and verified the vibration suppression effect of prestressed TMDs for OWTs. Lei et al. [21,22] and Liu et al. [23] developed multi-prestressed and bi-directional PTMDs. Zhang et al. [24] developed a novel TMD with an inerter device. This damper has been extensively investigated and exhibits remarkable performance in suppressing ice-induced vibrations and reducing fatigue damage accumulation. Researchers have conducted in-depth investigations on inerter-pendulum mass dampers for offshore wind turbines under wind-ice loads, and validated their superior performance in attenuating structural vibrations and extending fatigue life [25–27]. Wang et al. [28] improved the performance by a gradient metamaterial resonator. Li et al. [29] integrated energy harvesters with tuned mass dampers (TMDs) to enhance their vibration control performance. Jiang et al. [30] introduced an eddy current damping system into the TMDs to achieve real-time tuning of its damping.

Beyond passive control schemes, scholars have also proposed various active and semi-active vibration control strategies combined with intelligent algorithms [31–33]. These methods feature excellent adaptability to time-varying operating conditions, but generally require complex hardware support and entail high maintenance costs in harsh marine environments. In addition, researchers have developed high-fidelity coupling frameworks [34], real-time hybrid simulation methods [35], and physics-guided surrogate models [36] for offshore wind turbine dynamic analysis, greatly enhancing numerical fidelity and computational efficiency and providing robust numerical tools for the validation of vibration control schemes.

However, most existing TMD-related investigations are limited to a single operational condition. In practice, wind loads acting on offshore wind turbines are inherently time-varying, and the turbine's operational state continuously transitions among different working conditions in response to wind load fluctuations. Therefore, systematic comparisons and full-scenario performance assessments, including cut-in, rated, cut-out, and extreme wind conditions, remain scarce.

To fill the above research gap, this study performs a comprehensive performance evaluation of TMDs for monopile OWTs in strict accordance with the IEC 61400-1 [37] wind turbine design standard. Five typical load cases covering normal power generation

and extreme wind scenarios throughout the full service life are selected. The vibration mitigation efficiency and directional heterogeneity of TMDs are systematically quantified, and robustness analysis focusing on frequency detuning is conducted to reveal the mechanism of directional differences in detuning effects. This work supplements full-scenario performance data and can provide valuable references for TMD parameter design and engineering applications.

2. Numerical Modelling of the Offshore Monopile Wind Turbine with TMD

2.1. Definition and Dynamic Characteristics of Typical Operational States

To systematically evaluate the vibration mitigation performance of TMD under typical scenarios throughout the full-service life of wind turbines, this section adopts the NREL 5 MW wind turbine with OC3 foundation as the research subject in accordance with the IEC 61400 structural design standard for wind turbines, and five typical load cases are selected as listed in Table 1 [38]. Among these load cases, LC1~LC3 correspond to three typical wind speed conditions during the normal power generation phase of the wind turbine: LC1 is the cut-in wind speed load case (3 m/s), corresponding to the low-wind speed operation stage of turbine start-up and grid connection; LC2 is the rated wind speed load case (11.4 m/s), corresponding to the optimal operating state where the turbine delivers its rated power output; and LC3 is the cut-out wind speed load case (25 m/s). For all three aforementioned normal operating load cases, the Normal Turbulence Model (NTM) is adopted to simulate the turbulence characteristics of the atmospheric boundary layer wind field. LC4 and LC5 correspond to extreme wind conditions, which are adopted to verify the vibration mitigation performance of TMD under extreme loads. LC4 is the 1-year return period extreme wind speed load case (EWM-1, 40 m/s) simulated with the Normal Turbulence Model (NTM), whereas LC5 is the 50-year return period extreme wind speed load case (EWM-50, 50 m/s) using the Extreme Turbulence Model (ETM). These wind load cases are determined per the NREL 5 MW reference turbine specification and the IEC 61400 standard, encompassing full operational conditions and design-level extreme wind events.

Table 1. Description of wind load cases in this study.

Operational Conditions	OWT States	v_{Ref} (m/s)	Extreme Wind Model
LC1	Cut In	3	NTM
LC2	Rated	11.4	NTM
LC3	Cut Out	25	NTM
LC4	EWM-1	40	NTM
LC5	EWM-50	50	ETM

All load cases are numerically simulated over a total duration of 600 s. For statistical analysis, the transient response data in the first 100 s are excluded to eliminate the influence of initial conditions on the simulation results.

2.2. Wind Load

The turbulent wind field is generated using TurbSim [39]. A power-law profile is employed to represent the mean wind speed, and the fluctuating velocity components are synthesized based on the Kaimal spectrum. Figure 1 illustrates the time history of wind speed at the reference locations corresponding to load cases LC2 and LC5. Subsequently, the wind forces exerted on the tower are determined by Equation (1).

$$F_{\text{wind}} = \frac{1}{2} C_D \rho D(z) v(z) |v(z)| \quad (1)$$

where $D(z)$ is the tower diameter at height z , ρ represents the density of air, $v(z)$ is the instantaneous wind speed at height z , and C_D is the drag coefficient.

