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A state-of-the-art review on the vibration mitigation of wind turbines

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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

Wind energy as one of the renewable energies is serving as an indispensable role in generating new electric power. The worldwide installation of wind farms has considerably increased recently. To extract more wind resources, multi-megawatt wind turbines are usually designed and constructed with large rotors and slender tower. These flexible structures are susceptible to external dynamic excitations such as wind, wave and seismic loads. The excessive vibrations can compromise the wind energy conversion, lead to the structural fatigue damage and even result in the catastrophic failure of wind turbines in harsh environmental conditions. Various control devices have been proposed and used to mitigate the unwanted vibrations of wind turbines to enhance their safety and serviceability. This paper aims to provide a state-of-the-art review of the current vibration control techniques and their applications to wind turbines. Firstly, the widely used control strategies in engineering structures are briefly introduced. Their applications to suppress the adverse vibrations of the structural components of wind turbines, mainly the tower and blades, are then reviewed and discussed in detail. It can be concluded that the vibration mitigation of wind turbines is very challenging due to the fact that the dynamic behaviours of wind turbines are very complicated, which are associated with the aerodynamics, rotation of the blades, interaction between the tower and rotating blades, and soil-structure interaction, etc. Moreover, it is a challenge to straightforwardly use many of the conventional control devices because of the limited spaces in the tower and blades.

1. Introduction

Wind energy as one of the renewable energies plays an attractive means to generate new electric power. Wind farms have experienced rapid growth and expansion recently especially in the last decade. As reported by the Global Wind Energy Council, the worldwide installations of wind turbines reached about 539 GW at the end of 2017, with an increase of 2155% compared to that in 2011 [1]. Moreover, numbers of wind turbines are erected far away from coastlines to more efficiently extract the huge wind resources. The offshore wind power reached a historical record in 2017 with 4334 MW new installations, and the cumulative capacity was 18,814 MW [1]. Fig. 1 shows the global annual and cumulative installations of wind turbines from 2001 to 2017, and the total installations of offshore wind farms in 2011–2017 are shown in Fig. 2. It can be seen that though the offshore wind capacity in 2017 was only about 3.5% of the total wind capacity, it is growing very quickly and with great prospects.

Wind turbines can be broadly grouped into the horizontal and vertical axis categories depending on the orientation of the rotation axis of the blades. Fig. 3 shows the typical geometrical configurations of the horizontal and vertical axis wind turbines (HAWTs and VAWTs) [2]. As implied by the name, the blades of HAWTs rotate about the horizontal axis, and they are perpendicular to the direction of wind flow, while the blades of VAWTs rotate vertically and they are not required to face the wind. As the HAWTs dominate the utility-scale wind turbine market currently, only the research works on the vibration control of HAWTs are reviewed and discussed herein.

In the current state-of-the-art designs, multi-megawatt wind turbines with slender tower and large rotor are developed. For example, the tower height and rotor diameter of the conceptual Haliade-X 12 MW offshore wind turbine reach 150 m and 220 m respectively [1]. These structures are normally manufactured with light-weight and high-strength materials, they are thus very flexible and lightly damped and are susceptible to external dynamic excitations such as wind and wave loads, which constantly act on the offshore wind turbines during their entire service life. Moreover, many wind farms are constructed in the regions of high seismic risk (e.g. in the western United States and China [3]), earthquake can be another vibration source. The excessive vibrations of wind turbines can compromise the wind energy conversion

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Nomenclature

3D	three-dimensional
ATMD	active tuned mass damper
BVA	ball vibration absorber
CLCD	circular liquid column damper
CSI	control-structure interaction
EC-TMD	eddy current with tuned mass damper
FAST	fatigue, aerodynamics, structures and turbulences
FAST-SC	fatigue, aerodynamics, structures and turbulences with structural control
FE	finite element
HAWT	horizontal axis wind turbine
LQR	linear quadric regulator
MDOF	multiple degrees-of-freedom
MR	magnetorheological
MTMD	multiple tuned mass damper
PED	passive energy dissipation
PM	permanent magnet
SMA	shape memory alloy
STFT	short-time Fourier transformation
STMD	single tuned mass damper
TLCD	tuned liquid column damper
TLCGD	tuned liquid column gas damper
TLD	tuned liquid damper
TMD	tuned mass damper
VAWT	vertical axis wind turbine
VD-SJB	scissor-jack braced viscous damper

to electricity and decrease the fatigue life of structural components and may even lead to the catastrophic total collapse of wind turbines (see Fig. 4 [4]) under some extreme conditions. In addition, the gearbox, generator, etc. installed in the nacelle are very sensitive to the accelerations [5], the damage of these components will be very costly. It is therefore imperative to mitigate the adverse vibrations of wind turbines to protect the structural safety and maintain their serviceability. Regarding the sources for the damage, Chou and Tu [4] analysed 62 wind turbine accidents by collecting the historical failure data from 1997 to 2009, and they found that storms (34.1%) and strong winds (18.1%) were the two primary external forces causing onshore wind turbine collapse around the world.

The vibration of wind turbines induced by the wind, wave and/or seismic loads has received extensive attentions. Various control methods have been proposed, and extensive research works including numerical, experimental and analytical studies have been performed to investigate the effectiveness of the proposed methods. In this paper, the applications and effectiveness of these strategies for wind turbine vibration control are comprehensively reviewed and discussed. The structure of this paper is organized as follows: Section 2 briefly introduces the general control methods applied in engineering structures; the vibration control of the wind turbine tower and blades is reviewed in Sections 3 and 4 respectively; some discussions on the pros and cons of these control methods and the remaining challenges are made in Section 5.

2. Vibration control methods

Various methods have been developed and used to control the excessive vibrations of engineering structures when they are subjected to the external vibration sources [6–8]. These control methods can be

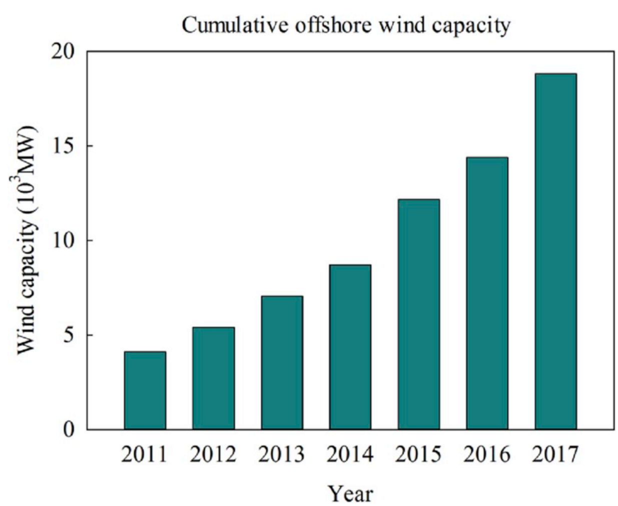


Fig. 2. Global offshore wind turbine installations in 2011–2017 (after [1]).

broadly divided into four categories, namely passive, active, hybrid and semi-active [9]. Based on the name, passive control does not input any energy into the system from the controller. It only dissipates the energy from the primary structure. Active controller direct inputs the energy (which requires a larger external energy source) to counteract the unwanted motion or achieve certain motion, such as dynamic positioning system in offshore vessels. Semi-active controller only inputs a small amount of energy to change the properties of the passive controller

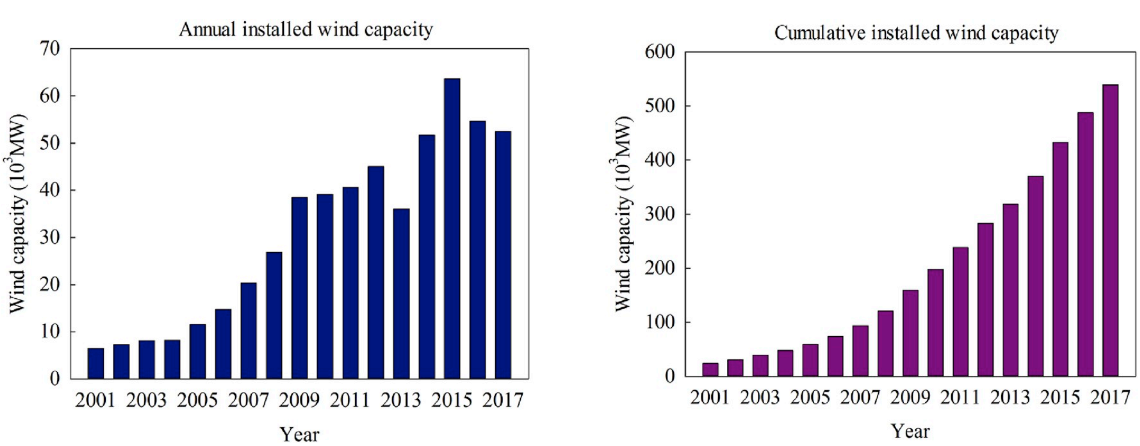


Fig. 1. Global annual and cumulative wind turbine installations in 2001–2017 (after [1]).

system instead of directly counteracting the motion, such as the frequency of the tuned mass damper (TMD), the damping effect of magneto-rheological (MR) damper. Hybrid approach generally involves both active and passive controlling devices. The basic characteristics of these control techniques are discussed in this section.

(1) Passive vibration control: Fig. 5(a) shows the mechanism of a structure controlled by the passive method [10]. As shown, the passive control system does not require any external power for its operation and the control forces are generated by utilizing the structural motion. Different passive energy dissipation (PED) devices were proposed and installed in structures to improve their dynamic behaviours such as the metallic yield dampers, friction dampers, viscoelastic dampers, viscous fluid dampers, TMDs, tuned liquid dampers (TLDs), tuned liquid column dampers (TLCDs), etc [11]. Though the effectiveness of these dampers have been validated in many previous studies, there are still some controversies on the control effectiveness of these passive dampers. For example, some researchers (e.g. Ref. [10]) argued that using TMD to mitigate seismic induced vibration of engineering structures is marginal since the TMD system is sensitive to the parameters of the connecting spring and dashpot, and the broad frequency contents in earthquake ground motions can significantly influence its control effectiveness.

