The Effect of Tuned Mass Damper Mass Ratio on Wind Turbine Vibration Mitigation

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Received: 3 October 2024 | Revised: 16 October 2024 | Accepted: 19 October 2024

ABSTRACT

This paper examines the efficacy of Tuned Mass Dampers (TMDs) in mitigating vibration in wind turbines under diverse excitation force conditions. The impact of TMD on the response of a wind turbine exposed to sinusoidal and random wind forces, at varying mass ratios μ_m: 0.02, 0.05, 0.10, and 0.20, was assessed through the use of a MATLAB SIMULINK model. The findings indicate that TMDs markedly attenuate vibration when subjected to sinusoidal forces, particularly at higher TMD mass ratios. In contrast, the reduction in vibration level in the presence of random wind forces is relatively modest, becoming more pronounced at higher TMD mass ratios. In addition, the internal forces generated by incorporating the TMD into the system were calculated for different mass ratio values. It was noted that these forces increased in proportion to the mass ratio, although they remained within reasonable limits. However, an increase in the TMD mass ratio has been observed to result in a corresponding increase in these forces. This underscores the importance of meticulous mass ratio selection for the optimal functioning of TMD systems. It suggests that dealing with complex, broadband excitation may entail inherent limitations. The findings of this study may prove valuable in enhancing the understanding of the stability and lifetime of wind turbines under dynamic wind conditions.

Keywords-wind turbine; Tuned Mass Damper (TMD); vibration mitigation; mass ratio

I. INTRODUCTION

Wind turbines are a vital component in the generation of renewable energy, capable of transforming kinetic energy from wind into electrical power. Wind energy is a clean and sustainable source of energy, which has the potential to reduce greenhouse gas emissions and reliance on fossil fuels. The size of wind turbines ranges from the relatively small units used by individuals to the much larger commercial models, the majority of which are installed in farms, both onshore and offshore. These turbines signal the advent of a more sustainable energy future, thereby making a significant contribution to the mitigation of climate change and the establishment of global energy security through the harnessing of the inexhaustible natural power of the wind [1]. Technological advancements have also been a significant contributing factor to the growth of onshore wind turbines. Technology advancement has resulted in the creation of larger and more efficient turbines, capable of harnessing a greater amount of energy from the wind. Moreover, research into aerodynamics, materials, and control systems has enhanced overall performance and reliability [2]. It is anticipated that the trajectory of onshore wind turbine growth will persist. The imperative need to address climate change, coupled with the ongoing research and development, will likely result in the emergence of even more efficient and cost-effective technologies. Wind energy, particularly onshore wind turbines, will continue to be a pivotal contributor to the transition to a more sustainable and environmentally conscious global energy landscape, offering a source of hope in the fight against environmental degradation [3]. Authors in [4] presented an experimental and numerical investigation of the effectiveness of applying a TMD for reducing vibration amplitudes and enhancing the overall structural response of wind turbines. They examined the intricate design considerations and pragmatic implementation of TMDs in wind turbine applications, contemplating mass ratio, damping ratio, placement locations, and integration methods. As previously stated, wind turbines are susceptible to a variety of environmental factors, including gusts and turbulence, which can potentially induce vibrations in the structure. Such an approach, however, could have adverse effects on the performance, structural integrity, and life expectancy of wind turbines. In this regard, they introduced the TMD, which is a device that is essentially a mass-damper-spring system designed to mitigate structural vibrations. Authors in [5] conducted an analytical investigation into the configuration of nonlinear TMDs as passive control devices for the reduction of vibrations in structures.