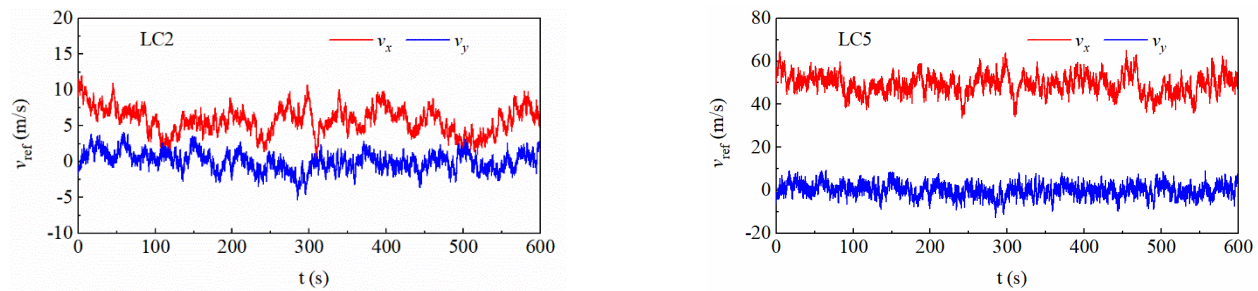


Figure 1. Wind speed variation at the reference point.

2.3. Wave Load

Sea wave conditions are defined via the JONSWAP wave spectrum, and the wave heights are presented in Figure 2. Wave forces acting on the MOWT are calculated according to the Morison equation (Equation (2)).

$$F_{wave} = \frac{1}{2}C_D\rho_w D(z)v_w(z)|v_w(z)| + \frac{\pi}{4}C_M\rho D_p^2\dot{v}_w(z) \quad (2)$$

where ρ_w is the seawater density, D_p is the monopile diameter, v_w is the velocity component of water particles, and C_D and C_M denote the drag coefficient and inertia coefficient, respectively.

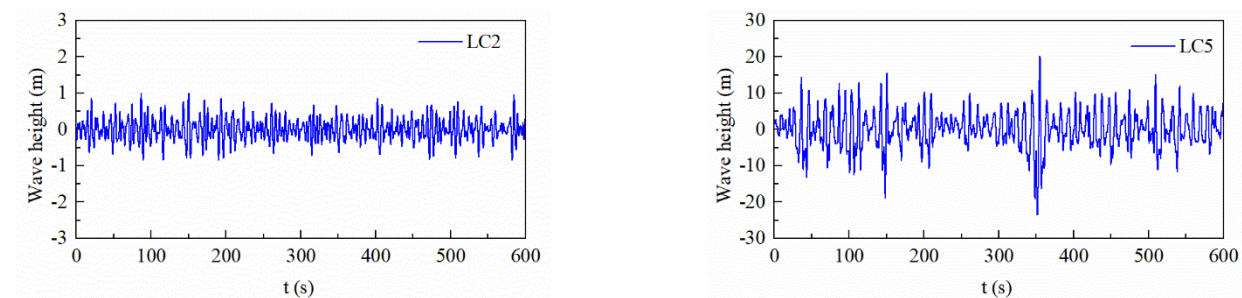


Figure 2. The time-history curve of wave height.

2.4. Modelling and Validation of the OWT

Simulations are performed using the commercial finite element software Abaqus 2022. For modelling convenience, the rotor–nacelle assembly is treated as a rigid body. The tower and monopile foundation are discretized using four-node reduced-integration curved shell elements with a uniform mesh size of 500 mm, and their material behaviour is defined by an elastic–perfectly plastic constitutive model. A systematic mesh sensitivity analysis has been performed to verify numerical convergence and solution reliability, and the final mesh scheme is selected to achieve a reasonable balance between computational accuracy and efficiency.

A tuned mass damper (TMD) with a mass equal to 3% of the combined mass of the nacelle, hub, and blades is attached to the nacelle via connector elements, and its stiffness and damping coefficients are assigned according to the optimal parameters reported by Den Hartog [40].

Table 2 compares the computed natural periods of the first four vibration modes with the test results. The maximum deviation between the finite element results and the test data is less than 1%, which confirms the reliability of the present model and demonstrates its adequacy for the subsequent analyses. By comparing with the mode shape characteristics of the NREL 5 MW reference wind turbine (Figure 3), the mode shape patterns and node

positions are completely consistent, which further verifies the accuracy of the mass and stiffness distribution of the finite element model.

Table 2. Parameters of MOWT obtained from experimental results [38] and FEM.

Mode	Description	Tested	FEM	Error
1	1st Tower Fore-Aft	3.65 s	3.61 s	0.82%
2	1st Tower Side-to-Side	3.62 s	3.60 s	0.55%
3	2nd Tower Fore-Aft	0.442 s	0.441 s	0.23%
4	2nd Tower Side-to-Side	0.426 s	0.432 s	1.41%

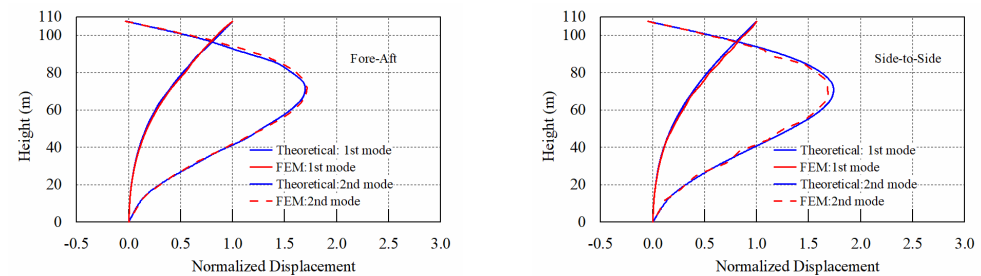


Figure 3. Validation of mode shapes of MOWT.