(2) Active vibration control: an active control system normally consists of sensors, controllers and actuators as shown in Fig. 5(b) [10]. The sensors are located on the structure to monitor the external excitations and/or structural responses, then the controllers collect the measured information and calculate the required control forces based on the prescribed control law, and finally the actuators which are powered by external sources provide the control forces to mitigate the structural responses. It is worth noting that the control configuration is referred as feedforward control when the control forces are regulated only based on the measured excitation (the left loop in Fig. 5(b), (c) and (d)), and feedback control is termed when the structural responses are measured (the right loop in the corresponding figures). When both the response and excitation are used, it is normally termed as feedback-feedforward control. In practice, usually one of these two control systems is selected as the primary controlling method. Although the active control method can effectively reduce the structural vibrations, the challenge of this method is that it is a combination of diverse disciplines including sensing technology, computer science, data processing, control theory, stochastic processes and structural dynamics [10]. Some of them are beyond the domain of traditional civil engineering. Moreover, the active control system requires external power, which makes it not applicable in some cases of power failure.

(3) Hybrid vibration control: to extract the advantages and overcome the drawbacks of passive and active control systems, the hybrid control system has been proposed. This system combines the passive and active systems together as shown in Fig. 5(c) [10]. In which, the passive control system can achieve part of the vibration control goal, less energy is thus transferred to the active system and less external power source is therefore required compared to a fully active control system. The active TMD (ATMD) is the most widely used hybrid vibration control system, and it is composed of a passive TMD and an active control actuator. The capability of this device to control the structural responses is mainly dependent on the motion of TMD (similar to the passive TMD system). The forces from the actuator are used to improve the control effectiveness of TMD and to increase its robustness to the possible variations in the structural dynamic characteristics.

(4) Semi-active control: similar to the passive control method, a semi-active control system shown in Fig. 5(d) also passively dissipate the energy from primary system. However, it can change the characteristics (stiffness, damping ratio, etc.) of the passive system in real time to achieve an overall higher energy dissipation efficiency than a pure passive system. Therefore, semi-active control devices are often regarded as controllable passive devices.

3. Vibration control of wind turbine tower

Instead of adopting the structural control methods as presented in Section 2, some researchers [12–19] used the pitch control and generator torque control approaches to reduce the wind loads acting on the wind turbine to suppress the dynamic responses of the tower. The control effectiveness of these two techniques is achieved at the expense of increasing the usage of blade pitch actuators. It also leads to the power output fluctuations. Moreover, the load reduction is normally limited. The primary objective of this paper is to review different structural control methods used in wind turbine vibration mitigation, the pitch and generator torque control are not discussed in detail. Interested readers can refer to the relevant literatures (e.g. Refs. [17,18]) for more information.

Extensive research efforts have been devoted in the vibration control of the wind turbine tower by using different control devices when the wind turbine is subjected to the wind, wave and/or seismic loads. As introduced in Section 2, these control devices can be generally divided into passive, active, hybrid and semi-active control strategies.

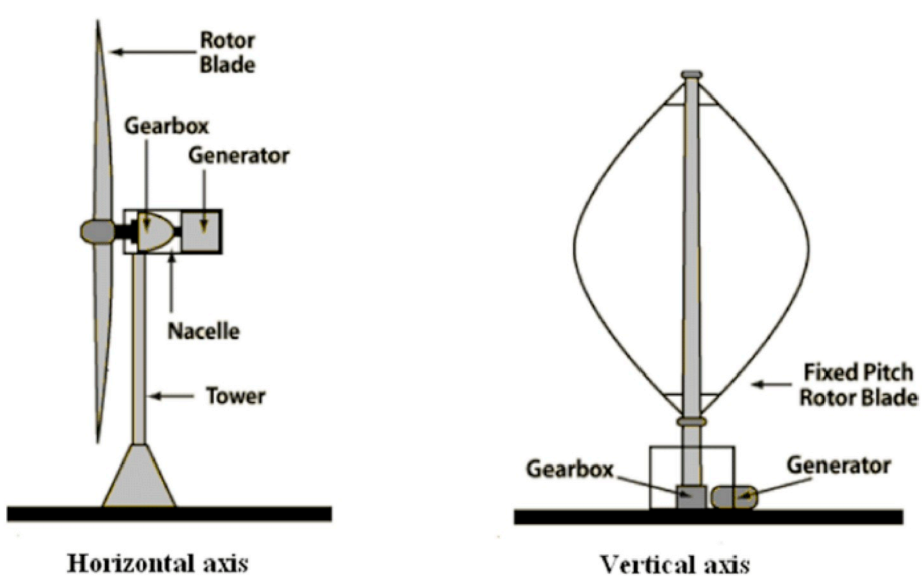


Fig. 3. Typical horizontal and vertical axis wind turbines (after [2]).

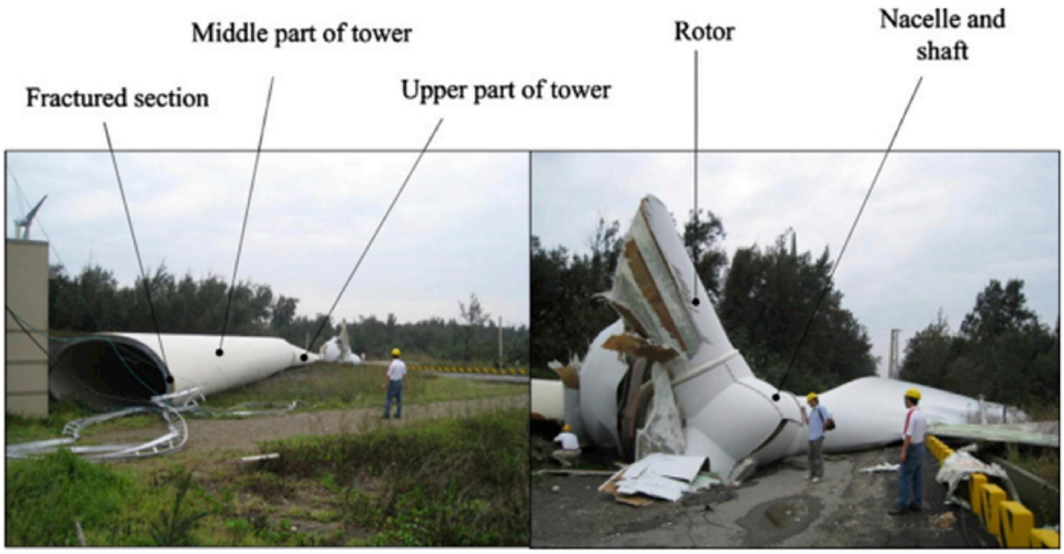


Fig. 4. On site photo of a collapsed wind turbine (after [4]).

3.1. Passive vibration control strategies

Passive control techniques are widely adopted to suppress the vibration of the wind turbine tower since no external power is needed and generally speaking their configurations are much simpler compared to the other control methods. A wide range of passive control devices have been proposed by different researchers after the pioneering work done by Enevoldsen and Mørk [20]. Among which, dampers such as TMDs, TLDs and TLCDs are extensively used due to their capabilities to enhance the structural damping.

3.1.1. STMD/MTMDs

Fig. 6 shows a typical TMD system, in which an additional mass is connected to the main structure by a spring and a dashpot. m_s, k_s and c_s are the mass, stiffness and damping coefficient of the main structure respectively, and m_T, k_T and c_T are the corresponding parameters for the TMD. The TMD frequency is tuned to the controlled frequency of the main structure such that the TMD will resonate out of phase with the main structure and a large amount of vibrating energy from the main structure is transferred to and dissipated by the TMD.

Murtagh et al. [21] installed a TMD in the nacelle to mitigate the wind-induced vibrations of the tower. In particular, the dynamic responses of the wind turbine without and with TMD were calculated by simplifying the tower and blades as a multiple degrees-of-freedom (MDOF) system. It was found that the displacements at the top of the tower in different rotational speeds of the blades were significantly reduced compared to the tower without any control device, which highlighted the feasibility of using TMD to control the vibration of wind turbine tower. Lackner and Rotea [22] made a modification to the aero-elastic code FAST (Fatigue, Aerodynamics, Structures and Turbulences) to accommodate structural control (FAST-SC). Two independent TMDs located in the nacelle, with one in the fore-aft direction and another in the side-to-side direction as shown in Fig. 7, were incorporated into FAST. The effectiveness of this control method were examined for the fixed-bottom monopile wind turbine, and the wind turbines with floating substructures such as barge, spar-buoy and tension-leg [22,23]. Considering the possible leakage of oil or gas of the viscous damper in the traditional TMD, Lian et al. [24] proposed an eddy current with TMD (EC-TMD) system to reduce the significant vibrations of the tower. Fig. 8 shows this contactless damper. The nonlinear damping force of this system is generated by the relative motion between the copper plate (a conductive metal) and permanent magnets (PMs), which is influenced by the geometrical dimensions of the PMs and copper plate, the distance between them and the layouts of the PMs.

