Enhancement of Wind Turbine Vibrational Behavior by using a Pendulum Tuned Mass Damper

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ABSTRACT

Wind turbines experience significant vibrations due to fluctuating wind loads, which can impact structural integrity and operational efficiency. This study examines the effectiveness of Pendulum Tuned Mass Dampers (PTMDs) for mitigating these vibrations. Two types of wind force inputs were analyzed: a sinusoidal function representing periodic wind fluctuations and a random function simulating turbulent wind effects. Numerical simulations were conducted to evaluate the influence of mass ratios (0.01, 0.02, and 0.05) and damping ratios (0.1, 0.02, and 0.05) on vibration suppression. The results indicate that the installation of a PTMD can reduce vibrations from 45% to 91% under varying operating conditions. The optimum vibration suppression of up to 91% was achieved when the damping ratio was 0.02 and the mass ratio was 0.01 under sinusoidal wind force excitation. A mass ratio of 0.05 also led to a decrease of 54% in nacelle oscillations, confirming the effectiveness of PTMD in promoting stability. An optimal damping ratio of 0.02 was found to effectively balance energy dissipation and structural stability, preventing excessive oscillations and maintaining system efficiency. These findings confirm that integrating a PTMD can enhance wind turbine performance by reducing fatigue loads and extending operational lifespan. By optimizing the PTMD parameters, engineers can achieve better vibration control, improving the stability and durability of wind turbines under varying wind conditions. This study underscores the importance of passive vibration control mechanisms in modern wind energy systems and provides valuable insights into enhancing their long-term reliability.

Keywords-wind turbine; pendulum tuned mass damper; vibrational behavior; mass ratio; damping ratio; structural stability enhancement

I. INTRODUCTION

PTMDs have effectively mitigated wind turbine vibrations, especially those caused by aerodynamic forces and structural dynamics [1]. This is achieved by tuning the pendulum's natural frequency to the turbine's vibrational frequency, creating a counterbalancing force that reduces oscillations [2]. When the turbine vibrates due to operational stress or wind, the PTMD moves in the opposite direction, absorbing and dissipating the energy. It has been observed that PTMDs can reduce vibrations along- and across-wind by 40-60%, based on factors, such as mass ratio, levels of damping, and pendulum length. Specifically, the passive operation of PTMDs, which does not require any external power, makes them suitable for offshore wind turbines, where high reliability and low maintenance are particularly important. PTMDs decrease cyclic stresses and, as such, increase the fatigue life of the turbine parts, therefore reducing wear and tear effects for a long period [3, 4]. However, their effectiveness depends to a great degree on accurate tuning and installation; hence, careful design and simulations are necessary. Finally, PTMDs have been demonstrated as practical and efficient means of vibration control in wind turbines by providing improved structural stability, operational performance, and overall energy output [5]. The application of PTMDs in wind turbines has evolved significantly over the years, stemming from early developments in vibration control for civil engineering structures. Initially, PTMDs were introduced in the mid-20th century to stabilize tall buildings, long-span bridges, and industrial towers against wind-induced oscillations. Engineers have recognized that excessive vibrations can lead to structural fatigue and reduced lifespan, prompting the exploration of passive damping systems. Over time, this technology has been adapted for use in wind turbines, where aerodynamic and operational forces cause significant oscillations in the nacelles, tower, and blades [1].

Wind turbines, especially offshore models, are highly susceptible to environmental loads, such as wind gusts and wave action. These dynamic forces can cause undesirable vibrations that compromise both the efficiency and structural integrity. Traditional Tuned Mass Dampers (TMDs) were first introduced into wind turbine systems to mitigate excessive movement, but the pendulum variant (PTMD) has emerged as a more effective solution due to its unique ability to counteract oscillations with a swinging motion. The pendulum mechanism allows the auxiliary mass to move in opposition to the turbine's motion, absorbing and dissipating vibrational energy without the need for external power sources [6, 7]. Recent studies have confirmed the effectiveness of PTMDs in wind turbine applications. Research published in 2023 showed that PTMDs with optimized mass and frequency ratios can reduce nacelle sway and tower displacement by over 50%. For instance, one study on offshore wind turbines found that implementing a PTMD with a mass ratio of 2% improved the damping efficiency and reduced the peak vibrations by approximately 10% compared to conventional TMDs. This highlights the importance of tuning PTMD parameters to match the specific dynamic characteristics of a wind turbine, ensuring maximum vibration mitigation and energy dissipation [8].

Another investigation into PTMDs for offshore wind turbines explored the impact of three-dimensional (3D) damping configurations [9]. Traditional TMDs are often limited to single-axis movement, but advanced PTMD designs now incorporate multi-directional motion to address vibrations in both the fore-aft and side-side directions. Authors in [9] demonstrated that a properly tuned 3D PTMD could significantly enhance the stability of turbines exposed to extreme wind and wave conditions. By integrating advanced modeling techniques, researchers have optimized PTMD performance, ensuring effective vibration control while minimizing additional structural loads [4, 10]. Furthermore, engineers have recognized the role of material selection and design optimization in improving PTMD efficiency. Modern PTMDs utilize lightweight yet durable materials to reduce the overall weight burden on the turbine while maintaining their effective damping properties. Computational simulations and experimental testing have also played crucial roles in refining PTMD designs, allowing engineers to predict their performance under various wind conditions [4, 11].