The location of the nonlinearity or the nonlinearity itself depends on the large displacements and the use of limiting devices in traditional TMDs. Consequently, they generally have poor control performance. The nonlinear characteristics of TMDs [6, 7], employ the complexification averaging method and the multiscale approach in deriving the optimal frequency formula. The modified design method proposed considers the effect of nonlinearity and presents superior control performance compared to the traditionally designed linear TMD. The numerical results demonstrate the accuracy of the new design formula and its efficacy in practical engineering applications. The findings of the study indicate that nonlinearity should be taken into account in the design of TMDs to achieve better control of resonance vibrations in a wide range of structures, including buildings and bridges. In an effort to enhance conventional TMD vibration controls in structures, authors in [8] introduced nonlinear characteristics. They developed an approximate analytical solution for TMD amplitude using the complex variable averaging method, taking into account the nonlinear effects of large displacements and limiting devices. The results of [9-11] demonstrate that nonlinear TMD parameters lead to a notable reduction in vibration levels and their effects at times prior to and after entering the nonlinear stiffness TMD, in contrast to the linear stiffness TMD. The novel technique employed in the paper markedly reduced the computational time in comparison to the conventional numerical approach. The results underscore the practical advantages of considering the nonlinear stiffness of TMDs during the design process, thereby extending the applicability of this approach to civil engineering, aeronautical engineering, and mechanical engineering. While traditional TMDs remain an effective solution, recent developments in vibration control have demonstrated that they have limits when subjected to nonstationary forces, as those encountered by wind turbines [12]. Particle Impact Dampers (PIDs) and Nonlinear Energy Sinks (NESs) represent two examples of nonlinear dampers that demonstrate enhanced performance, greater resilience, and increased flexibility in response to changing excitation conditions. These nonlinear solutions are of great importance for enhancing wind turbine stability and prolonging their operational lifespan under dynamic wind loads, particularly given their increasing prevalence in engineering domains [13].

Authors in [14] presented a mathematical model for optimizing the design of TMD for Floating Offshore Wind Turbines (FOWTs), with the objective of reducing structural vibrations caused by coupled wind and wave loads. The design is formulated as a feedback control problem, wherein the TMD parameters serve as control inputs with the objective of minimizing the FOWT's response. The methodology accounts for model uncertainties and physical constraints, such as the relative displacement of the TMD, by employing an iterative optimization approach based on Linear Matrix Inequalities (LMIs). The proposed design is validated through nonlinear dynamic simulations, which demonstrate significant reductions in tower displacement, platform pitch, and fluctuations in power generation across various load conditions [15]. The efficacy of a TMD in mitigating wind-induced vibrations is markedly contingent upon the frequency characteristics of the wind forces. The optimal functioning of this mechanism is contingent upon the wind forces causing the structure to vibrate at, or near, its natural frequency. Nevertheless, variable or high-frequency wind forces may restrict the efficacy of the TMD unless it is designed to address a broader range of frequencies. In other words, it is essential to tune the TMD in frequency to the expected range of wind loading forces in order to achieve effective vibration control [16, 17]. The goal of this study is to evaluate the effectiveness of a TMD in mitigating wind turbine vibrations subjected to wind forces, namely sinusoidal and random. The impact of TMDs with varying mass ratios is examined to ascertain how these devices influence the mitigation of wind turbine vibrations, with the objective of elucidating strategies to enhance the stability factor, performance, and lifetime of wind turbines in dynamic wind conditions.

II. METHODOLOGY

TMD is a mechanism employed in large-scale facilities, such as towers and wind turbines, with the objective of reducing and controlling vibration levels. The excitation force of such structures is typically the wind force, which is generally considered to be random. The model was developed on the assumption that the system would vibrate in one degree of freedom laterally, as shown in Figure 1. The variable m is the mass of the wind turbine, m_t is the mass of the TMD, c is the damping coefficient of the main structure, k is the fore-aft spring stiffness for the main structure, k_t is the fore-aft spring stiffness of the TMD, c_t is the damping coefficient of the tuned mass damper, and F_w is the wind force. The equations of motion for the TMD system are:

$$m\ddot{x} + (c + c_t)\dot{x} + (k + k_t)x - c_t\dot{x}_t - k_t x_t = F_w \quad (1)$$

$$m_t\ddot{x}_t - c_t\dot{x} - k_t x + c_t\dot{x}_t + k_t x_t = 0 \quad (2)$$

$$\begin{bmatrix} m & 0 \\ 0 & m_t \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{x}_t \end{bmatrix} + \begin{bmatrix} c + c_t & -c_t \\ -c_t & c_t \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{x}_t \end{bmatrix} + \begin{bmatrix} k + k_t & -k_t \\ -k_t & k_t \end{bmatrix}\begin{bmatrix} x \\ x_t \end{bmatrix} = \begin{bmatrix} F_w \\ 0 \end{bmatrix} \quad (3)$$