3. Comparative Evaluation of TMD Vibration Mitigation Performance

3.1. Nacelle Response

The fore-aft (F-A) and side-to-side (S-S) acceleration time-history responses of the nacelle under uncontrolled and TMD-controlled conditions for load case LC2 are illustrated in Figures 4 and 5, respectively. These responses arise from the coupled action of multiple excitation sources: the static structural deflection induced by steady wind loads serves as the response baseline, while the random component of turbulent wind loads and the periodic excitations associated with the rotor rotational frequency (1P) and blade passing frequency (3P) are superimposed, ultimately giving rise to hybrid vibration characteristics featuring narrowband dominance and broadband superposition. With the application of TMD control, the overall amplitude of the nacelle's fore-aft acceleration is significantly suppressed, with the peak acceleration reduced to 0.681 m/s^2 and a corresponding vibration mitigation rate of 58.2%.

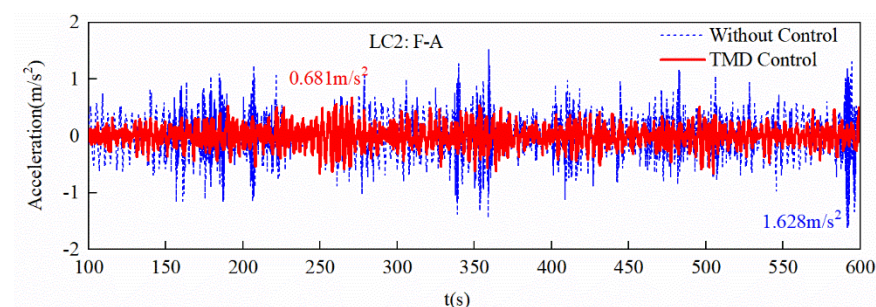


Figure 4. Time-history curves of nacelle acceleration under the LC2 load case (F-A).

As the S-S direction is not directly affected by the rotor axial thrust, the corresponding vibration is primarily induced by lateral turbulent components, structural modal coupling, and aerodynamic side forces. Consequently, the peak S-S acceleration is merely 0.409 m/s^2 , significantly lower than its fore-aft counterpart. With the application of TMD control, the peak S-S acceleration of the OWT is reduced to 0.225 m/s^2 , with a corresponding vibration mitigation rate of 45.0%. Furthermore, both the dispersion and fluctuation amplitude of the vibration response are significantly decreased (Figure 5).

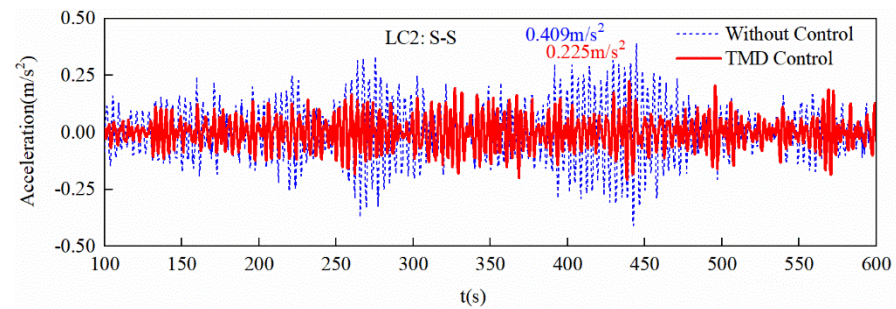


Figure 5. Nacelle side-to-side (S-S) acceleration time-history curves under load case LC2.

The vibration mitigation rates of TMDs for peak nacelle acceleration under various load cases are illustrated in Figure 6. Overall, TMDs can effectively reduce the peak nacelle acceleration across all load cases, and the vibration mitigation performance in the fore-aft direction is generally superior to that in the side-to-side direction.

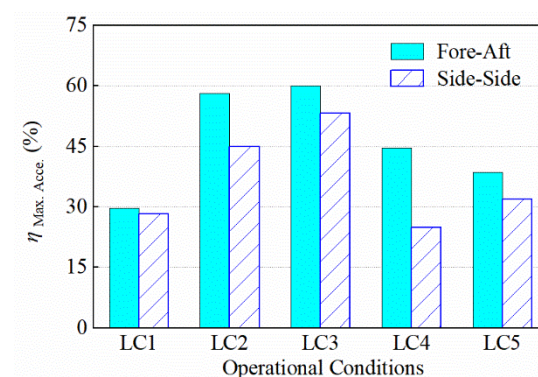


Figure 6. Reduction for peak nacelle acceleration under various load cases.