A PTMD is effective when its natural frequency matches the dominant vibration mode frequency of the structure, allowing it to efficiently counteract oscillations. The PTMD must have a sufficient mass ratio relative to the structure, be placed at the location of maximum displacement, and have optimized damping to balance the energy dissipation without excessive resistance. The system works best for structures with dominant, predictable vibrations, such as skyscrapers, bridges, and towers, especially under wind or seismic loads. However, its effectiveness decreases if the external forces are highly irregular or if the damper is poorly tuned. Different approaches have been proposed in which the growth of wind speed is modeled as either sinusoidal or random functions to provide room for normal and random impacts that arise naturally. The dynamic modeling of the nacelle assembly motion in this study was viewed as a mass-spring-damper system, thus allowing the representation of complex vibrating mechanisms [13]. The wind speed fluctuation was inserted into the simulations using a sinusoidal function for periodic fluctuation or a random function to simulate natural turbulence. The analysis started by estimating the combined forces exerted on the nacelle in the form of aerodynamic loads, structural vibrations, and environmental wind forces [12]. When PTMD was incorporated in the system, a mass ratio of 0.01 to 0.02 was used to ensure that the internal resistances of the structure were not increased, and the damping ratio ranged between 0.01 and 0.05. The forces on the turbine neck were computed, along with the influence of the turbine height on the forces. However, increasing the damping ratio beyond 0.02 had the opposite effect on vibration suppression. The forces acting on the turbine neck and the effect of turbine height on the values of these forces were calculated [14].

This study investigates the effectiveness of PTMDs in mitigating nacelle displacement of an NREL 5 MW wind turbine using a Single-Degree-Of-Freedom (SDOF) model in MATLAB/Simulink. Two types of wind excitation forces were considered to evaluate their effect on the nacelle response: a sinusoidal wave and a random force, both with a frequency of 1 rad/s.

II. METHODOLOGY

The turbine specifications used in this study were based on the NREL 5-MW wind turbine, which is a commonly adopted benchmark model. It is rated at 5 MW, with a total nacelle weight of approximately 298,000 kg, including the drivetrain and generator. The stiffness varies from component to component, with the nacelle-tower interface stiffness modeled on the order of 51.2 MN/m to effectively reel in dynamic behavior. This turbine can provide a reference for the design and analysis of large wind energy systems owing to its magnitude [15].

The modeling of the PTMD for the NREL 5 MW wind turbine was performed using an SDOF dynamic system in MATLAB/Simulink. The PTMD was integrated into the nacelle to counteract tower vibrations through its tuned oscillatory motion, as portrayed in Figure 1. The governing equation was derived using Lagrange's equations, incorporating mass, damping, and stiffness parameters. Wind excitation was applied as two types of input: a sinusoidal wave representing periodic wind loading and a stochastic random wave simulating turbulent conditions. Numerical simulations in MATLAB/Simulink were conducted to optimize the PTMD parameters for effective vibration suppression.