The mass ratio μ_m is defined as the ratio between the main mass and TMD mass [18-20]:

$$\mu_m = \frac{m_t}{m} \tag{4}$$

TMD stiffness ratio μ_k is defined as the ratio between the main stiffness and TMD stiffness [18-20]:

$$\mu_k = \frac{k_t}{k} \tag{5}$$

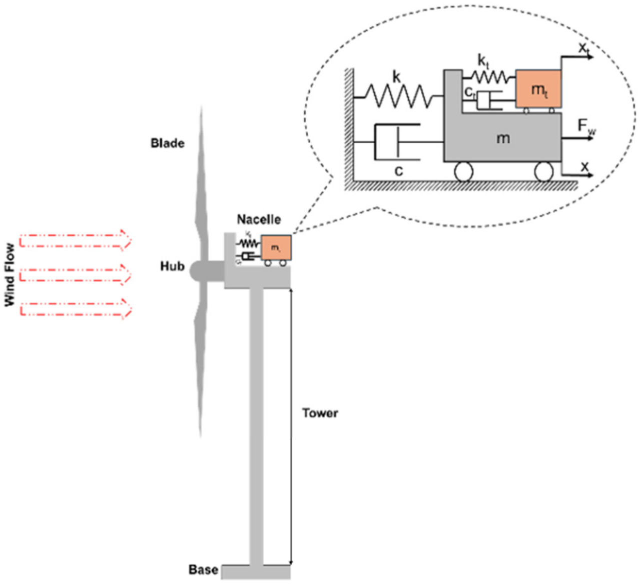

Fig. 1. Schematic of TMD of wind turbine.

For the TMD system to be effective, it is necessary that the frequencies of both the main mass and the TMD mass be equal. Consequently, the ratio between the two masses and the stiffness of the springs must also be equal. In this study, it is assumed that the ratios $\mu_m = \mu_k$. The damping coefficient c of the main structure can be expressed:

$$c = 2\zeta\sqrt{km} \tag{6}$$

The wind force F_W can be expressed as a function of wind speed at the tower u_h, which is:

$$u_h = \frac{u_{ref}}{\ln\frac{h_{ref}}{z_o}} \ln\frac{h}{z_o} \tag{7}$$

$$F_W = 0.5\,\rho_{air} A\, c_d u_h^2 \tag{8}$$

where, u_h is the wind speed at height h (m/s), u_{ref} is the reference wind speed, typically measured at a reference height h_{ref} (12 m/s), h is the height of the tower, where the wind speed is being calculated (90 m), h_{ref} is the reference height at which the wind speed u_{ref} is measured (10 m), z_o is the surface roughness coefficient (0.8-1.5, 1.2 was considered), F_W is the wind force acting on the structure (N), ρ_{air} is the air density (kg/m³), typically 1.225 kg/m³ at sea level under standard conditions, A is the projected area of the structure exposed to the wind (54 m²) and c_d is the drag coefficient, a dimensionless number depending on the shape and orientation of the object (1.2).

$$F_i = c_t\dot{x} + k_t x - c_t\dot{x}_t - k_t x_t \tag{9}$$

where, F_i is the internal force [18-20]. Table I presents the specifications of the wind turbine used in the modeling of the TMD system [21].

TABLE I. WIND TURBINE SPECIFICATIONS

Parameter	Symbol	Value
Number of Blades	b	3
Rotor Radius	r	75 m
Total Nacelle Mass	m	920,000 kg
Flap-Wise Spring Stiffness	k	5.215×10^7 N/m
Damping Coefficient	c	1,800,900 Ns/m
Damping Ratio	ζ	0.13
Tower Height	h	90 m
Avarage Wind Speed	u_h	12 m/s