Furthermore, the peak vibration mitigation rates exhibit a trend of initial increase followed by a subsequent decrease with rising wind speed: under the low-wind-speed cut-in load case (LC1), the peak mitigation rates in the fore-aft and side-to-side directions are relatively close at 29.7% and 28.3%, respectively, corresponding to a relatively limited vibration mitigation effect; under the rated wind speed load case (LC2), the vibration mitigation efficiency increases substantially, with the peak fore-aft mitigation rate reaching 58.2% and the side-to-side rate reaching 45.0%. Under the cut-out wind speed load case (LC3), the peak vibration mitigation performance reaches its optimum across all load cases, with the fore-aft mitigation rate reaching 60.0% and the side-to-side rate rising to 53.1%. Under extreme wind conditions, the peak vibration mitigation rates exhibit a decline: under load case LC4, the peak fore-aft mitigation rate drops to 44.6% and the side-to-side rate decreases to approximately 24.9%, representing the lowest levels among all load cases; under the LC5 case, the mitigation rates increase moderately, with the fore-aft and side-to-side directions reaching approximately 38.6% and 31.9%, respectively.

The root mean square (RMS) value of acceleration reflects the average energy level of structural vibration and is directly associated with structural fatigue damage accumulation. The corresponding vibration mitigation rates are illustrated in Figure 7. Under the cut-out wind speed load case (LC3), the RMS vibration mitigation performance of the TMD reaches its optimum among operational load cases, with a fore-aft RMS mitigation rate of 68.1% and a side-to-side rate of approximately 48.0%. Under the rated wind speed load case (LC2), the mitigation performance ranks second, with fore-aft and side-to-side rates of approximately 56.5% and 43.3%, respectively. Under the cut-in wind speed load case (LC1), the fore-aft and side-to-side mitigation rates are approximately 36.4% and 28.7%, respectively.

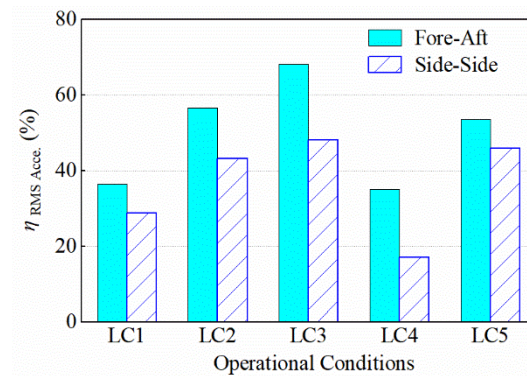


Figure 7. RMS reduction for nacelle acceleration under various load cases.

Under extreme wind conditions, the fore-aft RMS vibration mitigation rate for load case LC4 is 35.0%, while the side-to-side rate is merely 17.1%. Under the LC5 extreme turbulence load case, the vibration mitigation performance is superior to that of LC4, with the fore-aft and side-to-side RMS mitigation rates rebounding to 53.5% and 45.8%, respectively. A comparison of the peak and RMS vibration mitigation rates reveals that the fore-aft RMS vibration mitigation rates are generally higher than their peak counterparts, indicating that TMDs exhibit stronger overall energy suppression performance for stochastic vibration than their control effect on extreme peak responses. By contrast, the discrepancy between the peak and RMS vibration mitigation rates in the side-to-side direction is relatively minor, reflecting a higher degree of stochasticity in the side-to-side vibration and a closer coupling between the peak response and the average energy level.

In summary, TMDs exert stable and significant vibration mitigation effects on the nacelle acceleration of offshore wind turbines. They achieve optimal performance within the normal operating wind speed range from the rated wind speed to the cut-out wind speed, and their vibration suppression capability in the fore-aft direction is superior to that in the side-to-side direction.

3.2. Tower Response

Tower top displacement is a core indicator characterizing the overall structural deformation characteristics of offshore wind turbines. It directly governs the tower base bending moment and foundation load levels, serving as a critical parameter for structural ultimate bearing capacity verification and fatigue life assessment. Furthermore, it exerts a significant influence on the alignment accuracy and operational safety of the drive train within the nacelle.

Figure 8 depicts the time-history curve of the F-A displacement at the tower top under the LC2 load case. Under the uncontrolled condition, the F-A displacement at the tower top is characterized by narrow-band random fluctuations around the static offset baseline, with a peak displacement of 0.800 m. With the implementation of TMD control, the peak displacement decreases to 0.738 m, corresponding to a vibration reduction rate of merely 7.8%, which is consistent with Bai et al. [31]. This modest control efficacy can be attributed to the mechanism that the F-A displacement of the structure is primarily induced by the rotor thrust generated from wind energy capture by the wind turbine rotor. Owing to the relative stability of the rotor thrust, the overall static offset baseline of the structure remains largely unaltered, resulting in small-amplitude fluctuations of the tower top displacement and accordingly limited vibration suppression performance of the TMD.

Figure 9 presents the time-history curve of S-S displacement at the tower top under the LC2 load case. Unlike the F-A response, the S-S displacement exhibits no distinct static offset component, and the response oscillates symmetrically about the zero baseline. The

peak displacement reaches 0.202 m under the uncontrolled condition, while it reduces to 0.151 m with TMD control, yielding a vibration reduction rate of 25.2%. This pronounced control performance arises from the fact that under the LC2 load case, S-S vibration is directly induced by wind loads with large fluctuation amplitudes, which enables the TMD to exert a remarkable vibration suppression effect.