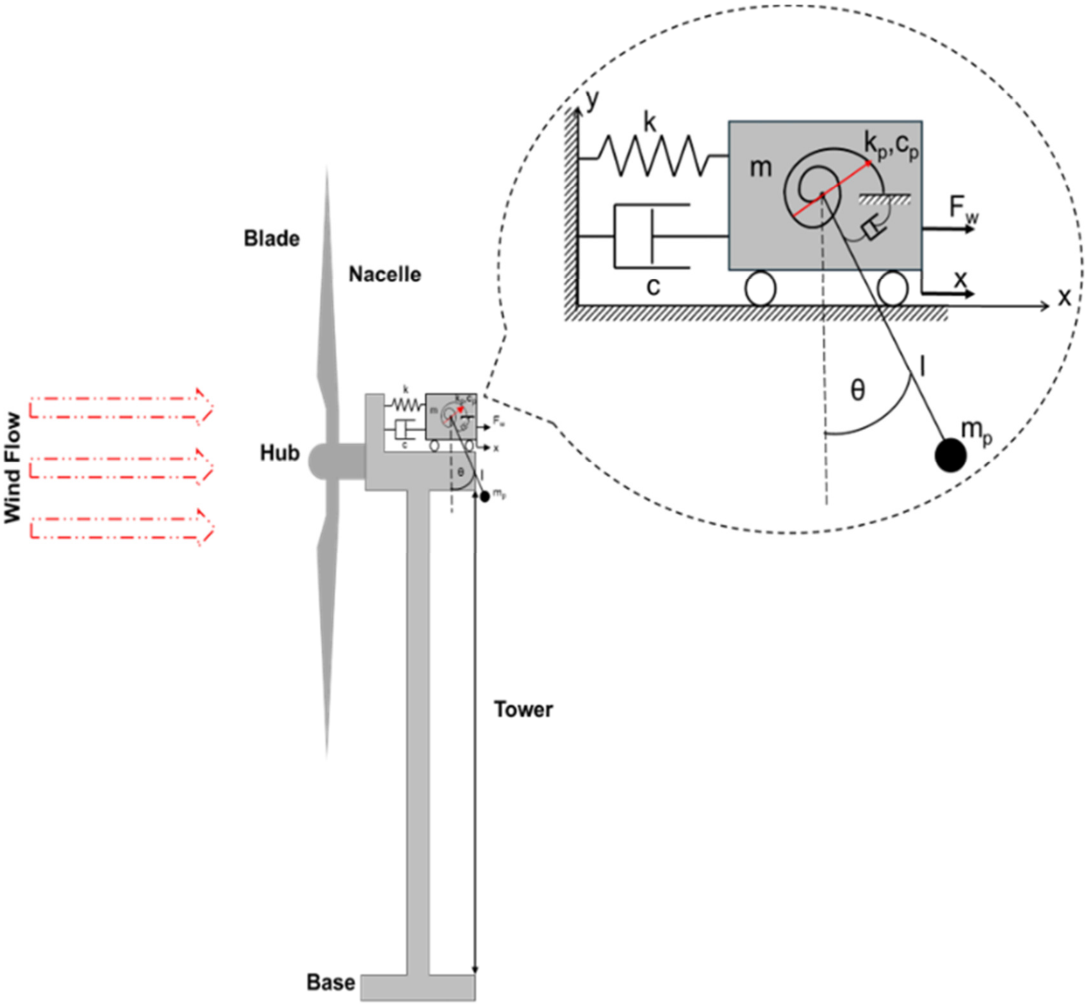

Fig. 1. Schematic of a wind turbine including the PTMD.

In Figure 1, m represents the wind turbine mass, m_p is the mass of the pendulum, $\boldsymbol{c}$ is the damping coefficient of the main structure, k is the fore-aft spring stiffness of the main structure, k_p is the torsional spring stiffness of the pendulum, c_p is the torsional damping coefficient of the pendulum, and F_w is the wind force.

The equations of motion for the PTMD system are as follows, and in the derivations of the equations it is assumed that $\sin\theta = \theta$, $\cos\theta = 1$, and $\theta^2 = 0$.

$$T = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}m_p(\dot{x} + l\dot{\theta}\cos\theta)^2 + \frac{1}{2}m_p(l\dot{\theta}\sin\theta)^2$$

$$= \frac{1}{2}m\dot{x}^2 + \frac{1}{2}m_p\left(\dot{x}^2 + 2\dot{x}l\dot{\theta} + l^2\dot{\theta}^2\right) + \cancel{\frac{1}{2}m_p l^2\dot{\theta}^2\theta^2}$$

$$= \frac{1}{2}m\dot{x}^2 + \frac{1}{2}m_p\dot{x}^2 + m_p l\dot{x}\dot{\theta} + \frac{1}{2}m_p l^2\dot{\theta}^2$$

$$U = \frac{1}{2}kx^2 + m_p gl\cos\theta + \frac{1}{2}k_p\,\theta^2$$

$$= \frac{1}{2}kx^2 + m_p gl + \frac{1}{2}k_p\theta^2$$

$$F_D = \frac{1}{2}c\dot{x}^2 + \frac{1}{2}c_p\dot{\theta}^2$$

After applying the Lagrange equations, the following dynamic equations of the system are obtained:

$$m\ddot{x} + m_p\ddot{x} + m_p l\ddot{\theta} + c\dot{x} + kx = F_w$$

$$m\ddot{x} + m_p\ddot{x} + m_p l\ddot{\theta} + c\dot{x} + kx = F_w \tag{1}$$

$$m_p l\ddot{x} + m_p l^2\ddot{\theta} + c_p\dot{\theta} + k_p\theta = 0$$

$$m_p l\,\ddot{x} + m_p l^2\,\ddot{\theta} + c_p\dot{\theta} + k_p\,\theta = 0 \tag{2}$$

After putting these equations in matrix form, we obtain:

$$\begin{bmatrix} m + m_p & m_p l \\ m_p l & m_p l^2 \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} c & 0 \\ 0 & c_p \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{\theta} \end{bmatrix}$$

$$+\begin{bmatrix} k & 0 \\ 0 & k_p \end{bmatrix}\begin{bmatrix} x \\ \theta \end{bmatrix} = \begin{bmatrix} F_w \\ 0 \end{bmatrix}$$

The mass ratio μ_m is defined as the ratio between the main mass and PTMD mass [16-18]:

$$\mu_m = \frac{m_p}{m} \tag{3}$$

The PTMD stiffness ratio μ_k is defined as the ratio of the main stiffness and PTMD stiffness [16-18]:

$$\mu_k = \frac{k_p}{k} \tag{4}$$

For the PTMD system to be effective, the frequencies of both the main mass and the PTMD mass must be equal. Therefore, the ratio between the two masses and the spring stiffness must be equal. In this study, it is considered that the ratios $\mu_m = \mu_k$.

For the PTMD system, the natural frequency is given by [17]:

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{k_p}{m_p}} = \sqrt{\frac{g}{l}} \tag{5}$$

where g is the Earth's gravity and l is the pendulum length.

The damping coefficient c of the main structure can be expressed as [16-18]:

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

The wind force F_W can be expressed as a function of wind speed at the tower u_h. The wind speed at the tower and wind force can be calculated using [16-18]:

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

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

where u_h is the wind speed at height h (m/s), u_{ref} (12 m/s) is the reference wind speed, typically measured at a reference height h_{ref}, h (90 m) is the height of the tower, where the wind speed is being calculated, h_{ref} (10 m) is the reference height at which the wind speed u_{ref} is measured, z_o (ranges between 0.8-1.5, it is set at 1.2) is the surface roughness coefficient, 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 (54 m²) is the projected area of the structure exposed to the wind, c_d (1.2) is the drag coefficient, a dimensionless number depending on the shape and orientation of the object.

Figures 2 and 3 show the wind force (input for the system) in sine wave and random forms, respectively. Both have a 1 rad/s wave frequency, and the random force is modeled with a standard deviation of 2.