III. RESULTS AND DISCUSSION

The mass ratio μ_m represents a crucial parameter for the efficiency of TMDs in wind turbines. The findings of simulations used to quantify the advantages of TMDs when employed to mitigate wind turbine vibrations induced by diverse excitation forces are presented below. The impact of varying μ_m on the vibration response of wind turbines is examined, and comparisons are drawn between sinusoidal and random forces. The forces applied to the system are of variable intensity, contingent on the wind speed. Thus, it is reasonable to consider the forces as representing a sinusoidal function for an average speed between 8 m/s and 15 m/s, and to calculate their effect on the structure. In the case considered in this study for the NREL 5 MW unit with a height of 50 meters, it was determined that the effective force is approximately 50 kN. The wind speed was set at 12 m/s with a standard deviation of 2 and a total time of 20 s, with a time interval of 0.01 s. The wind force loads in sine wave and random forms, respectively, are presented in Figure 2 generated by MATLAB code. Figure 2 (a) depicts the wind force as a sine wave with a wave frequency of 7.5 rad/s, while the random force is calculated using (6) and (7). In order for the TMD system to be effective, it is necessary to adjust the spring stiffness of the primary mass in accordance with the profile of the input forces. The frequency was then tuned based on these values, and it was found that the system was most effective at frequencies between 7 rad/s and 8 rad/s. Consequently, forces were applied at a frequency of 7.5 rad/s.

Figure 3 shows the efficacy of a TMD in mitigating vibration in a wind turbine, particularly in comparison to a configuration lacking such a device. There is a reduction in vibration amplitudes when a TMD is employed, with a mass ratio of 0.02, as opposed to a configuration without the TMD. The findings demonstrate that the TMD diminishes vibration amplitudes by approximately 30%, thereby imparting a discernible reduction in vibration across diverse operational scenarios. The efficacy of the TMD can be attributed to its capacity to absorb and dissipate the vibrational energy that would otherwise cause the turbine tower and blades to oscillate. This comparison demonstrates the efficacy of the TMD in stabilizing wind turbines and enhancing their performance under the influence of wind forces. The precise calibration of TMD settings, including its mass ratio, damping, and natural frequency, is of significant importance in achieving these outcomes. A 30% reduction in displacement is notable, as it indicates a reduction in stress on the turbine structure, which in turn reduces wear and extends the operational life of the turbine. This makes TMDs a practical solution for managing vibrations in wind turbines, enhancing both their reliability and overall performance. Further investigation of the efficacy of TMDs in different wind and structural conditions revealed results that were in agreement with those presented in [22].

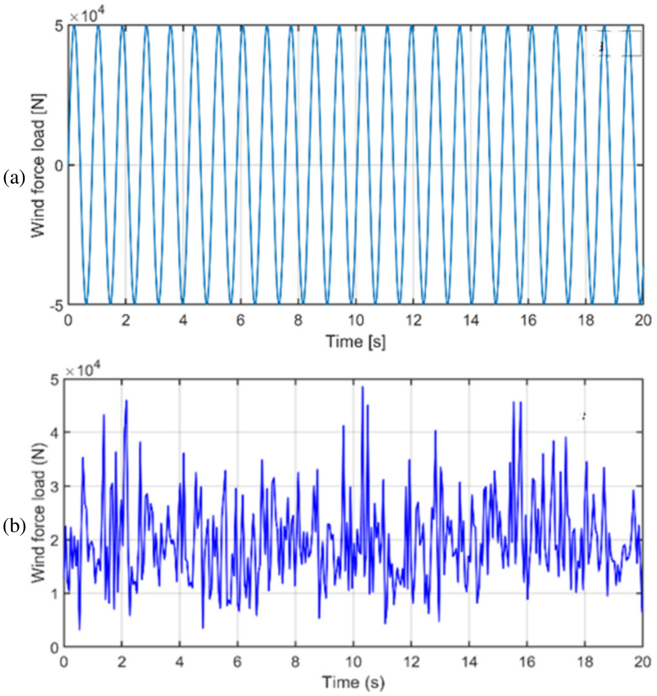

Fig. 2. Wind load force acting on the wind turbine: (a) sine wave, (b) random force.