In Refs. [21–24], the wind and/or wave loads were assumed as the external vibration sources and only a single TMD was installed in the nacelle. To some extent, this practice is reasonable since the energies of these two loading types are concentrated in a low frequency range, and normally only the first vibration mode of the tower can be excited, and the maximum displacement occurs at the tower top. Therefore, installing the control device at the location where the peak displacement appears, i.e. in the nacelle, is the most effective in reducing wind and wave induced vibrations. However, many wind farms are constructed in the areas with high seismic potentials [3], seismic load can be another vibration source during their lifetimes in these regions. When the wind turbine is subjected to an earthquake, the higher vibration modes might also be excited as the seismic energy has a broader frequency range, which can further contribute to or even govern the structural responses of the wind turbine. The peak displacement of the tower thus does not necessarily occur at the top but at other locations depending on which mode dominates the structural responses. In this case, using a single TMD in the nacelle and tuning it to the fundamental vibration frequency of the tower is not effective, and the damper should be installed at the location where the largest displacement occurs. To effectively control the tower vibrations under simultaneous actions of wind, wave and earthquake, Zuo et al. [25] proposed installing multiple TMDs (MTMDs) along the tower to mitigate the first and second vibration modes. In particular, three TMD arrangement scenarios were considered (Fig. 9): in Case 1, a single (large) TMD (STMD) was installed at the top of the tower; the STMD was divided into two small TMDs in Case 2, and they were installed at locations corresponding to the maximum amplitudes of the first two vibration modes; these two TMDs were further divided into six even smaller TMDs in Case 3. The total mass of the MTMDs (two and six) is the same as the STMD in the cases for comparison. Their numerical results showed that the MTMD system not only mitigated the vibration of tower induced by the fundamental vibration mode, but also the vibration induced by the higher modes. More importantly, the MTMD system is more robust compared to the STMD system, namely the system will be still effective even if one or more smaller TMDs are not functioning well, which makes this system more practical. Hussan et al. [26] also used two TMDs with one at the top of the tower and one at the base of the tower to mitigate the first and second vibration modes of a jacket-support offshore wind turbine tower under seismic excitations as shown in Fig. 10. Three different seismic ground motions were considered and the same conclusion was obtained as that in Ref. [25], i.e. MTMDs are suitable for multi-mode control while STMD is effective for

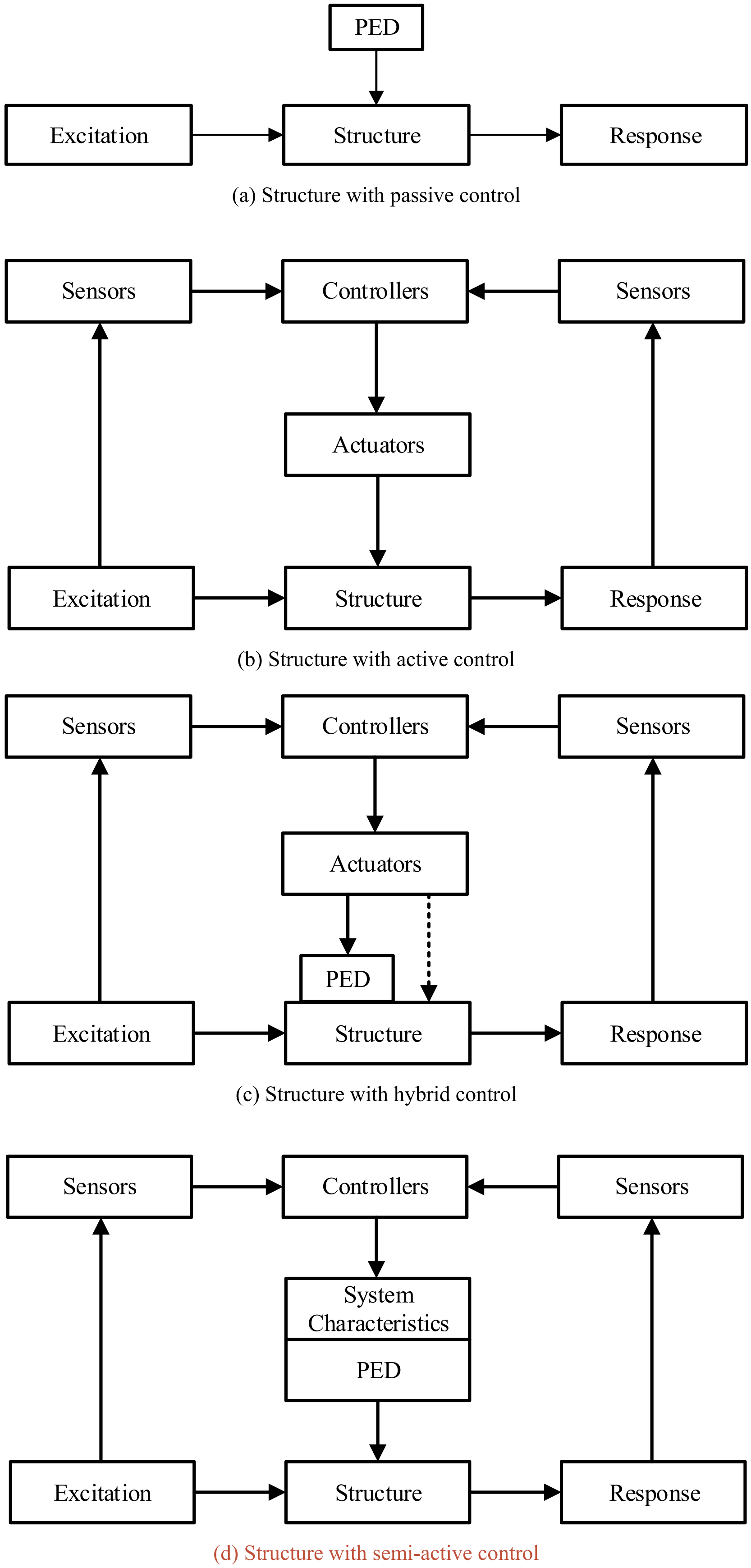


Fig. 5. Working mechanisms of different vibration control methods (after [10]).

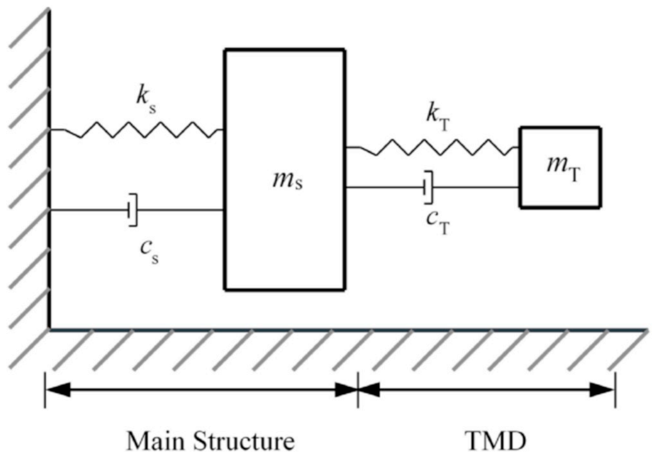


Fig. 6. A main structure-TMD system.

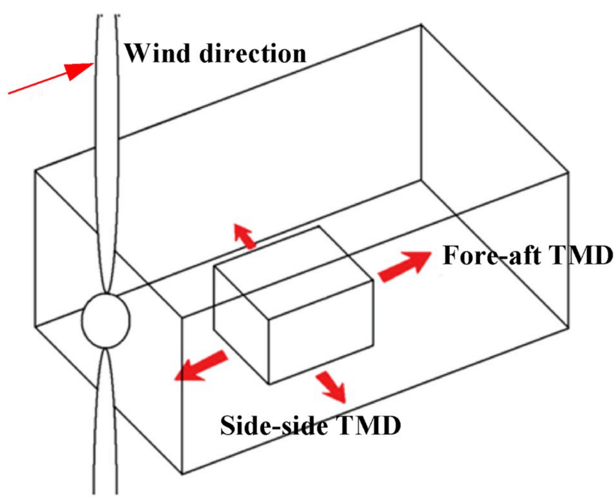


Fig. 7. Fore-aft and side-to-side TMDs in a nacelle (after [23]).

suppressing a single vibration mode.

To more efficiently extract wind resources, offshore wind turbines are moving away from the coastlines and into deeper waters. The wind turbines with fixed foundations (e.g. monopile and jacket foundations) are not be economically feasible when the water depth is more than 60 m [27]. In this case, floating wind turbines with spar-buoy, barge-type or tension-leg foundation might be better options. One of the challenges for floating offshore wind turbines is the pitch motion of the platform induced by the severe wind and wave, which may result in large displacements at the top of the tower and the tips of the blades, and these deformations can lead to considerable bending moments and shear forces at the bottom of the tower and the root of the blades, which deteriorate the structural fatigue life and decrease the electric generation capacity of floating offshore wind turbines. TMD was also used to control the platform pitch motions in the floating offshore wind turbines [28–33]. In particular, the TMD was installed in the nacelle in Refs. [28,29,31] (Fig. 11(a)), while it was in the platform in Refs. [30,32,33] (Fig. 11(b)). Numerical results showed that the TMD could mitigate the pitch motion of the platform under the combined actions of wind and wave. However, it should be noted that the vibration frequency corresponding to the pitch mode of floating offshore wind turbines is normally very low (e.g. 0.08 Hz in Ref. [28]), a large stroke is thus required when a TMD is applied to control the low frequency responses, which may not be practical due to the limited installation space. On the other hand, attaching an additional mass to the nacelle may bring structural stability problems for floating offshore wind turbines [33]. To eliminate this drawback, the mass of the ballast was suggested to be increased substantially. In addition, it is necessary to point out that installing the TMD in the platform (Fig. 11(b)) would deteriorate the control effectiveness since the largest displacement induced by the pitch motion occurs at the top of the tower.