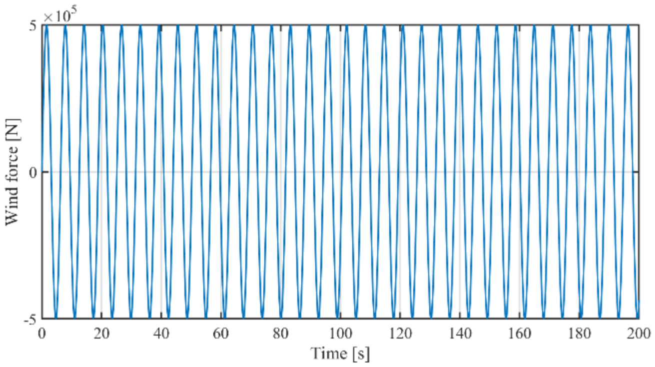

Fig. 2. Wind force input as sine wave (frequency of 1 rad/s).

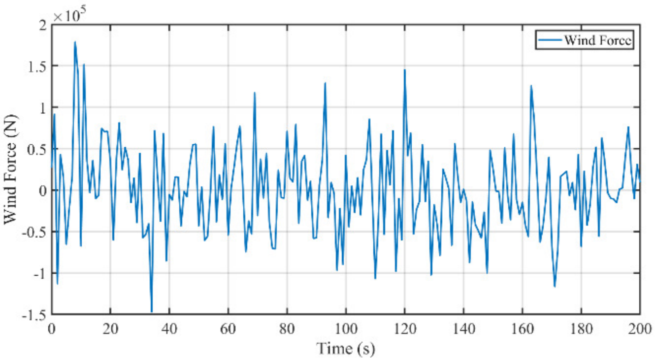

Fig. 3. Wind force input as random force (frequency of 1 rad/s).

III. RESULTS AND DISCUSSION

In this section, the vibration displacements are provided, along with an analysis of the PTMD effect in minimizing wind turbine vibrations. The results were used to evaluate the nacelle displacement for various damping and mass ratio configurations under sinusoidal and random wind force inputs. By varying the major parameters, namely damping ratio values of 0.1, 0.02, and 0.05 in combination with mass ratio values of 0.01, 0.02, and 0.05 an assessment of the oscillation-minimizing and system-stabilizing effectiveness of the PTMD were investigated. Using comparative graphs, the difference between the controlled and uncontrolled cases is shown and the role of PTMD in reducing unwanted vibrations is demonstrated. Furthermore, investigations were conducted to determine how variations in the external wind load affect the vibration-attenuating efficiency. This information is instrumental in determining the optimal PTMD configuration for improving wind turbine performance, while laying emphasis on how important it is for a PTMD to be tuned exactly for the highest damping efficiency. Finally, the observed trends and their implications are discussed and a comparison of these concepts with previous studies is conducted to validate the proposed approach.

As depicted in Figure 4, the system analysis shows a significant reduction in the vibration amplitude when comparing the performance before and after the addition of damping. This confirms the effectiveness of PTMD in minimizing vibrations and enhancing structural stability. Based on the given parameters, namely mass ratio of 0.01, frequency ratio of 1, and damping ratio of 0.1, the vibration reduction percentage ranged between 45% and 82%. Similar findings have been previously reported confirming the effectiveness of the PTMD in vibration mitigation if it is well designed with appropriate mass, frequency, and damping ratios. The vibration reduction percentage of 45%–82% agrees with similar studies, where analogous parameter settings translate into considerable vibration attenuation [19, 20]. This consistency corroborates the validity of the present findings and confirms the effectiveness of PTMD in enhancing structural stability, as demonstrated in previous studies [19, 20].

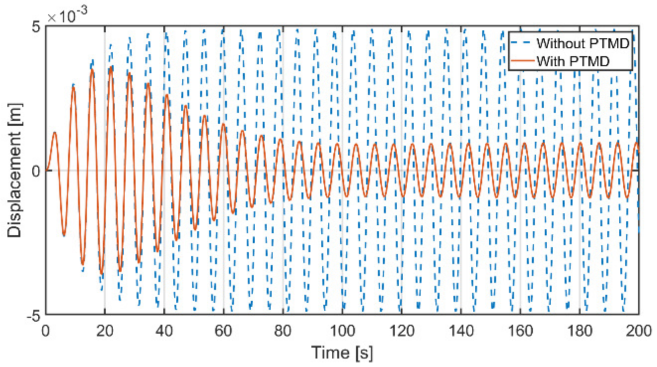

Fig. 4. Nacelle displacement variations when damping ratio is 0.1, mass ratio is 0.01, and sinusoidal wind force is applied with frequency ratio of 1.

The results in Figure 5 exhibit the nacelle displacement variations at a damping ratio of 0.02, mass ratio of 0.01, and a sine wave wind force frequency ratio of 1 with input frequency 1 rad/s. The results indicate that the vibration reduction percentage ranged from 45% to 91%, highlighting the effectiveness of the PTMD in minimizing structural vibrations. This substantial reduction is particularly beneficial in engineering applications, such as high-rise buildings, long-span bridges, and wind turbine towers, where excessive oscillations can compromise structural integrity and operational efficiency. This improved performance can be attributed to the ability of the PTMD to absorb and dissipate kinetic energy, leading to a stabilized dynamic response. These results agree with previous studies, where the performance of a PTMD with a mass ratio of 0.05 under different conditions was investigated [21]. The study reported displacement reduction ratios ranging from 40% to 73.81%, aligning with the vibration reduction range of 45% to 91% observed in the current research. Additionally, Authors in [22] demonstrated that PTMDs significantly enhance the damping of structural systems vibrations, leading to effective vibration attenuation. Although the specific parameters differ, the overall conclusion supports the present work's findings on the effectiveness of PTMDs in reducing vibrations.

