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Using multiple tuned mass dampers to control offshore wind turbine vibrations under multiple hazards

Haoran Zuo, Kaiming Bi, Hong Hao *

Centre for Infrastructure Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia

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ABSTRACT

Offshore wind turbines can be built larger and lighter than they used to be due to the application of new materials. These large and flexible structures are vulnerable to external vibration sources such as wind, sea wave and earthquake excitations. It is necessary to mitigate the dynamic responses of offshore wind turbines to ensure the safety of these structures. Extensive research works have been carried out to mitigate the vibrations of the tower and/or blades of offshore wind turbines. Almost all the previous studies on the offshore wind turbine tower vibration control propose installing the control device at the top of the tower, i.e. in the nacelle. This method is effective to suppress the fundamental vibration mode of the tower, in which the maximum displacement occurs at the top of the tower. This practice is reasonable when wind and/or sea wave loadings are of interest since the energies of these vibration sources are concentrated in the low frequency range, and normally only the fundamental vibration mode of the tower is excited. On the other hand, offshore wind turbines may locate in the seismic prone areas, earthquake loading can be another vibration source during their lifetimes. When offshore wind turbines are subjected to earthquake excitation, higher vibration modes might be also excited. These higher vibration modes can further contribute to the structural responses and in certain circumstances they may even dominate the structural responses. In this case, installing the control device only in the nacelle will not be effective and more control devices should be installed at certain locations along the tower. In other words, one single control device will not be effective to control the tower vibrations if both the fundamental and higher vibration modes are of interest. This paper proposes using multiple tuned mass dampers (MTMDs) to control vibrations from the fundamental and higher modes of offshore wind turbine tower under multiple hazards, i.e. under the combined wind, sea wave and earthquake excitations. The effectiveness of the proposed method is numerically investigated. It should be noted that only the vibration of the tower is of interest in the present study. The vibration control of the blades is out of the scope of this paper, which will be further investigated.

1. Introduction

Wind turbines are becoming an attractive way to produce electrical energy nowadays. To more effectively extract the vast wind resources throughout the lifetimes of wind turbines, larger rotor and slender tower are adopted in the current designs with the development of new technologies and materials. For example, the rotor diameter and tower height of the latest NREL 5 MW three-bladed wind turbine reach 126 m and 87.6 m respectively, while the maximum wall thickness of the tower is only 0.027 m [1]. These thin wall wind turbines are vulnerable to external vibration sources such as wind and sea wave loadings, which are the constant vibration sources that offshore wind turbines experience during their whole lifetimes irrespective of their locations. Moreover, many wind turbines are located in the earthquake prone areas such as China, USA, Japan and New Zealand [2]. Seismic loading is another possible vibration source during their lifetimes [2]. In this case, the offshore wind turbine is subjected to simultaneous wind, sea wave and earthquake loads and the influence of earthquake loading on the structural responses of offshore wind turbine should be considered. Actually many guidelines and standards (e.g. [3–5]) clearly state that the wind turbine needs to be designed to resist seismic load when it is located in the seismic prone area. The simultaneous wind, sea wave and seismic loadings can lead to excessive vibrations to the tower and blades of wind turbines, which in turn can compromise the wind energy output and even result in the collapse of the tower [6]. It is therefore important to

* Corresponding author.
E-mail address: hong.hao@curtin.edu.au (H. Hao).

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mitigate these adverse vibrations to protect wind turbines and to improve their overall dynamic performances.

Extensive research works have been carried out by different researchers to mitigate the vibrations of tower and/or blades of a wind turbine by using different vibration control devices [7]. Since the aim of this study is to propose a method to mitigate the tower vibration, only the previous works on the tower vibration control are summarized here. These devices can be generally divided into passive [8–13] and active [14] categories depending on whether external power is needed. Compared to the active control devices, passive vibration control methods need no external power. They are therefore more widely used in engineering practices. For example, Lackner and Rotea [8], Murtagh et al. [9] and Stewart and Lackner [10] proposed using tuned mass dampers (TMDs) to control tower vibrations; Colwell and Basu [11], Mensah and Dueñas-Osorio [12] and Chen et al. [13] suggested using tuned liquid column dampers (TLCDs); Chen and Georgakis proposed a rolling-ball damper [15] and a spherical tuned liquid damper [16]; Zhang et al. [17] suggested a ball vibration absorber. The effectiveness of these proposed dampers were either numerically [8–12] or experimentally [13,15–17] studied. The results confirmed these dampers can be used to mitigate the adverse vibrations for wind turbine towers.