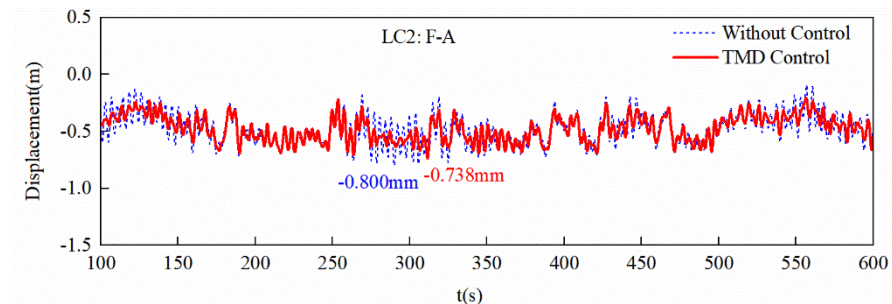


Figure 8. Time-history curves of tower-top displacement under the LC2 (F-A).

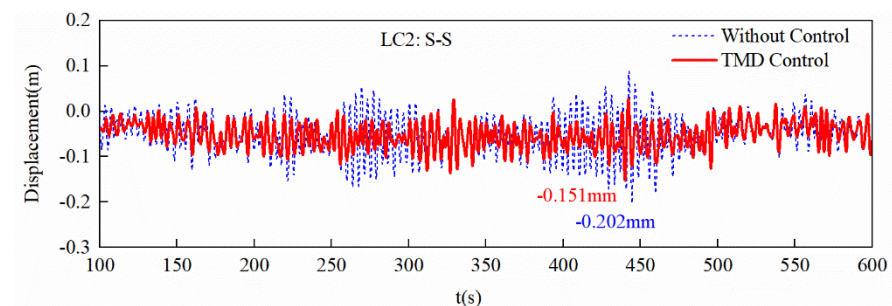


Figure 9. Time-history curves of tower-top displacement under the LC2 (S-S).

Figure 10 depicts the time-history curve of F-A displacement at the tower top under the extreme LC5 load case. Subjected to the 50-year return period extreme turbulence, the wind turbine exhibits substantially elevated fluctuation intensity and randomness in its displacement response. Under the uncontrolled condition, the peak displacement reaches 0.758 m, accompanied by a pronounced increase in instantaneous large-amplitude displacement spikes. Consequently, with the implementation of TMD control, the peak displacement at the tower top is reduced to 0.550 m, yielding a vibration reduction rate of 27.4%. The displacement spikes induced by extreme turbulence are effectively suppressed, and the dispersion of the overall displacement fluctuations is mitigated accordingly.

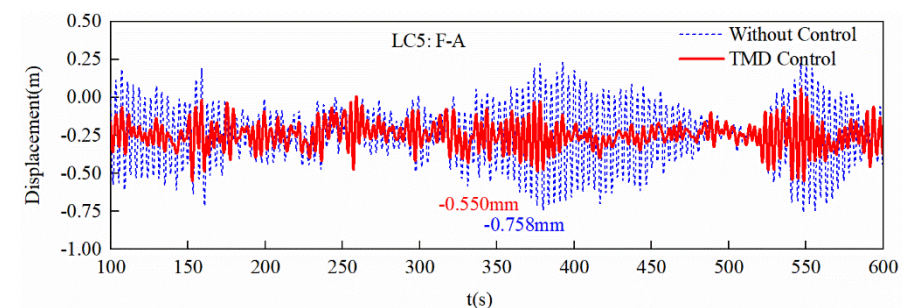


Figure 10. Time-history curves of tower-top displacement under the LC5 (F-A).

Figure 11 presents the vibration reduction in tower-top peak displacement achieved by TMD control under various load cases. The TMD delivers moderate control efficacy over the tower-top peak displacement, and its vibration reduction performance during turbine operation is significantly lower than that under the parked condition. Overall, the

F-A peak displacement vibration reduction rate exhibits a trend of initial slight fluctuation, followed by a substantial increase, and a mild decline under extreme load cases as wind speed rises. Specifically, the rate stands at approximately 10.4% under the low cut-in wind speed case (LC1), decreases slightly to 7.8% under the rated wind speed case (LC2), and jumps sharply to around 34.9% under the cut-out wind speed case (LC3). Under extreme wind conditions, the peak vibration reduction for LC4 and LC5 falls slightly to 28.7% and 27.5%, respectively.

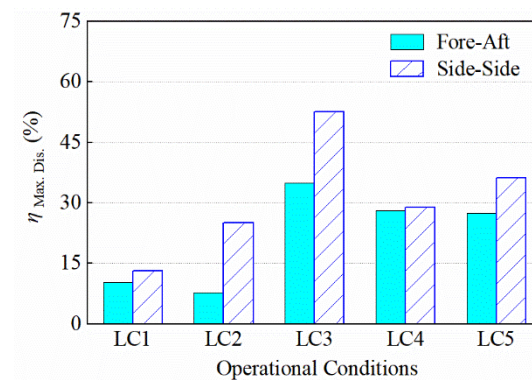


Figure 11. Reduction for peak tower-top displacement under various load cases.

The S-S peak displacement vibration reduction rate follows a broadly similar trend to its F-A counterpart and corresponds to markedly higher vibration mitigation performance across all load cases. Specifically, it reaches 13.2% under the LC1 case, climbs to 25.1% under LC2, and peaks at approximately 52.5% under LC3. Under extreme wind conditions, the rate declines to 28.9% for LC4 and rebounds to 36.2% for LC5.