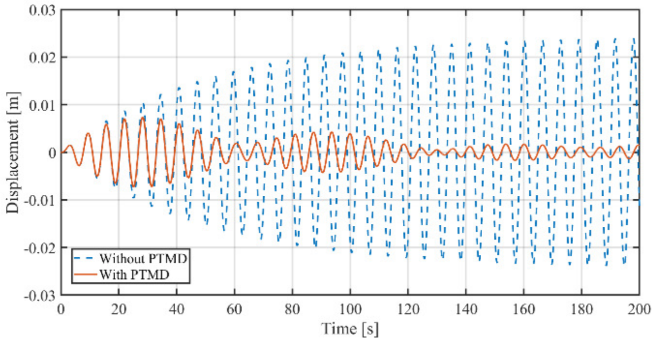

Fig. 5. Nacelle displacement variations when damping ratio is 0.02, mass ratio is 0.01, and sinusoidal wind force is applied with frequency ratio of 1.

A close examination of Figure 5 reveals a beating phenomenon. As is evident in the "Without PTMD" case, the oscillations of the displacement exhibited a periodically changing amplitude. This is due to the interference between two closely positioned natural frequencies within the system, resulting in a periodic increase and decrease in the intensity of the oscillations. Beating is caused by the superposition of two waves with frequencies that have a very small difference, creating a slow modulation of the net amplitude with the underlying vibration taking place at a higher frequency. This phenomenon indicates weak intrinsic damping or that the vibrations persisted for an extended period without significant energy loss. In contrast, the "With PTMD" case shows a dramatic reduction in oscillation amplitude and that the displacement fades away with time. This suggests that the PTMD effectively dissipates and absorbs vibrational energy, eliminating resonance behavior and eradicating unwanted oscillations. By providing additional damping and changing the system dynamic response, the PTMD prevents energy from oscillating between successive closely spaced modes, thereby eliminating the beating effect. This indicates the importance of TMDs in the vibration control of wind turbines, where unwanted oscillations can lead to structural fatigue or failure.

Figure 6 shows how the presence of PTMD improves the stability of wind turbines. With a damping ratio of 0.05, the oscillation was reduced by up to 54% compared to the case without the PTMD. This reduction occurs because the PTMD absorbs the excess energy generated by the wind, thereby reducing the vibrations and improving the turbine performance. Essentially, the PTMD works by absorbing and dissipating the excess motion caused by the wind, helping to stabilize the turbine. This leads to less vibration and a more efficient system overall. The performance of the PTMD largely depends on careful tuning processes, which are of paramount importance because the system dynamically responds to varying wind conditions without any direct human intervention. Effective tuning ensures that the frequency and damping of the damper match the structural behavior of the turbine to optimize energy dissipation and reduce oscillations. If not properly tuned, the PTMD can become useless or even counterproductive and end up enhancing vibrations instead of suppressing them. Moreover, well-tuned PTMDs enhance the lifespan of turbine components through minimizing structural fatigue, thus ensuring increased reliability and efficiency. Such aspects underscore the significance of advanced tuning techniques for maximizing the PTMD performance in offsetting fluctuating wind impacts on turbine stability. These results are consistent with those of previous studies. For instance, authors in [23] discussed the application of PTMDs for mitigating wind-induced vibrations in structures. Authors in [22] emphasize the effectiveness of PTMDs in absorbing excess energy and reducing oscillations, which aligns with the present study's results.

The effects of varying the mass ratio from 0.02 to 0.05 on the nacelle displacement when the damping ratio is 0.02 and the frequency ratio is 1 are plotted in Figures 7 and 8, respectively.

The graphs illustrate the nacelle displacement over time with and without the PTMD. The dashed blue line represents the system without PTMD, whereas the solid red line represents the response with PTMD. The results clearly show that the PTMD helps to reduce nacelle vibrations. Without the damper, the displacement amplitudes gradually increased, indicating the buildup of oscillations over time. In contrast, with the PTMD in place, the oscillations remained controlled, and the displacement stayed within a smaller range. The impact of the mass ratio of the PTMD can be seen in how effectively it reduces peak displacements. By adding PTMD, a portion of the vibrational energy was absorbed and dissipated, preventing excessive motion. The solid red line in the graph confirms that the nacelle experienced a significantly lower displacement when the damper was applied.

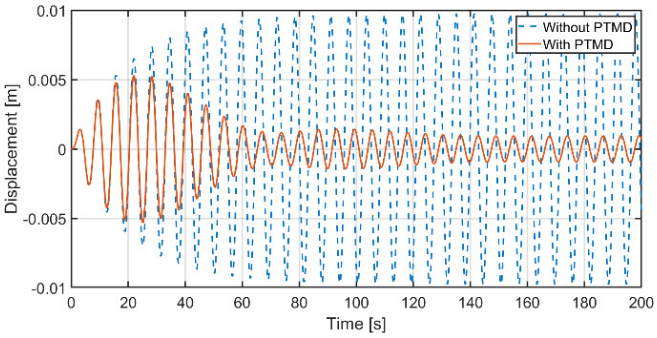

Fig. 6. Nacelle displacement variations when damping ratio is 0.05, mass ratio is 0.01, and sinusoidal wind force is applied with frequency ratio of 1.