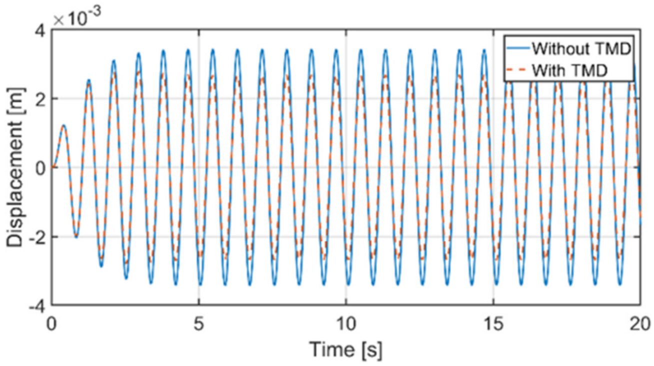

Fig. 3. Displacement with and without TMD excited by sine wave (μ_m=0.02).

Figure 4 portrays the impact of incorporating a TMD on the wind turbine's vibration displacement when the mass ratio is 0.05. Furthermore, a comparison is made between this scenario and one in which a TMD is not installed under the same conditions. The results clearly indicate that the installation of a TMD significantly reduces the vibration levels experienced by the wind turbine. In particular, a comparison of cases with and without a TMD reveals a decrease in vibration displacement of approximately 38% when the TMD is installed. This indicates that the TMD has the potential to enhance the structural integrity and durability of wind turbines subjected to dynamic loading conditions by effectively attenuating the vibrational response induced by the sine wave input force. The results are in accordance with those reported in [22].

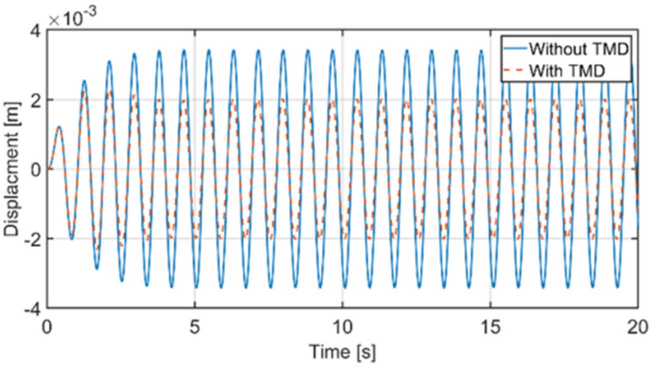

Fig. 4. Displacement with and without TMD excited by sine wave (μ_m=0.05).

Figure 5 displays the impact of a TMD on the vibration displacement of a wind turbine, with a mass ratio of 0.1, in comparison to the effects observed in the absence of a TMD. The findings demonstrate that the implementation of a TMD significantly reduces the vibration levels in wind turbines. It is reasonable to conclude that the deployment of a TMD results in a reduction of vibration displacement by approximately 50%, with a precise value of 49%.

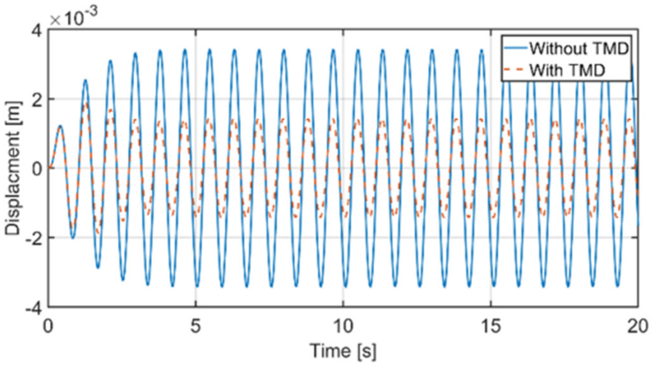

Fig. 5. Displacement with and without TMD excited by sine wave (μ_m=0.10).

Figure 6 shows the impact of incorporating a TMD on the vibration displacement of a wind turbine with a mass ratio of 0.2, relative to the absence of a TMD. In both scenarios, the wind force is sinusoidal. It was observed that the use of a TMD resulted in a notable reduction in vibration levels, with the maximum displacement for vibration being more than 70% lower than in the absence of a TMD. The same experiments were conducted with a mass ratio of 0.02, 0.05, 0.10, and 0.20, respectively. However, in this instance, the excitation force was treated as a random force that varied with the wind speed and height of the turbine. This change is more favorable in that it demonstrates how the wind's ever-changing nature will also affect the wind turbine's vibration response. The effect of different mass ratios was also examined to ascertain the extent to which a TMD can mitigate the vibrations caused by wind-induced random excitations and to identify the structural response of the turbine under variable wind loading conditions [23].

