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Bi-directional vibration control of offshore wind turbines using a 3D pendulum tuned mass damper

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A R T I C L E I N F O

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A B S T R A C T

Offshore wind turbines suffer from excessive bi-directional vibrations due to wind-wave misalignment and vortex induced vibrations. However, most of existing research focus on unidirectional vibration attenuation which is inadequate for real applications. The present paper proposes a three dimensional pendulum tuned mass damper (3d-PTMD) to mitigate the tower and nacelle dynamic response in the fore-aft and side-side directions. An analytical model of the wind turbine coupled with the 3d-PTMD is established wherein the interaction between the blades, the tower and the 3d-PTMD is modeled. Aerodynamic loading is computed using the Blade Element Momentum method where the Prandtls tip loss factor and the Glauert correction are considered. JONSWAP spectrum is adopted to generate wave data. Wave loading is computed using Morisons equation in collaboration with the strip theory. Via a numerical search approach, the design formula of the 3d-PTMD is obtained and examined on a National Renewable Energy Lab (NREL) monopile 5 MW baseline wind turbine model under misaligned wind, wave and seismic loading. Dual linear tuned mass dampers (TMDs) deployed in the fore-aft and side-side directions are utilized for comparison. It is found that the 3d-PTMD with a mass ratio of 2% can improve the mitigation of the root mean square and peak response by around 10% when compared with the dual linear TMDs in controlling the bi-directional vibration of the offshore wind turbines under misaligned wind, wave and seismic loading.

1. Introduction

Because of advantages such as higher wind speed, less visual impacts and less noise constraints in the marine area, offshore wind plants are becoming increasingly attractive for wind energy production. However, the combined wind-wave loading and other environmental effects will render the offshore wind turbines (OWTs) suffering from excessive vibration, adversely influencing the system performance and the structural integrity. In this regard, structural vibration control, which has been successfully employed in civil structures, is being studied in recent years to mitigate the vibration of OWTs.

Three basic control strategies have been developed: passive, semi-active and active [1,2]. Passive control of offshore wind turbines has been studied actively in the passed decade. Murtagh et al. [3] studied the control of the wind turbine along-wind vibration using a passive tuned mass damper (TMD). Colwell et al. [4] used the tuned liquid column damper to control the vibration of an offshore wind turbine. Research findings indicated that the tuned liquid column dampers could increase the tower fatigue life. Lackner et al. [5] used dual linear passive TMDs placed in the nacelle to control the fore-aft and

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side-side vibration. It was found that the dual TMDs can reduce the structural response. For seismic protection, Sadek et al. [6] proposed the optimum design formula for TMDs. Their findings showed that considerable reduction would result under seismic loading if parameters are selected to make the first two modal damping of the structure-TMD system equally large. Although the passive control techniques can provide mitigation when the design parameters are finely tuned, they might lose their effectiveness due to environmental or system variations.

In comparison, semi-active control devices are more applicable to systems with time-variant parameters. Semi-active TMDs (STMDs) have been investigated and demonstrated effective in controlling vibration of linear and nonlinear systems subjected to stationary and non-stationary excitations [7–9]. Weber [10] utilized a semi-active vibration absorber with real-time adjusted magnetorheological damper (MR-SVA) to mitigate harmonic loading induced vibrations. It was found that the MR-SVA outperforms the passive TMD. Huang and Arrigan et al. [11,12] explored the mitigation of wind turbine blades using the STMDs retuned in real-time via a short time Fourier transform (STFT) based control algorithm. The authors found that the STMDs could mitigate the blade responses under varying operational or environmental conditions. Sun et al. [13] further advanced the control algorithm used in Refs. [7,11,12] by incorporating the tuning of damping ratio. The authors examined the performance of the modified control algorithm for seismic protection and observed improved mitigation effect. Recently, Sun [14] studied the mitigation of offshore wind turbines under multiple hazards consisting of wind, wave and seismic loading using the STMD. It was found that the STMD outperforms the passive TMD in mitigating the structural response under the combined effects of multiple hazards, soil effects and structural damage.