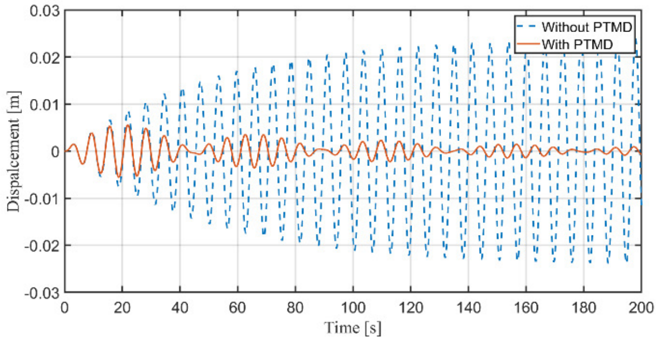

Fig. 7. Nacelle displacement variations when damping ratio is 0.02, mass ratio is 0.02, and sinusoidal wind force is applied with frequency ratio of 1.

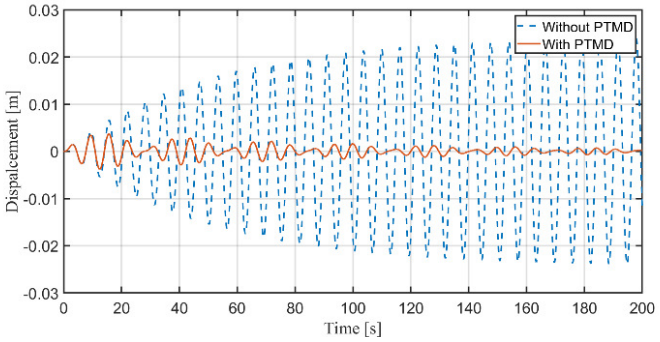

Fig. 8. Nacelle displacement variations when damping ratio is 0.02, mass ratio is 0.05, and sinusoidal wind force is applied with frequency ratio of 1.

Using a PTMD improves the stability of the system by minimizing oscillations, which can help reduce structural stress and potential long-term damage to the wind turbine. This highlights the importance of optimizing the mass ratio for better vibration control. The results obtained to evaluate the impact of the mass ratio on the nacelle displacement align with the findings of recent studies, which indicate that increasing the mass ratio of the PTMD enhances its effectiveness in mitigating vibrations [24].

Figures 9, 10, and 11 display how different damping ratios (0.01, 0.02, and 0.05, respectively) affect the nacelle displacement while maintaining a constant mass ratio of 0.01 and a random wind force is applied. The dashed blue line represents the displacement without the PTMD, whereas the solid red line represents the displacement with the PTMD. At a damping ratio of 0.01, the PTMD slightly reduced the displacement, but the oscillations continued for a longer time. When the damping ratio increased to 0.02, the displacement decreased more noticeably, as the PTMD absorbed more energy and helped suppress the vibrations. At the highest damping ratio of 0.05, there was a significant reduction in the nacelle displacement, and the oscillations dampened out much faster, making the system more stable. These results highlight that a higher damping ratio leads to better vibration control and reduces structural stress on the wind turbines. However, excessive damping can also influence the overall system response, making it essential to find the right balance for optimal performance [25].

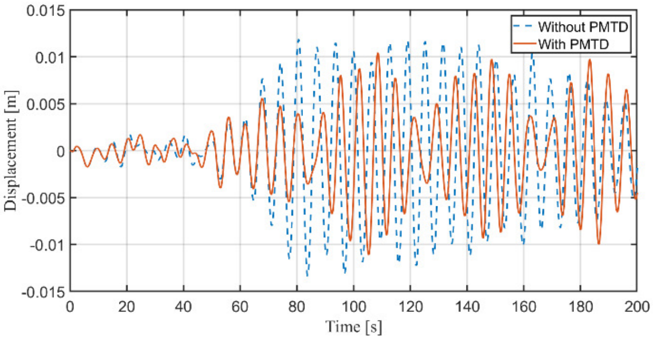

Fig. 9. Nacelle displacement variations when damping ratio is 0.1, mass ratio is 0.01, and random wind force is applied with frequency ratio of 1.

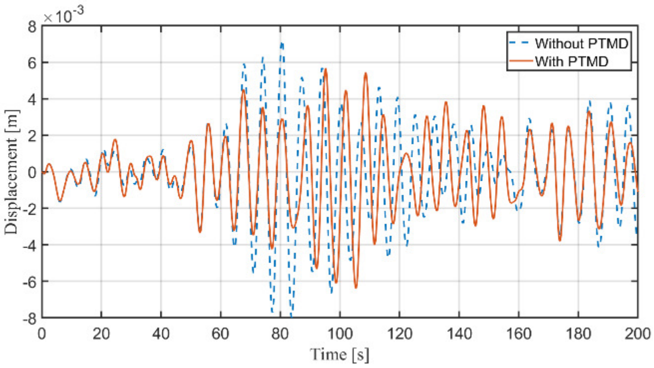

Fig. 10. Nacelle displacement variations when damping ratio is 0.02, mass ratio is 0.01, and random wind force is applied with frequency ratio of 1.

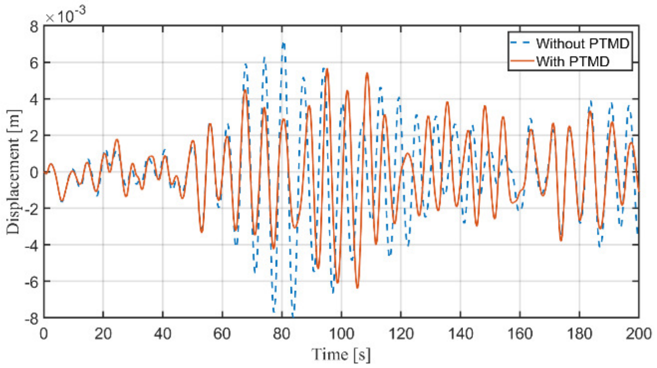

Fig. 11. Nacelle displacement variations when damping ratio is 0.05, mass ratio is 0.01, and random wind force is applied with frequency ratio of 1.