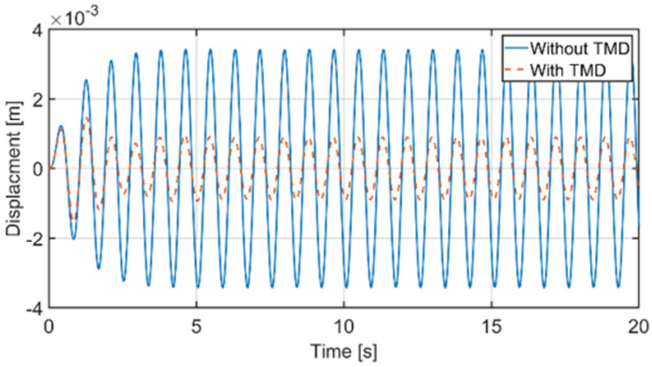

Fig. 6. Displacement with and without TMD excited by sine wave (μ_m=0.20).

Figures 7-10 illustrate the vibration displacement for mass ratios of 0.02, 0.05, 0.1, and 0.2, respectively, when the system is exposed to a random force. The findings indicated that the usage of TMD in conjunction with a random wind force did not result in a notable decline in vibration levels when compared to the absence of TMD. Nevertheless, as the mass ratio increases, a slight discrepancy is observed, indicating a reduction in the contribution of vibration, although not to a significant extent. This discrepancy does not reflect a notable enhancement, as random forces encompass a range of frequencies that present a challenge for the TMD system to adapt to. In order for the TMD to operate at peak efficiency and to accommodate the varying frequencies of random wind forces, it would require a variable stiffness spring. The use of a TMD is beneficial to wind turbines, as it systematically suppresses vibrations, particularly those of a sinusoidal nature. An increase in mass ratio has been observed to result in improved vibration suppression, with reductions of up to 70% achieved at higher ratios of 0.20. However, the effect of random wind forces is less pronounced, though still exhibiting a similar trend of increasing as mass ratio increases. It is therefore important to ensure that the TMD is properly tuned in order to facilitate the control of vibrations, and hence enhance the stability and durability of the wind turbine. Figures 11 and 12 show the vibration displacement in terms of Root-Mean-Square (RMS) values at the wind turbine structure under various mass ratios with a sine wave and random force inputs, respectively. It is noteworthy that the case without a TMD was represented at a mass ratio of zero. The TMD has been observed to significantly reduce vibration levels, with greater effectiveness noted as mass ratio increases under sinusoidal force excitation. In the case of random force, the improvement is marginal, however, there is a slight increase in mass ratio. The results demonstrate the efficacy of TMD in controlled force scenarios, whereas its impact under random forces is comparatively limited. The findings align with those in [23], where authors implemented a quick response controller to adapt the spring stiffness, demonstrating that this approach is highly effective in reducing vibration levels.

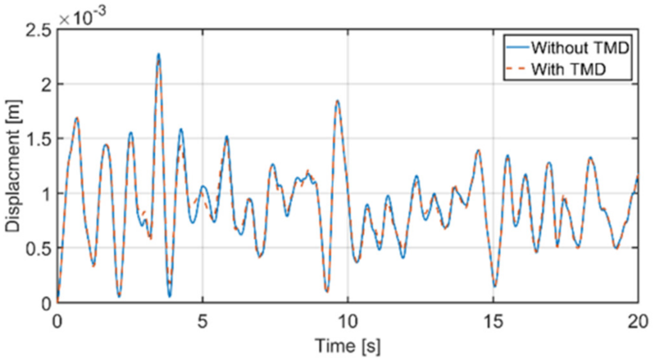

Fig. 7. Displacement with and without TMD excited by random force (μ_m=0.02).