Almost all the previous studies on the tower vibration control suggested installing the control devices at the top of the tower, i.e. in the nacelle. In reality, there is very limited space in the nacelle, which makes the installation of the dampers not straightforward. More importantly, previous studies mainly consider wind [9,12] and/or sea wave [10,11] as the vibration sources. The energies of these loadings are concentrated in the low frequency range, hence they normally excite the fundamental vibration mode of the tower only, and the maximum displacement occurs at the top of the tower. Installing the control devices in the nacelle is therefore effective. However, when a wind turbine is subjected to earthquake shaking [18–20], the higher vibration modes might be also excited since the energy of an earthquake loading is within a broader frequency range. These higher vibration modes can further contribute to the structural responses and may even govern the total structural responses in certain cases. Then the largest displacement does not necessarily occur at the top of the tower but at certain location along the tower depending on which mode dominates the response. In this case, installing the control device at the top of the tower may not be effective, and the control devices should be installed at locations along the tower where large displacement occurs. Therefore, for an offshore wind turbine located in the seismic prone area, both the fundamental and higher vibration modes of the tower might be excited due to the possible wind, sea wave and earthquake excitations. To effectively control the tower vibration of an offshore wind turbine under these multiple hazards, multiple control devices are necessary.

Applying multiple control devices to mitigate the vibrations of engineering structures has been reported by some researchers. For example, Abe and Fujino [21] and Kareem and Kline [22] reported that multiple tuned mass dampers (MTMDs) are more effective than a single TMD (STMD) in the vibration control of engineering structures when they are subjected to earthquake and/or wind loads. Elias et al. [23] investigated the effectiveness of using MTMDs to control the fundamental and high vibration modes of a reinforced concrete (RC) chimney under earthquake excitation. A parametric study was conducted to find the most suitable masses and damping ratios for different TMDs [23]. Moon [24] suggested dividing a single large TMD into multiple small TMDs and applying MTMDs vertically along the height of the building to control wind induced vibrations of the structure. Moon's study revealed that MTMDs can effectively control the multiple vibration modes of a high-rise building and the control effectiveness will not be obviously decreased compared to the STMD method [24]. Moreover, another two obvious merits can be appreciated by adopting this method. Firstly, this method can significantly facilitate the TMD installation since the mass of each MTMD is much smaller compared to the single large TMD. The reliability of the control system can be significantly enhanced in case some of the MTMDs do not function properly. This method is believed effective for the wind turbine vibration control as well. However, to the best knowledge of the authors, no open literature reports the study of the effectiveness of using MTMDs to control the tower vibrations of wind turbines.

This paper proposes using MTMDs to control the tower vibrations of wind turbines when they are subjected to the simultaneous wind, sea wave and earthquake excitations. The effectiveness of the proposed method is numerically investigated by using the finite element code ABAQUS. The tower responses of the original wind turbine (without control devices) are compared with those controlled by STMD and MTMDs. The robustness of the proposed method is also discussed by arbitrarily assuming some dampers do not work properly.

2. Optimization of STMD/MTMD systems

STMD/MTMD systems have been widely used to control the vibrations of engineering structures due to the simplicity and effectiveness of the systems. Fig. 1(a) shows a standard STMD system, in which an auxiliary mass (m_T) is attached to the vibrating main structure by a spring and a dashpot. The natural frequency of the TMD is tuned to the vibration frequency of the main structure so that the damper will resonate out of phase with the main structure and a large amount of structural vibrating energy is transferred to the TMD and dissipated by the damper. For a MTMD system, as implied by the name, multiple TMDs instead of a single TMD are attached to the main structure by the springs and dashpots. Fig. 1(b) shows a structure-MTMD system with n TMDs. Again the springs are used to tune the frequency of the MTMD system and the energy is dissipated by the multiple dashpots.

The tuned frequency ratios and damping ratios of the dampers are the key parameters that can significantly influence the effectiveness of the STMD/MTMD systems. Numerous methods have been proposed by different researchers (e.g. [21,25–33]) to obtain the optimal TMD parameters after the pioneering work done by Den Hartog [34]. In the present study, the displacement response of the tower is of interest and numerical searching technique is used to minimize the mean square displacement of the tower under a given mass ratio.

As will be presented in Section 3, the natural frequencies of different modes of the example wind turbine are well separated with each other, the springs and dashpots used to control different vibration modes of the tower therefore can be optimised separately. To further facilitate the optimization, the following two assumptions are made [35]: (1) the natural frequencies of MTMDs are uniformly distributed around their average natural frequency; (2) each TMD has the same mass and damping coefficient to achieve a better effectiveness on the vibration control of the tower.

For a structure-MTMD system as shown in Fig. 1(b), the vibration frequency of the main structure can be calculated as $\omega_S = \sqrt{k_S/m_S}$, where m_S and k_S are the mass and stiffness of the main structure respectively. For a MTMD system with n TMDs, the frequency of the jth TMD in the MTMD system can be estimated based on the first assumption as [36]

$$\omega_j = \omega_T\left[1 + \left(j - \frac{n+1}{2}\right)\frac{\beta}{n-1}\right] j = 1, 2, \ldots n \tag{1}$$