Figures 12 and 13 show that varying the mass ratio of the PTMD influences the nacelle displacement in a wind turbine subjected to a random force at a frequency of 1 rad/s. The damping ratio was fixed at 0.02, with a frequency ratio of 1. The dashed blue line represents the nacelle response without PTMD, whereas the solid red line demonstrates the response to PTMD. As illustrated in Figure 10, for the lowest mass ratio (0.01), the PTMD provided only a minimal reduction in nacelle displacement. Although PTMD helps in moderating some oscillations, the response still exhibits significant fluctuations, and vibrations persist for an extended period. When the mass ratio increased to 0.02, as can be seen in Figure 12, the PTMD became more effective, leading to a more noticeable reduction in the displacement amplitude. This indicates that the damper dissipates energy more efficiently, helping to suppress oscillations and improve overall stability. At the highest mass ratio of 0.05, as depicted in Figure 13, the PTMD achieved the most substantial vibration suppression. The amplitude of the displacement was significantly reduced, and the oscillations dampened out more rapidly than at lower mass ratios. This suggests that a heavier PTMD can better absorb and counteract the vibrational energy affecting the nacelle. However, while increasing the mass ratio improves vibration reduction, it also introduces additional inertia into the system, which may influence the overall dynamic response of the wind turbine. An excessive mass in the PTMD can lead to secondary effects, such as altering the natural frequencies of the turbine or affecting its structural integrity.

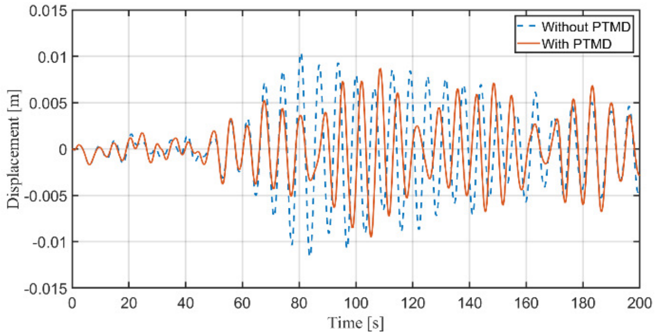

Fig. 12. Nacelle displacement variations when damping ratio is 0.02, mass ratio is 0.02, and random wind force is applied with frequency ratio of 1.

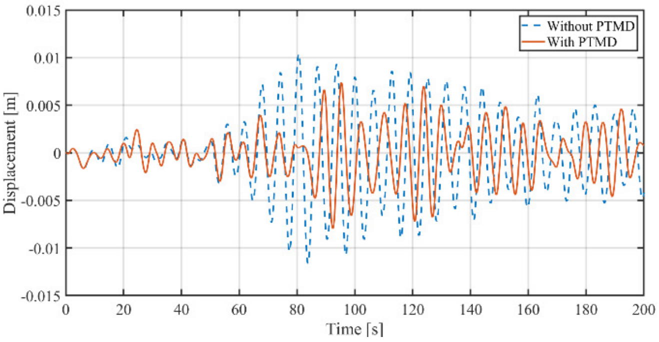

Fig. 13. Nacelle displacement variations when damping ratio is 0.02, mass ratio is 0.05, and random wind force is applied with frequency ratio of 1.

Figure 14 shows that applying the PTMD effectively reduced the vibration displacement of the wind turbine, as indicated by the decreasing downtrend of the Root Mean Square (RMS) with a higher mass ratio (μ). In the absence of PTMD, the displacement was 0.0055 m, whereas all PTMD cases showed lower values, substantiating its effectiveness. Higher reduction is observed at high mass ratios, but the gain is leveled as μ increases, indicating that an optimal value mass ratio exists. For lower μ values, the suppression of vibration is noticeable but not very crucial. As μ increases, the damping effect increases significantly. However, excessive mass may introduce structural complexities or additional costs with minimal gain. This phenomenon of diminishing return suggests that the selection of the optimal μ is essential to provide vibration control, structural stability, and economic viability. In wind turbines, vibration reduction enhances stability, reduces mechanical stress, and extends the life of the turbine. Efficient damping techniques, such as PTMD, enhance the performance of turbines, reduce maintenance costs, and improve overall sustainability. Therefore, the PTMD system design should consider careful planning of the mass ratio to ensure optimal performance while maintaining efficiency and cost-effectiveness in wind energy applications.

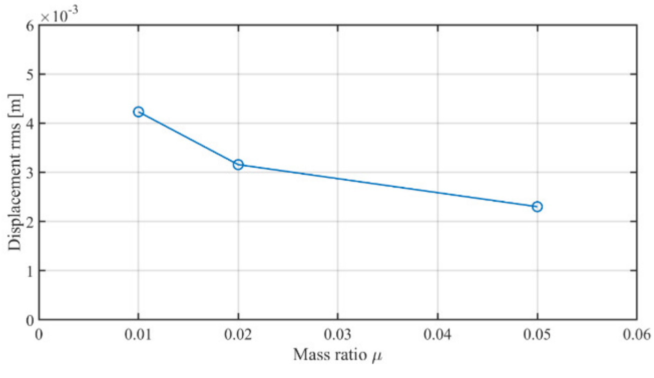

Fig. 14. RMS values of displacement for PTMD at 0.02 damping ratio.