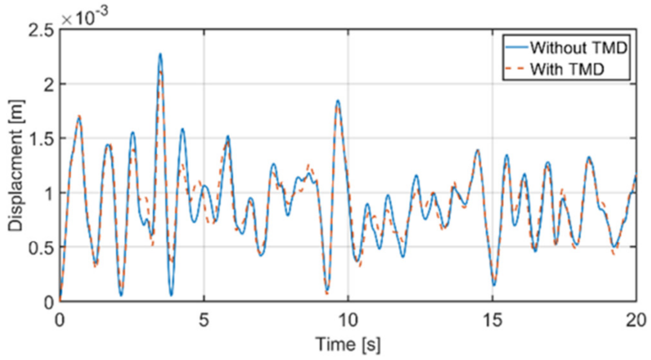

Fig. 8. Displacement with and without TMD excited by random force (μ_m=0.05).

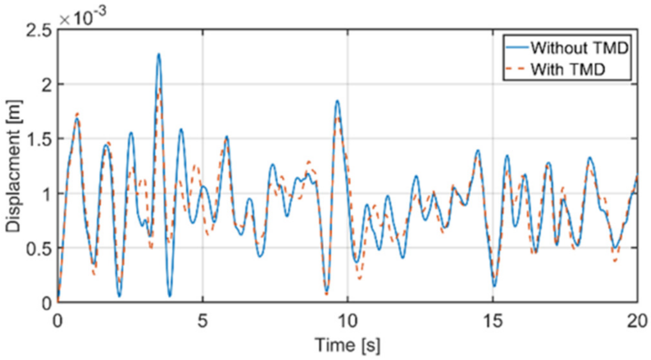

Fig. 9. Displacement with and without TMD excited by random force (μ_m=0.10).

As evidenced in Figure 12, the TMD system's passive mode, which lacks a rapid controller capable of modifying the spring stiffness of the nacelle, is ineffective in reducing vibration levels, with only minimal impact observed in the presence of randomly distributed forces. This suggests that the TMD system is effective. However, it requires a robust controller capable of rapid adjustments to the spring stiffness.

The internal forces that resulted from providing the tower system with a TMD will be examined using the MATLAB SIMULINK tool to ascertain their impact on the wind tower. The internal forces were calculated as the sum of the forces exerted on the main mass as a result of the installation of the TMD system. This led to a reduction of vibrations in the tower area of the wind turbine.

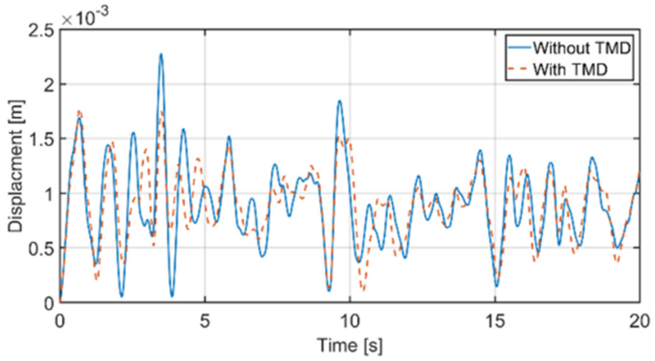

Fig. 10. Displacement with and without TMD excited by random force (mass ratio μ_m=0.20).

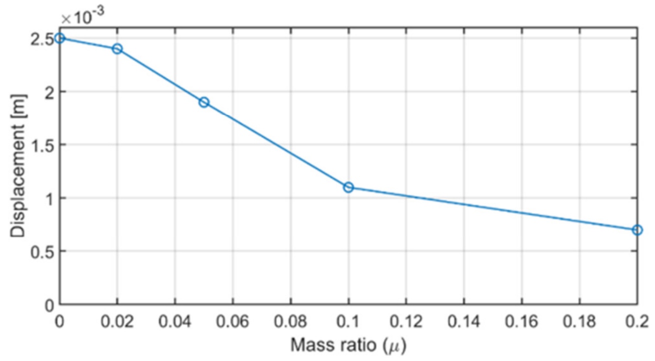

Fig. 11. RMS values of displacement with and without TMD excited by sine wave force.

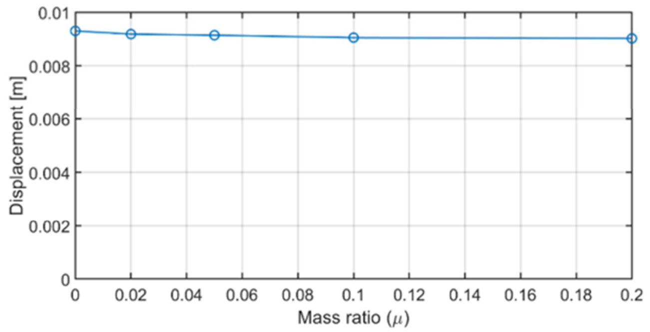

Fig. 12. RMS values of displacement with and without TMD excited by random force.