Figure 12 presents the vibration reduction in RMS of tower-top displacement achieved by TMD under various load cases. The S-S vibration mitigation performance consistently outperforms its F-A counterpart, and both attain their peak control efficacy under LC3.

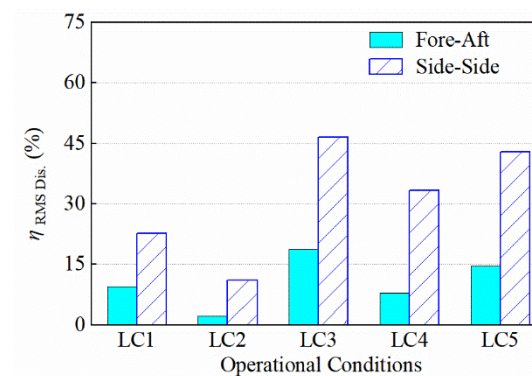


Figure 12. Reduction in RMS of tower-top displacement under various load cases.

The F-A displacement RMS vibration reduction remains at a relatively low level across all load cases. Specifically, the rate stands at approximately 9.4% under the LC1 case, and drops to the lowest value of merely 2.1% across all load cases under the rated LC2 condition. Such limited TMD control efficacy can be attributed to the fact that F-A displacement is dominated by the displacement component induced by rotor thrust. Under the parked turbine condition, the rate rises to 18.7% for LC3. For extreme wind conditions, the vibration reduction for LC4 and LC5 is approximately 7.9% and 14.6%, respectively.

The TMD delivers a more pronounced vibration reduction performance for the S-S displacement RMS of OWTs. The vibration reduction stands at 22.7% and 11.0% under the LC1 and LC2 load cases, respectively. Under the parked turbine condition, the vibration

mitigation efficacy of the TMD is substantially improved, reaching approximately 46.5% under the LC3 case. Under extreme wind conditions, the vibration reduction for the LC4 and LC5 load cases is 33.3% and 42.8%, respectively.

3.3. Foundation Response

Figure 13 presents the vibration reduction rates of peak foundation reaction forces achieved by TMD under various load cases. The control efficacy of TMD for S-S foundation reaction forces is significantly superior to that on F-A foundation reaction forces. Furthermore, the F-A vibration reduction rates remain at an extremely low level overall, and even exhibit a slight negative control effect under extreme load cases.

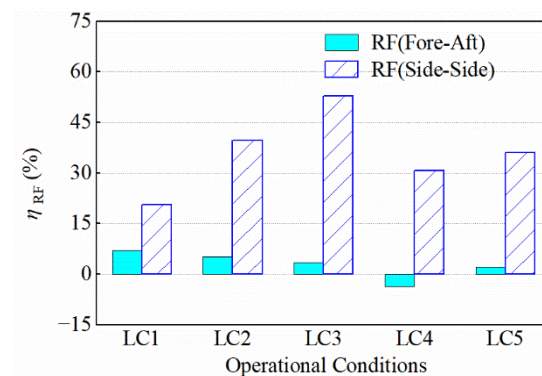


Figure 13. Vibration reduction for peak foundation reaction force.

In terms of F-A foundation reaction forces, the vibration reduction efficacy remains quite limited across all normal operating load cases. Specifically, the vibration reduction rate stands at approximately 7.2% for the LC1 cut-in wind speed case, around 5.1% for the LC2 rated wind speed case, and merely 3.4% for the LC3 cut-out wind speed case. Under extreme wind conditions, the control efficacy further deteriorates. A negative vibration reduction rate of approximately −3.6% is observed under the LC4 case, while the corresponding value for LC5 is 2.1%. These results indicate that the TMD exerts a very limited control effect on the peak F-A foundation reaction forces. Under extreme load conditions, the inertial impact of the TMD mass may conversely lead to a slight increase in the peak foundation reaction forces.

The TMD delivers remarkable vibration control efficacy for S-S foundation reaction forces, with its vibration reduction rate following an evolutionary trend of an initial increase followed by a decrease as wind speed rises. Specifically, the rates reach approximately 20.7% and 39.6% under the LC1 and LC2 load cases, respectively, and attain the peak value of around 52.8% across all load cases under the LC3. Under extreme wind conditions, the rate drops to 30.7% for LC4, while it rebounds to 36.1% for the LC5 extreme turbulence case.

Figure 14 presents the vibration reduction rates of peak foundation bending moment achieved by TMD under various load cases. Contrary to the distribution pattern observed for foundation reaction forces, the TMD delivers significantly superior control efficacy for F-A foundation bending moment relative to its S-S counterpart. Furthermore, the overall magnitude of vibration reduction for foundation bending moment is higher than that for foundation reaction forces.

In the F-A direction, the TMD vibration reduction rate for foundation bending moment increases from 15.5% under the LC1 cut-in wind speed case to 52.7% under the LC3 cut-out wind speed case. Under extreme wind conditions, the value stands at approximately 30.1% for the LC4 case and 36.3% for the LC5 extreme turbulence case. These findings indicate that the control efficacy of TMD on F-A vibration is primarily manifested through the mitigation

of structural bending responses, with its control efficiency for foundation bending moment markedly outperforming that for foundation reaction forces.