Figure 15 illustrates the impact of the damping ratio (ζ) on the RMS displacement of a wind turbine when a PTMD is applied. The RMS displacement was 0.0055 m initially without PTMD, indicating high levels of vibration. Following the application of the PTMD, a sharp reduction in displacement is evident, confirming the effectiveness of the damper in suppressing the structural oscillations. As the damping ratio is increased from a very low level (approximately 0.01) to approximately 0.02, the displacement decreases significantly, demonstrating the initial effectiveness of the added damping. Beyond this, however, the reduction in vibration tapers off, which suggests that excessive damping does not result in further significant gains. This reaction is in accordance with the principles of structural dynamics, where there is an optimal level of damping beyond which there are diminishing returns from the added damping. The results indicate that a well-tuned damping ratio is required to balance the reduction in vibration and structural efficiency. Overdamping can lead to unnecessary design complexities or increased cost with no benefits. The results validate that PTMD is an effective approach to counter wind turbine vibrations, thereby enhancing structural stability, reducing fatigue loads, and increasing operational life. Future research could explore how the damping ratio, mass ratio, and frequency tuning interplay to maximize the PTMD performance for real wind energy harvesting applications.

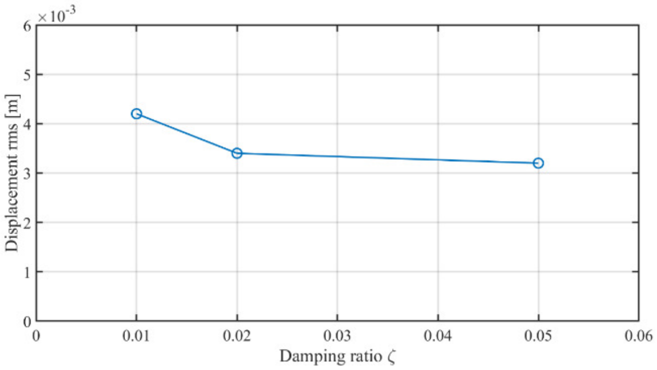

Fig. 15. RMS values of displacement for PTMD at 0.01 mass ratio.

Overall, the results highlight the importance of optimizing the PTMD mass ratio to balance vibration control effectiveness and system dynamics. For the lowest mass ratio (0.01), the PTMD provided a minimal reduction in the nacelle displacement. Although it helped to moderate some oscillations, the response still exhibited significant fluctuations, and the vibrations persisted for an extended period. When the mass ratio increased to 0.02, the PTMD became more effective, leading to a noticeable reduction in the displacement amplitude. This indicates that the damper dissipated energy more efficiently, suppressing oscillations and improving overall stability. At the highest mass ratio of 0.05, the PTMD achieved the most substantial vibration suppression. The amplitude of the displacement was significantly reduced, and oscillations dampened out more rapidly than at lower mass ratios. This suggests that a heavier PTMD can better absorb and counteract the vibrational energy affecting the nacelle. However, increasing the mass ratio also introduces additional inertia into the system, potentially influencing the overall dynamic response of the wind turbine. An excessive PTMD mass can alter the natural frequencies of the turbine or affect its structural integrity.

These findings highlight the importance of optimizing PTMD's mass ratio to balance vibration control effectiveness and system dynamics. A properly tuned mass damper significantly enhances nacelle stability, reduces fatigue loads, and extends the operational lifespan of wind turbines. However, selecting the ideal mass ratio requires careful consideration of structural constraints and the turbine's specific dynamic characteristics [15].

IV. CONCLUSIONS

The results of this study confirm that the addition of a Pendulum Tuned Mass Damper (PTMD) significantly reduces wind turbine vibrations, resulting in better structural stability and functional efficiency. The PTMD achieved vibration reductions ranging from 45% to 91% under sinusoidal wind excitation, with the highest reduction observed at a damping ratio of 0.02 and a mass ratio of 0.01. Additionally, when the mass ratio was increased to 0.05, the oscillations were reduced by up to 54%, indicating the effectiveness of mass optimization for vibration suppression. The PTMD effectively absorbed and redistributed the kinetic energy within the system, leading to substantial vibration suppression and resonance mitigation.

In contrast, when subjected to random excitation, the PTMD performance varied, achieving vibration reductions between 15% and 50%. However, its effectiveness was significantly influenced by the damping ratio, as increasing damping reduced the system's ability to absorb and dissipate vibrational energy, leading to diminished vibration suppression efficiency. Moreover, the operating conditions, such as mass ratio and damping ratio play a crucial role in designing and optimizing PTMD parameters for maximum efficiency. Fine-tuning the mass and damping ratio based on real-world operating conditions is essential for achieving an optimal performance.

The findings demonstrate that effective vibration suppression depends on the precise calibration of these parameters, necessitating advanced simulations and testing to ensure that PTMD's dynamic performance aligns with the specific needs of wind turbine systems. Based on these results, PTMD is an effective solution for mitigating structural vibrations and enhancing the stability of dynamic systems, particularly in engineering applications exposed to periodic and random loads, such as high-rise buildings, long-span bridges, and wind turbines. However, further research is required to optimize the PTMD design by adjusting the damping characteristics and mass distribution to maximize vibration attenuation. This study highlights the importance of PTMD as a passive vibration control strategy, with future advancements expected to enhance its performance in complex engineering applications.

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