It is well known that the control performance of a TMD system is significantly influenced by the mass ratio of the control device to the main structure, and a large mass ratio generally results in better and more robust control effect. By installing a single large TMD in the nacelle of the wind turbine as assumed in the previous studies [21–24,28,29,31] is not feasible since many equipment in the nacelle such as the gearbox, generator, yaw system, brake etc. occupy most space there, making the spare space in the nacelle for additional TMD mass very limited. The MTMD system as suggested by Zuo et al. [25] and Dinh et al. [34] might be more practical since the mass of each TMD is much smaller compared to the STMD. Very recently, some researchers (e.g. Hu et al. [35]) proposed using inerter-based TMD system to reduce the physical mass of a conventional TMD system. An inerter device can transform the linear motion into the high-speed rotational motion, it therefore can significantly (up to 200 times as reported in Ref. [36]) amplify the physical mass of the system. In Ref. [35], three different configurations as shown in Fig. 12 were employed to constitute the passive network, in which *Y*(s) is the inerter-based device and *b* is the amplified physical mass. FAST-SC was used to investigate the effectiveness of the proposed method on controlling the dynamic responses of a barge-type floating offshore wind turbine when it was subjected to the wind and wave loads. It was observed that this novel system could more effectively mitigate the displacement at the top of the tower while maintaining similar TMD working space as the system without inerter, and configuration C3 provided the most evident improvements among these three configurations. Zhang et al. [37] then installed configuration C3 in the nacelle, and investigated its effectiveness to control the seismic induced vibrations of a monopile wind turbine tower. Their numerical results showed that the same control effectiveness of a traditional TMD system could be achieved with a much smaller mass in the inerter-based TMD system,

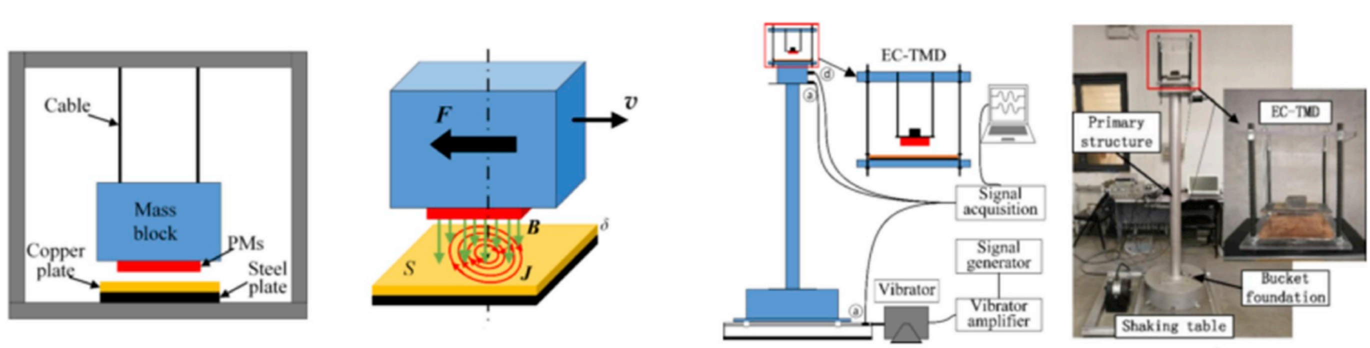


Fig. 8. Damping mechanics and experimental layouts of the EC-TMD system (after [24]).

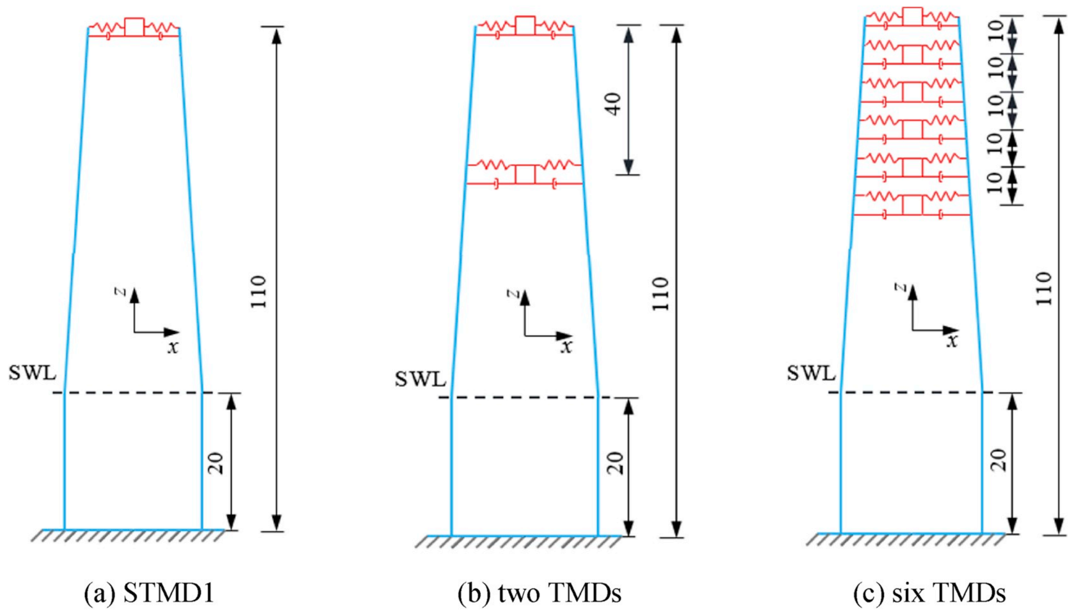


Fig. 9. Three different TMD arrangements adopted in Ref. [25].

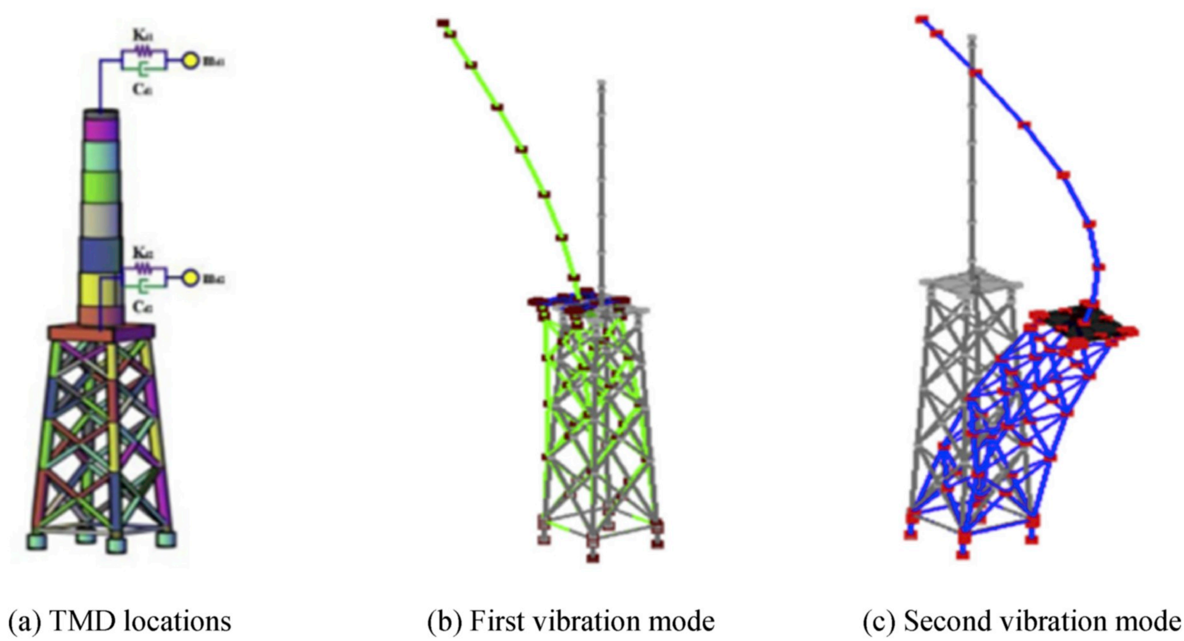


Fig. 10. TMD arrangement and vibration modes of a jacket-support offshore wind turbine (after [26]).

and the stroke of the tuned mass was obviously reduced.

3.1.2. Bidirectional TMD

In the above studies [21–25,28–35], wind was assumed as the main driving force for the wave, and wind and wave loads were acting on the tower in the same direction, i.e. the fore-aft direction of the tower (the out-of-plane direction of the blades). Only the control of the fore-aft vibration of the tower was therefore considered. However, recorded metocean data indicated that the directions of wind and wave are not necessarily always aligned [38], which leads to the simultaneous vibrations of the tower in both the side-to-side (the in-plane direction of the blades) and fore-aft directions. Moreover, the wind loads applying on the blades can result in the side-to-side vibration of the tower since the blades have pre-twisted shape, which makes the wind loads on the blades have a component in the in-plane direction. Large tower responses in the side-to-side direction thus might appear because of the low aerodynamic damping in this direction. Stewart and Lackner [38] and Tong et al. [39] suggested installing two linear TMDs in both the fore-aft and side-to-side directions of the tower (see Fig. 7), and the influence of the angle between the wind and wave was investigated in Ref. [38]. This control method was also adopted by Zhao et al. [40] (Fig. 13), and shake table tests were carried out to mitigate the fore-aft and side-to-side vibrations of the tower subjected to different seismic inputs. Recently, a three-dimensional (3D) pendulum TMD was proposed by Sun and Jahangiri [41–43], and it is shown in Fig. 14. Numerical results showed that this novel pendulum system outperforms the dual TMDs in mitigating the root mean square and peak responses of the tower under the misaligned wind and wave excitations. The fatigue life improvement of the tower by using this control system was discussed in Refs. [43,44]. However, it is worth noting that the frequency of the

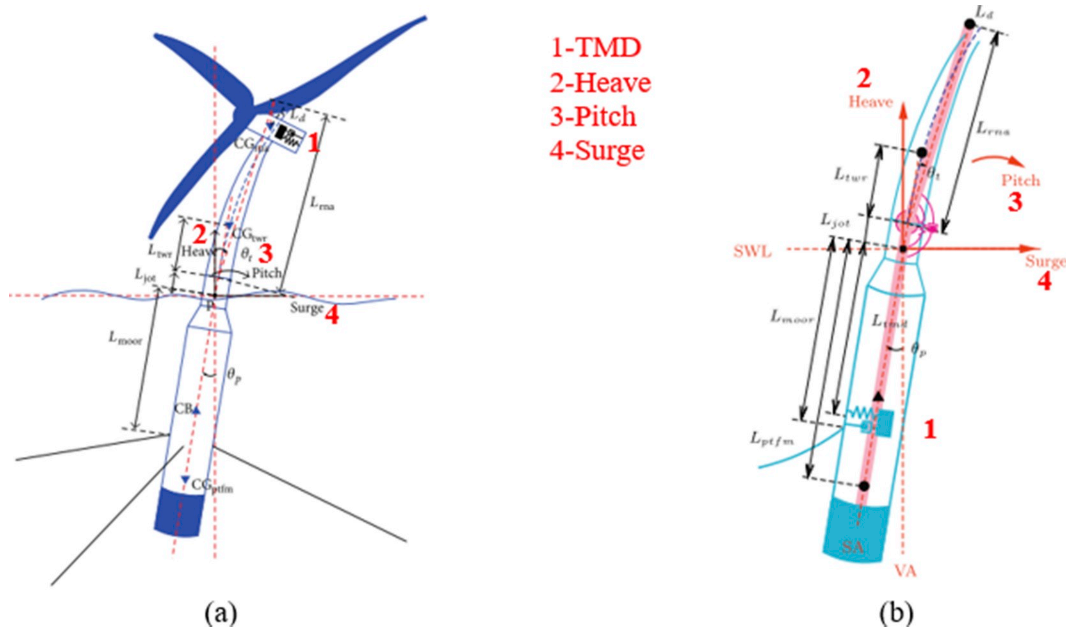


Fig. 11. Using TMD to control the vibration of floating offshore wind turbines with TMD installed (a) in the nacelle (after [29]) and in the spar-buoy platform (after [30]).