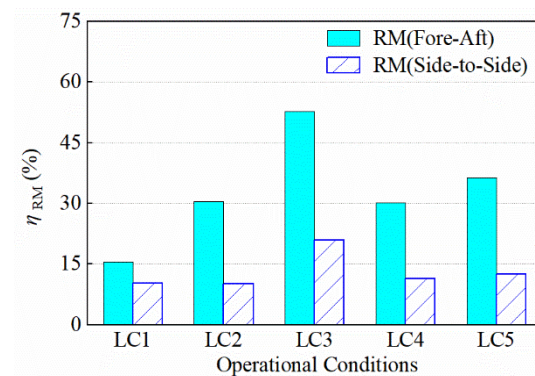


Figure 14. Vibration reduction rates of TMD for peak foundation bending moment.

In terms of S-S foundation bending moment, the vibration reduction rates remain at a relatively low level overall, with minor fluctuations across different load cases. Specifically, the rates under the LC1 and LC2 cases are both approximately 10%, and rise to around 21.0% at the LC3. Under extreme load cases, the vibration reduction performance declines again, reaching approximately 11.3% for LC4 and 12.6% for LC5, both of which are significantly lower than the vibration reduction efficacy of F-A bending moment under the corresponding load cases.

4. Robustness Assessment Under Frequency Detuning

The vibration reduction performance of the TMD is highly sensitive to its frequency deviation. In practical engineering applications, factors including manufacturing and installation errors, material property degradation, environmental temperature variations, and shifts in wind turbine operating conditions can readily cause the natural frequency of the TMD to deviate from its design tuning value, thereby inducing the detuning effect. In this section, five groups of frequency detuning ratios (i.e., -20% , -10% , 0% , 10% , and 20%) are configured to investigate the influence pattern of detuning degree on the vibration reduction efficacy for peak nacelle acceleration and peak tower-top displacement under the LC2 and LC5 load cases.

Figure 15 presents the vibration reduction rates of peak S-S nacelle acceleration achieved by TMD under the LC2 load case at different detuning ratios. As the frequency deviation increases in both the positive and negative directions, the vibration reduction rate gradually deteriorates. Specifically, the rate drops to approximately 29.2% at a negative detuning ratio of -20% , and to around 32.4% at a positive detuning ratio of $+20\%$. These findings indicate that the vibration reduction performance of the TMD for S-S nacelle acceleration is relatively sensitive to frequency detuning. Once the TMD deviates from its optimal tuning point, the vibration control efficacy will exhibit pronounced degradation.

By contrast, the variation pattern of the F-A acceleration vibration reduction rate with the detuning ratio is completely opposite to that in the S-S direction. At a detuning ratio of 0, the vibration reduction rate stands at the lowest level across the entire parameter range, at approximately 58%. As the detuning degree increases in both positive and negative directions, the vibration reduction rate conversely rises significantly. Specifically, the rates reach 71.3% and 72.6% at detuning ratios of -10% and $+10\%$, respectively, and 73.0% and 73.4% at detuning ratios of -20% and $+20\%$, respectively.

Figure 16 presents the vibration reduction rates of peak tower-top displacement under the LC2 load case at various detuning ratios. The overall variation trend is consistent with

that of the acceleration response, yet with a relatively milder fluctuation amplitude. For S-S displacement, the vibration reduction rate likewise exhibits a unimodal distribution pattern. Specifically, it decreases to 21.6% at a negative detuning ratio of -10% , and further drops to approximately 14.7% at -20% negative detuning. Under positive detuning conditions, the rate reaches around 23.2% at $+10\%$ detuning and 22.3% at $+20\%$ detuning. For F-A displacement, the TMD vibration reduction rate rises to approximately 11% at -10% negative detuning, while the corresponding value stands at 9.0% at $+10\%$ positive detuning.

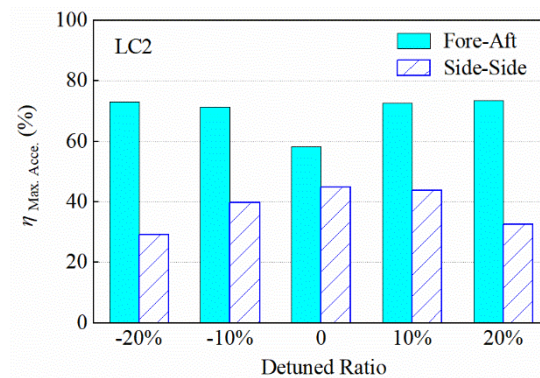


Figure 15. Influence of TMD frequency detuning on the reduction in nacelle acceleration under the LC2.

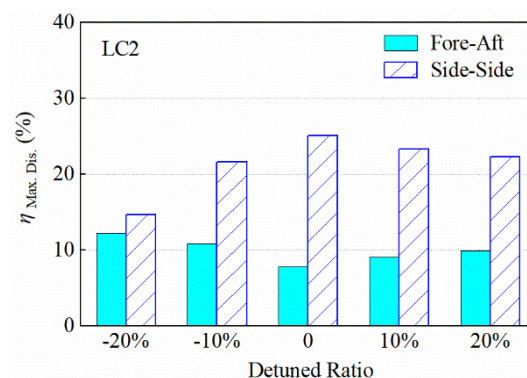


Figure 16. Influence of TMD frequency detuning on the reduction in peak tower-top displacement under the LC2.