It is evident that the TMD functions correctly when the spring stiffness is calibrated to resonate with the force frequency. It should be noted that the internal forces are present within the structure. However, for the purposes of this study, they are not a significant factor. As exhibited in Figures 13 and 14, the internal forces are typically within acceptable limits with respect to the externally applied loads in both scenarios. Moreover, a reduction in mass ratio has been observed to result in an increase in internal forces, accompanied by a notable improvement in vibration levels. This demonstrates a correlation between the mass ratio, the degree of TMD efficiency, and the induced internal forces.

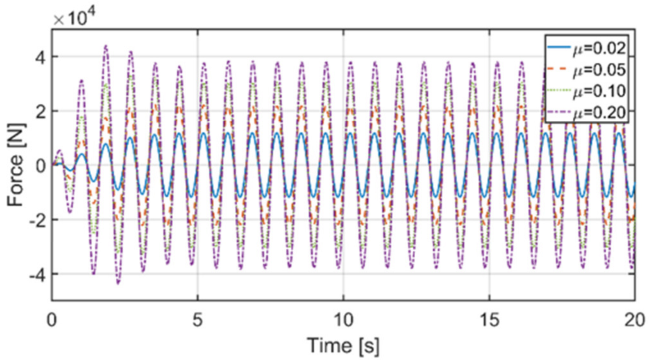

Fig. 13. Structural internal forces at different mass ratios with sinusoidal force.

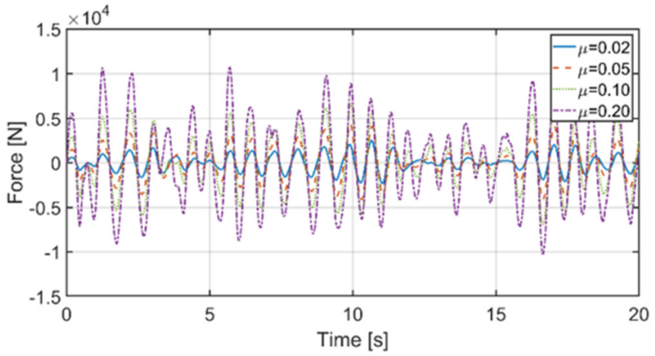

Fig. 14. Structural internal forces at different mass with random force.

IV. CONCLUSIONS

The analysis of the modelling of Tuned Mass Dampers (TMDs) for the mitigation of wind turbine vibration, using disparate excitation forces, including sinusoidal (also designated as deterministic) and random wind forces, has yielded substantial insights. The inquiry indicates that TMDs are highly efficacious in markedly reducing vibratory responses when wind turbines are subjected to sinusoidal forces, with diminished responses exhibiting an incremental increase in mass ratio. This observation underscores the significance of optimal TMD parameters, such as the natural frequency of the TMD and the mass ratio, for effective vibration control. At a mass ratio of 0.20, TMDs mitigated vibratory displacements by over 70%, thereby confirming the effectiveness of TMDs as a method for wind turbine control from agreed-upon loading, such as wind. Alternatively, when the turbine was subjected to random wind forces, the installation of the TMD system resulted in only a slight reduction in vibration levels compared to the case without the TMD. However, this modest reduction increased as the mass ratio was augmented. This outcome was anticipated, given that the intrinsic nature of random wind forces gives rise to a broad frequency spectrum that is highly variable and less predictable than wind loading with sinusoidal forces. The results of this study suggest that TMDs have the potential to extend the lifespan and enhance the performance of wind turbines under more predictable wind loading conditions. The findings also lend support to the further exploration and testing of adaptive or variable stiffness TMDs for the mitigation of complex random wind forcing problems. In conclusion, this study contributes new information to the fields of renewable energy and wind turbine technology, specifically with regard to the structural integrity and operational longevity of wind turbines.

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