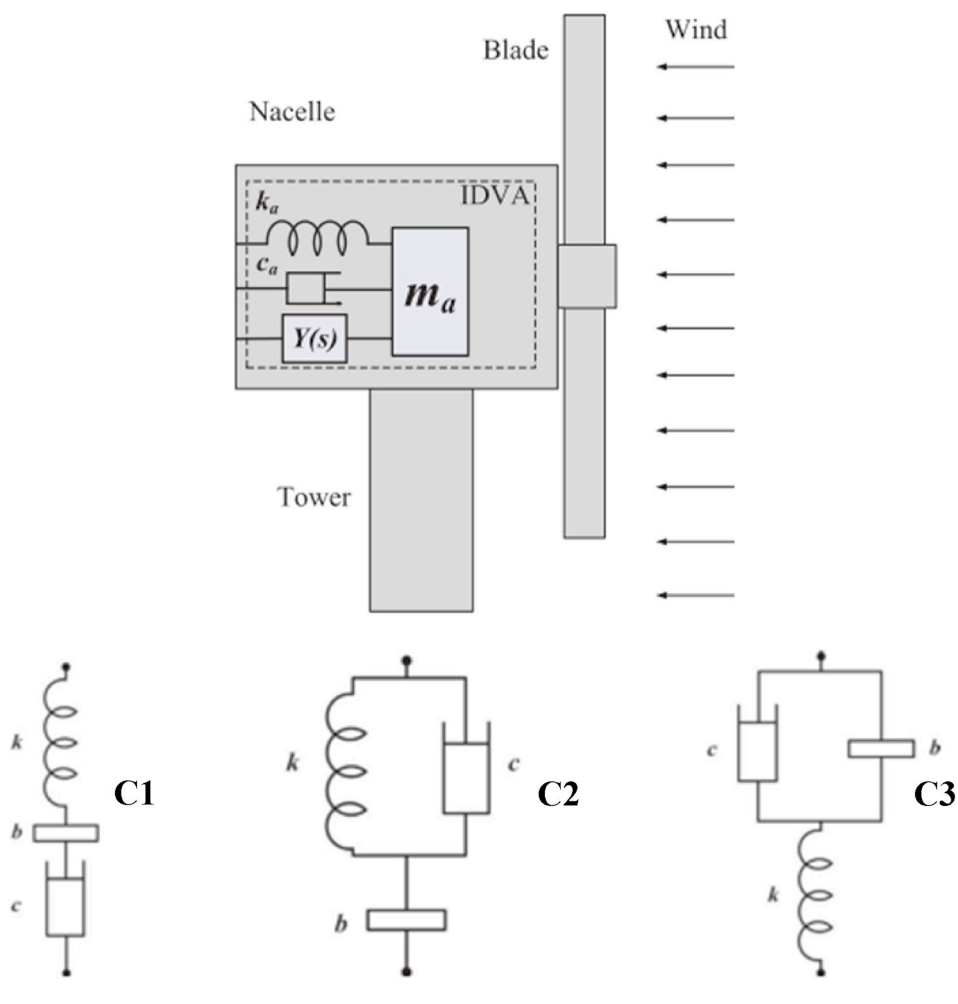


Fig. 12. Schematic of the inerter-based TMD system and three configurations for $Y(s)$ (after [35]).

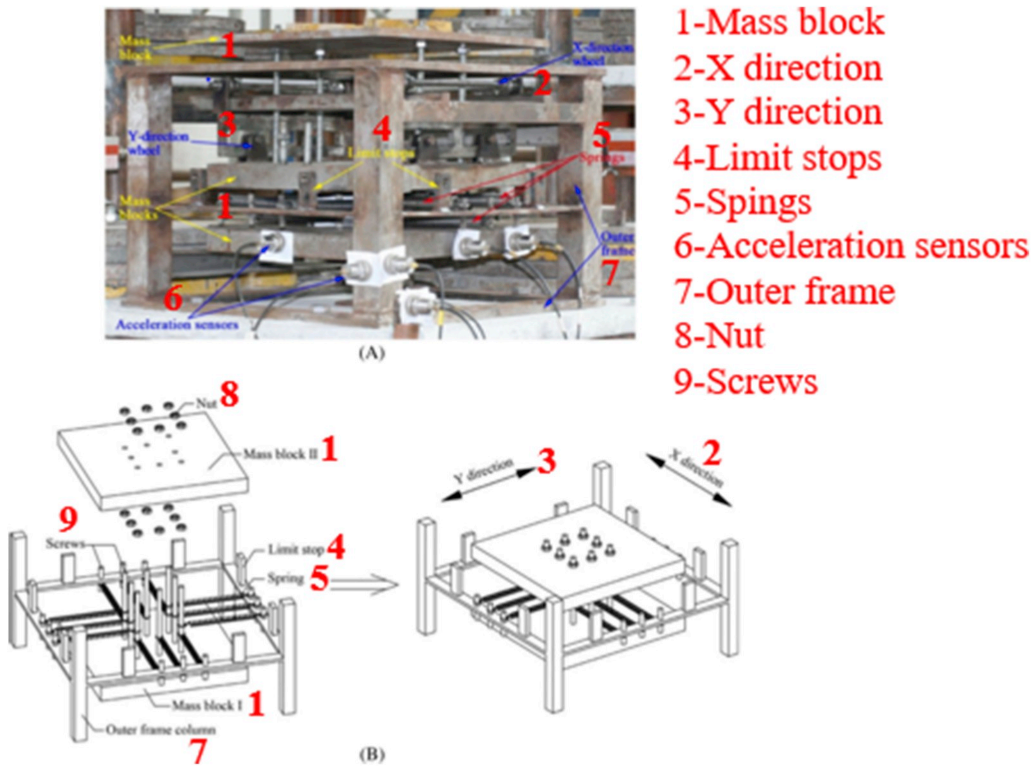


Fig. 13. Two linear TMDs installed in the nacelle (after [40]).

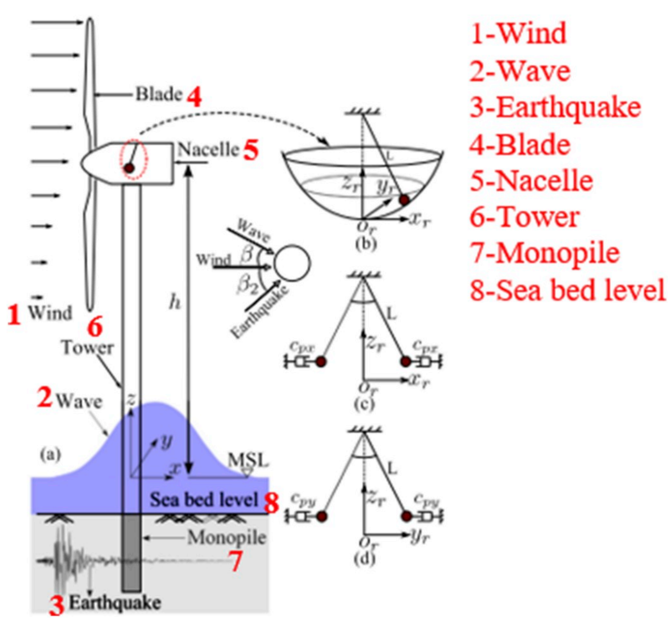


Fig. 14. 3D pendulum TMD proposed by Sun and Jahangiri (after [41–43]).

pendulum TMD can only be changed by the pendulum length, and the length increases with the increasing of the mass ratio of TMD, which may impede its practical applications due to the limited space in the nacelle as aforementioned.

3.1.3. TLCD/TLCGD

Besides TMDs, TLCDs are commonly adopted in the vibration control of wind turbine tower. Different from a TMD system, a TLCD system is composed of a U-shaped container that is partially filled with liquid with a mass ratio between the liquid and main structure of 1–2%. As shown in Fig. 15, the liquid can move back and forth between the left and right columns of the container through an orifice opening. The structural response is mitigated because of the movement of the liquid, the damping of the orifice plate and the gravitational restoring force form the liquid. To obtain better control performance, the geometries of the U-shaped container such as the horizontal and vertical length and cross sectional area of the column, and the diameter of the orifice should be properly designed. The research works on the vibration control of the tower by using TLCDs have been numerically [45–50] and experimentally [48,51] studied. In which, Colwell and Basu [45] firstly proposed

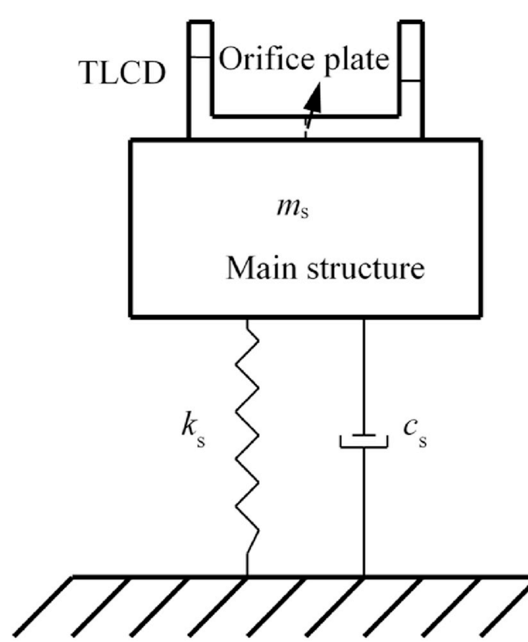


Fig. 15. A main structure-TLCD system.