Active control of vibrations have been studied and demonstrated effective under operational or environmental variations [15,16]. Staino et al. [17] used active tendons mounted inside the blade to control the edgewise vibration of wind turbine blades. The authors concluded that the proposed control scheme can significantly mitigate the response of the blades. Fitzgerald et al. [18] utilized an active tuned mass damper (ATMD) to control the in-plane vibration of the blades. It was found that the ATMD can provide better reduction than the passive TMDs. Etedali et al. [19,20] used an ATMD controlled by proportional-derivative (PD), proportional-integral-derivative (PID) and hybrid linear quadratic regulator (LQR)-PID controllers for seismic protection of buildings. The authors found that the PD/PID and LQR-PID controlled ATMD can provide remarkable reduction for tall building under seismic loading.

However, most of the aforementioned literatures focus on unidirectional response (fore-aft motion) mitigation while the real OWTs suffer from bi-directional vibration (fore-aft and side-side) due to wind-wave misalignment, vortex induced cross-wind vibration and other misaligned loading such as earthquakes. Perhaps the dual TMDs used in Ref. [5] could mitigate the vibration in the fore-aft and side-side directions, there are still several limitations existing in this approach. First, the optimal mass allocation (given total TMD mass) and the optimal arrangement (relative angle between the two TMDs) are correlated with the probabilistic distribution of the magnitude and directionality of the external loading and thus can always be a challenge for the design. It is probable that the utilization efficiency of the two TMDs can be relatively low. For instance, the TMD in the fore-aft direction is fully involved while the one in the side-side direction is almost at rest when only the fore-aft vibration is induced, and vice versa. In addition, the dual TMDs require more space, larger mass and more cost for the installation and maintenance.

Due to the simplicity of installation and maintenance, pendulum tuned mass dampers (PTMDs) have been investigated and widely applied in high-rise slender buildings. The natural frequency of the pendulum is tunable through varying the pendulum length. Gerges et al. [21] determined the optimum design formula for planar PTMDs under wind and earthquake excitations represented by white noise. To account for space motion of the PTMDs, Roffel et al. [22] proposed the optimum design formula for the PTMD aiming to minimize the acceleration root mean square (RMS) of slender tall buildings under wind loading. It was shown that the optimum design parameters in Ref. [22] were obviously different from the optimum design proposed in Ref. [21]. The difference is partly due to the fact that the optimum objective in [21] is to minimize the displacement RMS while the optimum objective in [22] is to minimize the acceleration RMS. In addition to the application in tall buildings, Battista et al. [24] reported that the PTMDs could significantly mitigate the wind-induced cross-line vibration of power transmission towers. Recently, Sun et al. [9,25] investigated planar adaptive PTMDs (APTMDs) whose natural frequency and damping properties can be retuned in real-time to account for structural or environmental variations. The authors found that the APTMDs could effectively reduce the vibration and prevent the occurrence of bifurcation in nonlinear systems.

To address the limitations of the dual TMDs approach, the present paper proposes a three dimensional pendulum tuned mass damper (3d-PTMD) to control the bi-directional vibration of the monopile OWTs. Since the wind turbine tower is axial-symmetric, the natural frequencies of the fore-aft and side-side directions are almost identical. This renders the 3d-PTMDs suitable for wind turbine bi-directional vibration mitigation. Novelty of the present study is twofold. First, on the basis of the author's previous work[14], a nonlinear mathematical model of the monopile offshore wind turbines coupled with the 3d-PTMD will be established. Aerodynamic loading, wave loading, seismic loading and gravity loading are incorporated in the model. Second, the optimal design parameters to minimize the nacelle displacement RMS will be determined using a numerical search approach. On the basis of this, the effectiveness of the proposed 3d-PTMD in controlling the bi-directional vibration will be evaluated under misaligned wind-wave and seismic loading. The dual TMDs designed based on [26] are used for comparison. It is found that the 3d-PTMD outperforms the dual linear TMDs in controlling the bi-directional vibration caused by misaligned loading. Furthermore, the proposed 3d-PTMD experiences a much smaller stroke than the dual TMDs, which is of significant value for practical application.