However, under the parked wind turbine condition, the vibration reduction performance degrades progressively with increasing detuning degree in both the F-A and S-S directions (see Figures 17 and 18).

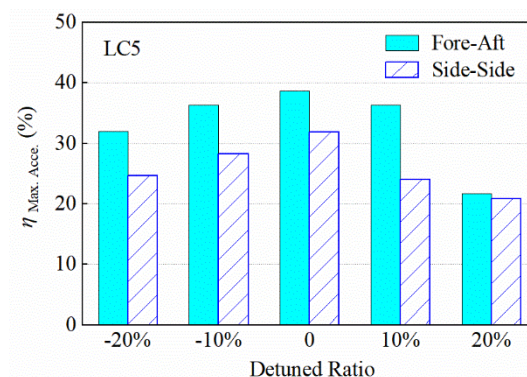


Figure 17. Influence of TMD frequency detuning on the reduction in peak nacelle acceleration under the LC5.

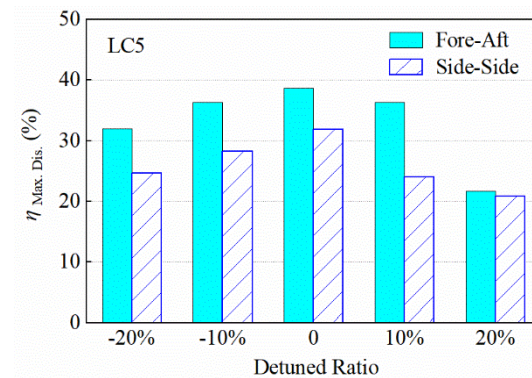


Figure 18. Influence of TMD frequency detuning on reduction in peak tower-top displacement under the LC5.

The results can be attributed to the following mechanisms. Under both parked and operating conditions, the S-S structural vibration is dominated by the first-order lateral bending mode, and the excitation originates from single-frequency narrow-band turbulence (i.e., wind loads). Accordingly, the vibration reduction performance is highly sensitive to frequency detuning, and the energy absorption efficiency of the TMD declines markedly once it deviates from the optimal tuning point. In contrast, under the operating condition, the F-A structural vibration is governed by the multi-frequency coupling of the first-order bending mode and 1P/3P periodic excitations. Moderate frequency detuning can broaden the effective energy absorption frequency band of the TMD, enabling it to cover more excitation energy peaks. As a result, the vibration reduction performance conversely improves with an appropriate increase in detuning degree.

5. Discussion

The TMD mass ratio is fixed at 0.03 in this work. Future work should explore a broader range of mass ratios for varying vibration demands. Moreover, this study considers only wind-wave loads, but OWTs may be exposed to combined earthquake–wind–wave excitations, which require further assessment. Additionally, our analysis is based on a monopile foundation; other foundation types exhibit different dynamic properties, so the effectiveness of TMDs on such OWTs needs validation.

6. Conclusions

Focusing on the typical operating and extreme load cases throughout the full life cycle of offshore wind turbines, this paper systematically evaluates the vibration reduction performance of tuned mass dampers (TMDs) and analyzes their robustness against frequency detuning. The main conclusions are summarized as follows:

(1) The vibration reduction performance of TMDs exhibits pronounced differences across various load cases and response indicators. The TMD delivers the most stable and prominent control efficacy for nacelle acceleration, with its vibration reduction efficiency following a trend of initial increase followed by decrease as wind speed rises, and reaching the optimal performance across all load cases under the cut-out wind speed parked condition. However, for tower-top displacement and foundation reaction forces, the vibration reduction capacity under normal operating conditions is considerably weaker than that under the parked condition.

(2) The control efficacy of TMDs on tower displacement and foundation loads exhibits pronounced differences across various load cases and wind directions. Under normal operating conditions, the TMD exerts a very limited vibration reduction effect on F-A tower-top displacement, with a peak vibration reduction rate of merely 7.8% under the

rated wind speed case, which is significantly lower than the 34.9% achieved under the cut-out wind speed parked condition. F-A foundation reaction forces gain barely effective control, and a slight negative vibration reduction effect even emerges under extreme wind conditions.

(3) The influence of TMD frequency detuning on its vibration reduction performance depends on the operating condition of the wind turbine. Both positive and negative detuning result in degraded vibration reduction efficiency under parked conditions and for S-S responses under operating conditions. By contrast, for F-A responses under operating conditions, owing to the multi-frequency coupling of 1P/3P periodic excitations, moderate frequency detuning can broaden the effective energy absorption frequency band of the TMD and enable it to cover more excitation energy peaks, which conversely improves the vibration reduction performance.

Author Contributions: Conceptualization, Y.L.; Methodology, Y.L.; Software, H.Y.; Validation, J.Z., H.Y. and S.W.; Investigation, Y.L.; Data curation, S.L. and L.G.; Writing—original draft, Y.L.; Writing—review & editing, J.Z.; Funding acquisition, J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Nantong (Grant Nos. JC2023025, JC2024058).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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