using a single TLCD to reduce the vibration of the tower under different wind speeds without considering the dynamic behaviours of the blades. Due to the constrained space in the nacelle as discussed above, Mensah and Duenas-Osorio [47] divided the single TLCD into two smaller ones with the same mass ratio to construct the fragility curves of the wind turbine tower without and with control devices. With one in the nacelle and another installed near the top of the tower, the numerical results demonstrated that the two TLCDs only marginally increased the tower fragility compared to the single TLCD case. This observation is the same with those reported in Zuo et al. [25]. By comparing the control effectiveness of installing a TMD and a TLCD in an offshore monopile wind turbine respectively, Hemmati et al. [52] found that the TMD system performed better when the wind turbine was in the operational condition, while the TLCD system outperformed the TMD in the parked condition. In order to achieve a better overall control effectiveness in the whole lifetime of a wind turbine, a combined TLCD-TMD system was suggested in Ref. [52]. Moreover, similar to the TMD placed in the nacelle or platform to control the pitch motion of floating offshore wind turbines as mentioned in Section 3.1.1, Tong et al. [53] used a bidirectional TLCD on a barge to reduce its pitch and roll motions simultaneously under wind and wave excitations.

Motivated by the concept of TLCDs, a new control device dubbed tuned liquid column gas damper (TLCGD) was developed by Hochrainer and Ziegler [54], and has been applied in the vibration control of offshore wind turbines recently [55,56]. Similar to TLCD, TLCGD is a U-shaped container partially filled with liquid, but the vacancy in the two sealed vertical columns is occupied by pressurized gas. The major difference between the TLCD and TLCGD systems is that the frequency of TLCD can be tuned by the geometrical configurations only, while the frequency of TLCGD can be changed by the initial gas pressure besides the geometries of the container. The numerical results showed that, different from the conventional TMD system [57], the TLCGD with higher mass was more sensitive to the selected frequency of the device, such that it might impose destructive effect to the structure in the case with ill-regulated frequencies.

3.1.4. TLD

TLD system is also widely used to control the tower vibrations. The TLD system, which normally consists of a tank partially filled with liquid (see Fig. 16), can significantly reduce the main structural vibrations by tuning the sloshing frequency of the liquid to the controlled frequency of the main structure, which can be achieved by varying the water level. When the main structure vibrates under external excitations, the liquid in the tank begins to slosh and imparts inertial force onto the main structure, such that the motion of the main structure is controlled. Compared to the TMD system, the TLD system is more superior in the aspects of low initial cost, virtually free of maintenance and ease of frequency tuning. Different geometrical shapes of TLDs have been developed by different researchers such as spherical [58], annular [59,60] and rectangular [61,62] as shown in Fig. 17, and the effectiveness of using these TLDs for wind turbine tower vibration mitigation has been experimentally [58,61,62] or numerically [59,60] investigated. However, it is worth noting that the relatively low energy dissipation capacity of pure water sloshing prevents the TLD from reaching its optimal control effectiveness. To enhance the energy dissipation during the water sloshing, Zhang et al. [62] installed some damping screens in the water tank (Fig. 17(c)) to generate turbulence flow when the water passed through the damping screens to improve the performance of the TLDs. Although the TLDs can effectively control the tower vibrations, the challenge of this system is that the irregular liquid slope deforming due to water sloshing in the tank makes it not easy to accurately estimate the motion of the water, which in turn brings some difficulties to the design of TLDs.

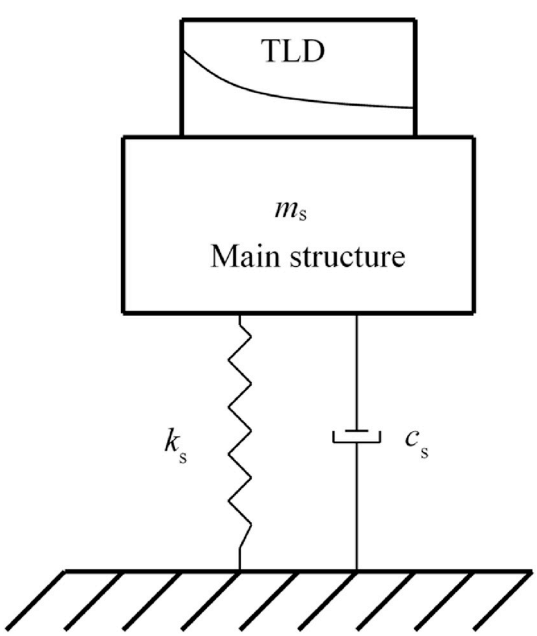
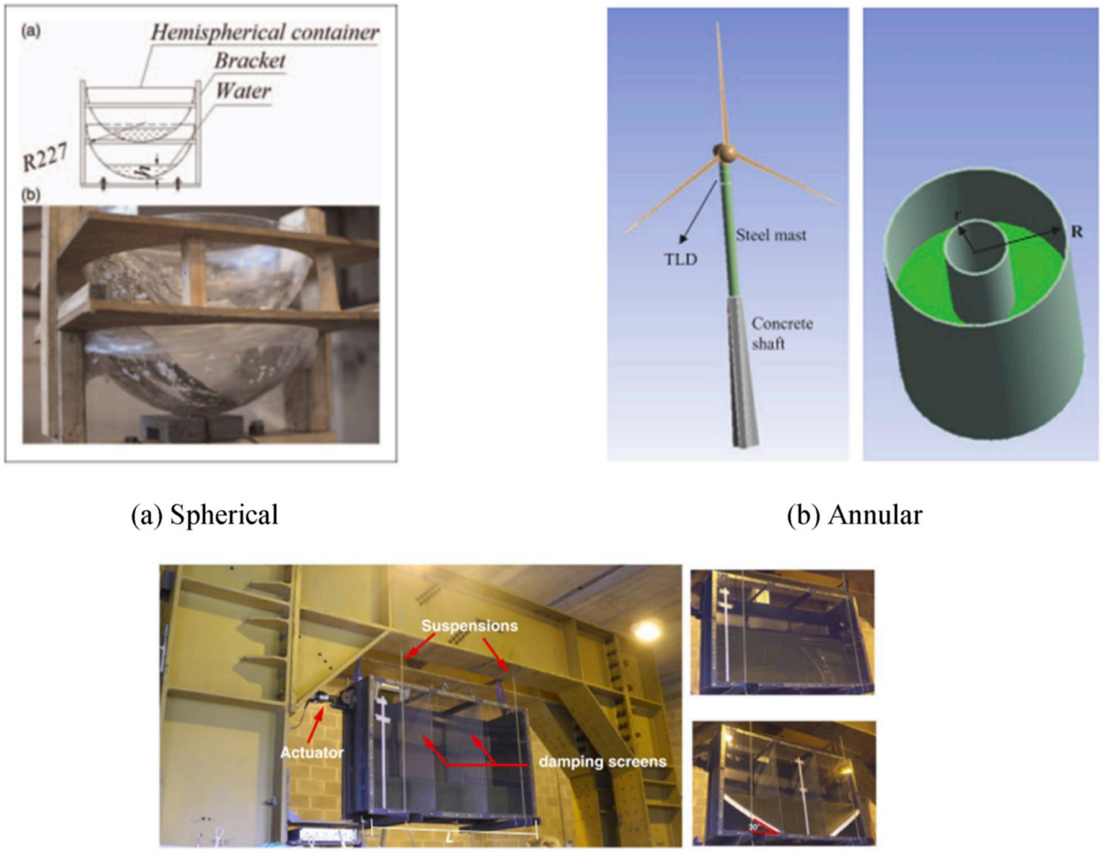


Fig. 16. A main structure-TLD system.

3.1.5. Novel devices

Besides the traditional TMDs, TLCDs and TLDs, some other control devices have also been developed to mitigate the excessive vibrations of the wind turbine tower such as the friction damper [63], scissor-jack braced viscous damper (VD-SJB) [64], ball vibration absorber (BVA) [65,66], tuned rolling ball damper [67] and double-response damper [68,69], and they are shown in Figs. 18 and 19 respectively. As shown in Fig. 18(a), the friction damper was installed to the tower with an additional supporting system (normally brace). The biggest challenge of employing friction damper in the wind turbine tower is that its control performance is dependent on the deformations of the tower, and a larger distance between the supporting system connected to the lower and upper parts of the tower can generate larger damping force and thus better control effectiveness, however, which is not practical in real application. To overcome this limitation, a scissor-jack braced system for amplifying the damper stroke was proposed as shown in Fig. 18(b).

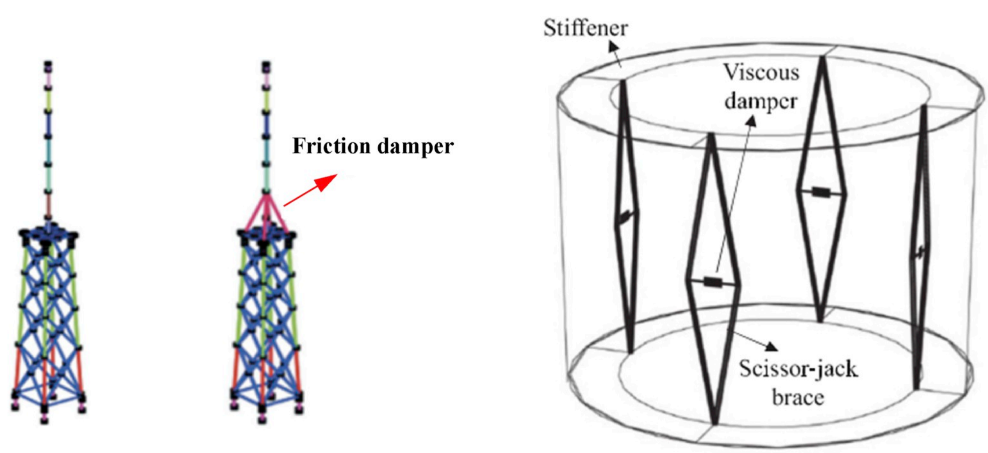
As shown in Fig. 19(a), there are three main components in the BVA, which are a steel ball, an arch path and two steel plates that limit the motion of the ball. A pad made from composite material was placed on the arc path to increase the friction during the movement of the ball [65,66]. The vibrating energy of the tower can be dissipated by the rolling motion of the ball as well as the friction between the ball and pad. However, it should be noted that the BVA is a unidirectional control device and can only control the vibration of the tower in one direction due to its design. Chen and Georgakis [67] proposed using tuned rolling damper as shown in Fig. 19(b) to overcome this problem. In this rolling damper, the steel balls in a spherical container can roll freely against the vibration of the tower, which thus has a good vibration control performance at any direction. For a tuned rolling damper, the rolling frequency of the steel balls is inversely proportional to the root of the radius of the spherical container. Tuning the rolling frequency of the damper to the vibration frequency of the tower (which is normally very low due to its flexible characteristics) thus requires a spherical container with large diameter, which impedes its application in the vibration control of the tower since the space in the nacelle is limited as mentioned above. Combining the characteristics of tuned rolling and particle dampers, Chen et al. [68,69] developed a new double-response damper as shown in Fig. 19(c), which is a container with spherical bottom surface and cylindrical vertical wall filled with multiple steel balls. Similar to the tuned rolling damper, the balls in the double-response damper can roll in the container, while the movements of these balls are constrained by the cylindrical vertical wall. The vibrating energy of the tower can be



(a) Spherical (b) Annular

(c) Rectangular

Fig. 17. Different geometrical types of TLDs (after [58,59,61,62]).



(a) Friction damper (b) VD-SJB

Fig. 18. Offshore wind turbine without and with (a) friction damper (after [63]) and (b) VD-SJB (after [64]).

absorbed through the motions of balls and the collisions between the balls and cylindrical vertical wall.

3.2. Active, hybrid and semi-active methods

Compared to the passive control methods, active, hybrid and semi-active control techniques have received less attention on the vibration control of the wind turbine tower. This is because the required external power sources and complicated control algorithms impair their practical applications. To the knowledge of the authors, only Rahman et al. [70] adopted a completely active controller to mitigate the tower vibration under different types of loads. In the limited research works on the vibration mitigation of the tower with hybrid control, ATMDs were most commonly used (e.g. Refs. [28,71–73]), and different control algorithms were proposed such as *H* infinity [28,73], static state feedback [71], adaptive sliding-mode [72], etc. In Refs. [28,71], the parameters of the passive TMD and the control force were optimized separately. The tower responses without damper and with ATMD and TMD in the frequency

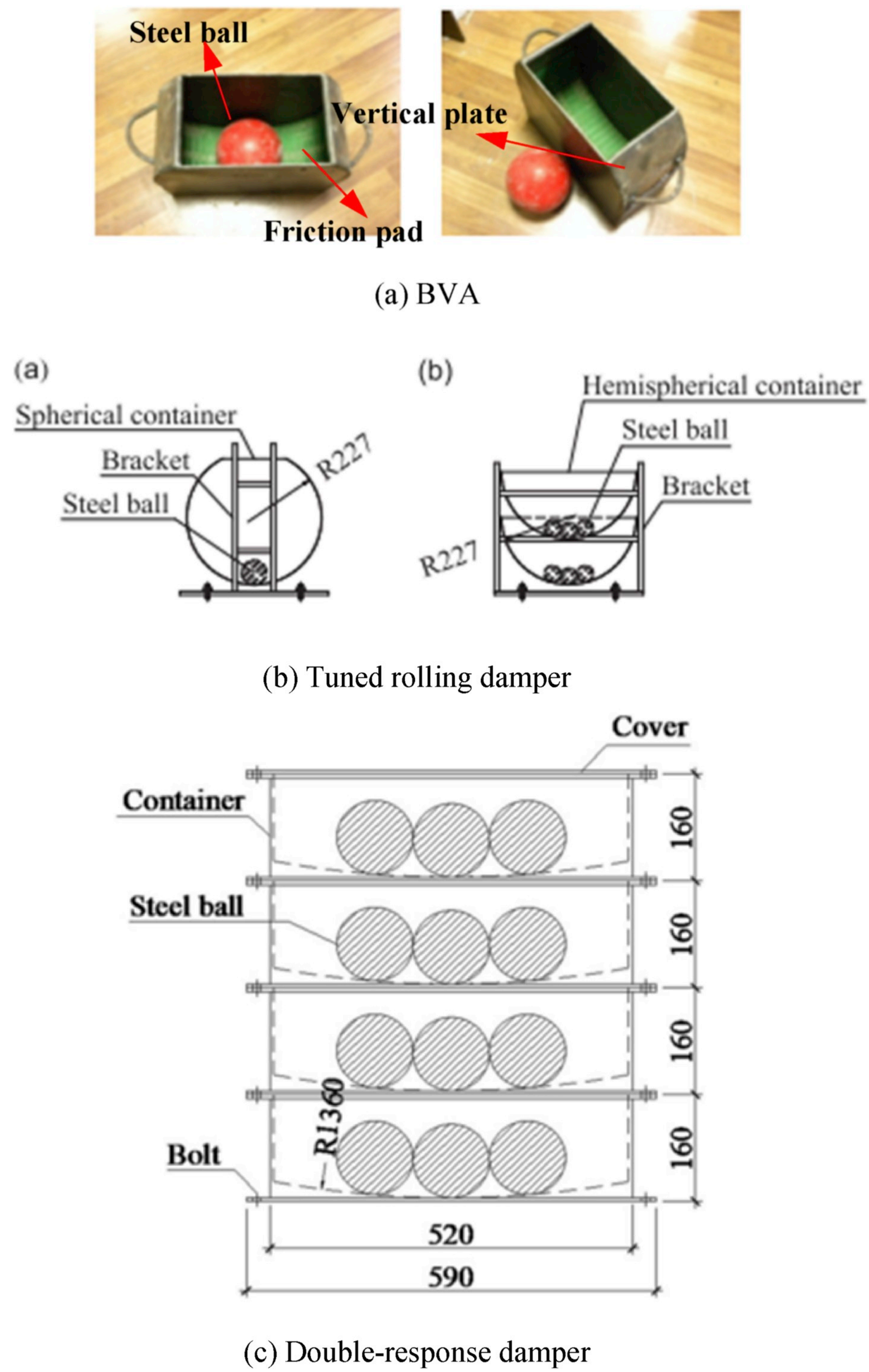


Fig. 19. Different steel ball dampers (after [65–69]).

and time domains were investigated and compared. In comparison to the passive TMD, the ATMD could achieve a better control performance with a smaller tuned mass, but the displacement of the mass in the damper was increased. To improve the practicality of the ATMD, Hu and He [74] and Cong [75] advised that a stroke limiter as shown in Fig. 20 could be used to restrain the overlarge displacement of the ATMD, and a contact nonlinear model between the ATMD and the stroke limiters was developed in Ref. [74]. Besides the above deterministic analyses, Fitzgerald et al. [76] studied the effect of ATMD on the reliability of the tower as a function of wind speed in a probabilistic frame. It should be noted that, the actuator in the ATMD system not only provides the control forces to the system, it also imposes another effect called control-structure interaction (CSI) into the system. Stewart and Lackner [77] developed a sophisticated model to consider this interaction effect and found that models included CSI were slightly more effective in reducing the vibrations of the tower, and the electric actuator with a small gear ratio could decrease the effect of CSI. This study provided insight into how to design the mechanical components of the actuator to minimize the unwanted CSI.

For the semi-active control method, Caterino [78] experimentally

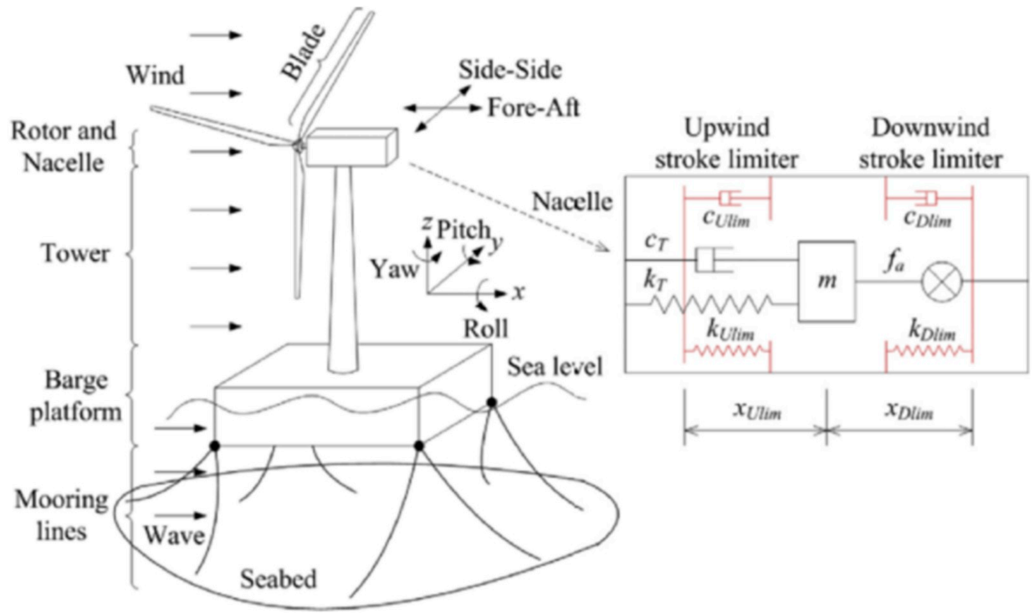


Fig. 20. Barge-type floating offshore wind turbine with a stroke-limited ATMD (after [74]).

investigated the use of MR dampers to reduce the bending stress at the base of a 1/20 scaled wind turbine tower by changing the properties of MR dampers based on a given control algorithm to realize a real time regulation of the stiffness of the tower. In this system, two elastic springs and two MR dampers were installed in parallel at the base of the tower as shown in Fig. 21. The two springs were used to allow resetting the tower to its initial position at the end of the tests. Experimental results indicated that the MR dampers could evidently reduce the peak stress at the base of the tower at the cost of increasing the displacement responses at the top of the tower. Martynowicz [80], Rezaee and Aly [79] and Park

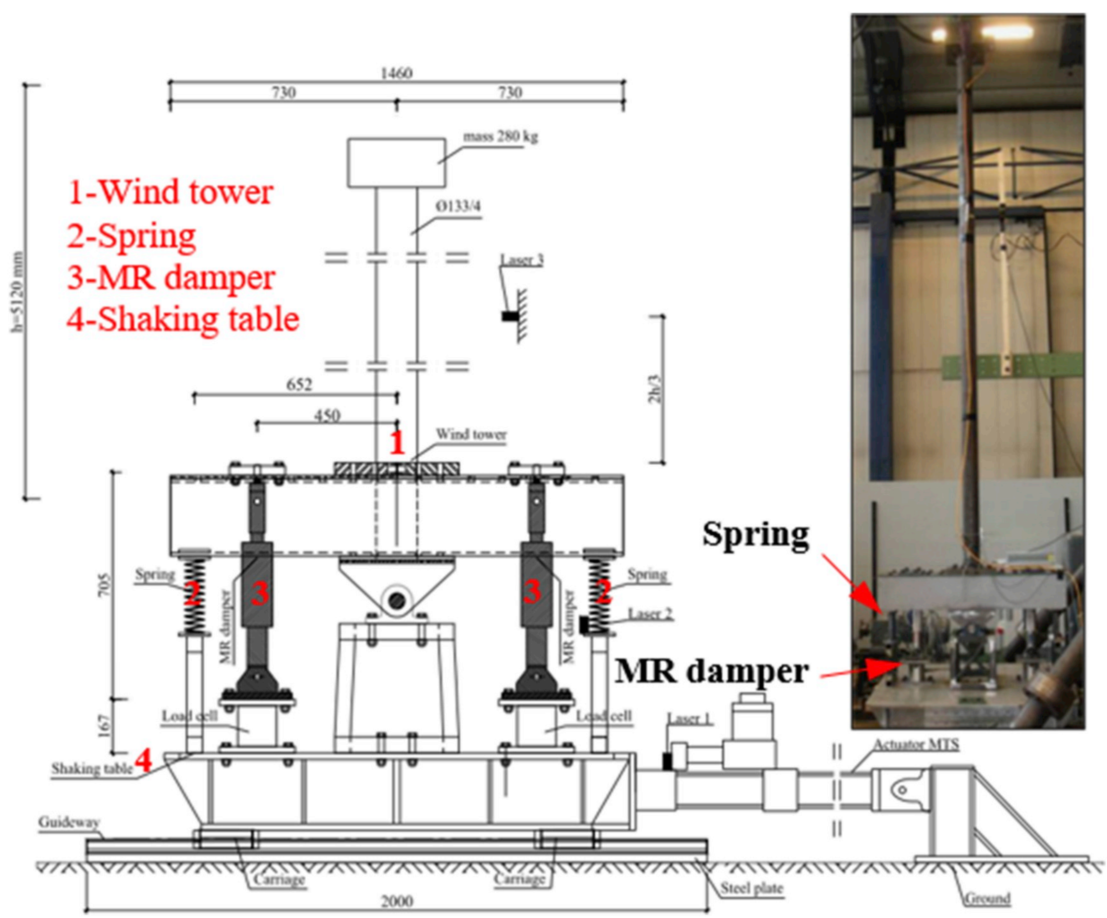


Fig. 21. Experimental setup of a wind turbine tower with MR dampers (after [78]).

et al. [81] used an MR damper connected to the additional mass in the nacelle by adjusting the damping of the TMD to act as an semi-active TMD. An outer bracing MR damper system connected to the tower was also proposed in Ref. [79] and it is shown in Fig. 22. In this system, the damper should be connected directly to the top of the tower to maximize the control efficiency. This is however not practical in wind turbines since the tower is quite tall and the bracing system should be as low as possible to avoid the interference with the blades. To solve this problem, the authors used a level mechanism to amplify the damping force [79]. These two systems could effectively mitigate the displacements and accelerations for both the parked and operating wind turbines when they were subjected to wind, wave and seismic loads. However, it should be noted that this outer bracing MR damper system is not feasible in the marine environment due to its special design, and it can only be used in the onshore wind turbines.

Under extreme loads, certain damages may occur in the pile foundation or the wind turbine tower. Moreover, the soil surrounding the pile may partially lose its stiffness under cyclic loads. All these factors may result in the change of vibration frequency of the tower. In other words, the natural frequency of the tower is time-variant in these cases. Due to the frequency variation, the passive TMD system might be mistuned and this mistuning effect will be escalated as damages continue to accumulate in the pile and tower, which leads to the malfunction of the passive TMD system. In certain scenarios, the mistuned TMD may even amplify the structural responses. Considering the soil-pile interaction effect and the possible damages in the foundation and tower, Sun [82,83] and Hemmati and Oterkus [84] suggested that the stiffness of the semi-active TMD should be adjusted according to the instantaneous responses of the tower as well as the damping of the control system. To this end, short-time Fourier transformation (STFT) was adopted to capture the time-varying frequency of the tower and then the frequency of the semi-active TMD was tuned according to this instantaneous frequency of the tower. Their results indicated that soil-structure interaction and damages of the foundation and tower decreased the frequency of the tower, and the semi-active TMD system optimized based on the time-dependent frequency of the tower performed much better compared to the conventional TMD system.

In addition, Karimi et al. [85] used a semi-active TLCD to control the tower responses, in which the valve in the horizontal tube was semi-actively controlled. It should be noted that the traditional TLCD system with water flowing through the orifice has certain inherent limitations. For example, large volume of water is needed due to the low density of water, which thereby restricts its application in wind turbine towers where the space is limited as discussed. Another issue is that the orifice aperture is not easy to be controlled, which makes most of the semi-active control algorithms very complicated, and more importantly it is very difficult to apply instantaneous control to the structure. Due to these limitations, Sarkar and Chakraborty [86,87] proposed using MR fluid instead of water in the TLCD. MR fluid is heavier and the required space is thus much less compared to water. Moreover, the flow characteristics of MR fluid can change almost immediately in the presence of magnetic field, which makes this damper react very quickly to the external changes.

It should be noted that, in most previous studies on vibration control of wind turbine tower, the wind turbine was assumed in the parked condition and the blades were considered a lumped mass located at the tower top. The studies on the influence of the rotating blades on the control effectiveness of those passive, active, hybrid, semi-active methods are limited, and it deserves further investigations. In fact, the wind loads acting on the blades are directly influenced by the geometrical configurations and rotational velocity of the blades [88]. Moreover, the vibration characteristics of the wind turbine in the operating condition can be changed by the blades [89,90] since the centrifugal stiffness generated by the rotating blades can increase the stiffness and frequencies of the blades, which in turn indirectly affect the dynamic responses of the wind turbine. Very recently, Zuo et al. [91,92] developed a detailed 3D finite element (FE) model of an offshore monopile wind turbine in ABAQUS, and the tower and blades were explicitly modelled to investigate the dynamic responses of the parked and operating wind turbines. Numerical results showed that, compared to the operating condition, the structural responses were considerably underestimated when the parked condition was assumed, which indicates that assuming the wind turbine in the parked condition may lead to an unsafe design of the structural components.

4. Vibration control of wind turbine blades

In order to maximize the output of wind energy, the rotor diameter of wind turbines have been increased exponentially in the past decades, which in turn results in the violent vibrations of the blades. The vibrations of the blades can happen in the in-plane (edgewise) and out-of-plane (flap-wise) directions since the wind loads acting on the twisted blades can be projected into the in-plane and out-of-plane directions as mentioned before. The in-plane vibration of the blades is lightly damped due to the low aerodynamic damping in this direction, and the vibration amplitude induced by the turbulence thus can be quite large which in

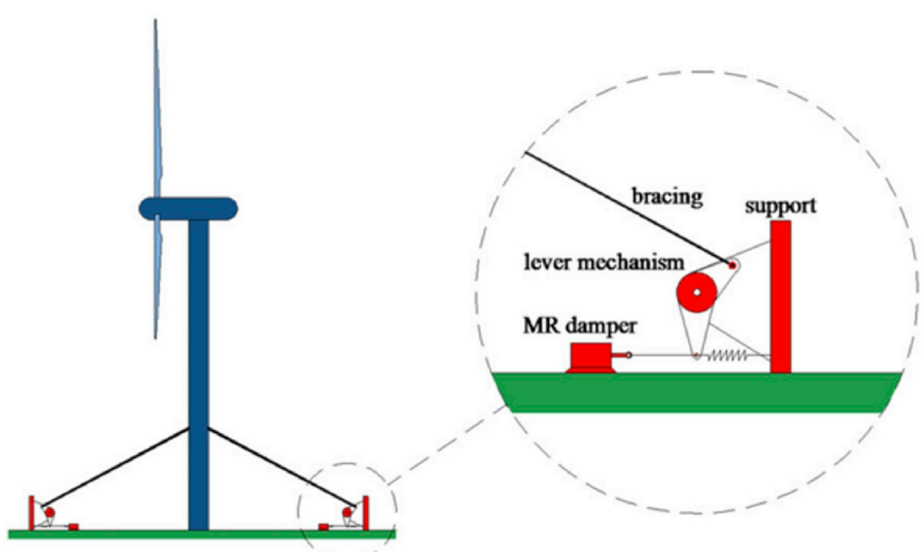


Fig. 22. Outer bracing MR dampers connected to the wind turbine tower (after [79]).

turn may significantly shorten the fatigue life of the blades. The blades vibrate in the out-of-plane direction that is similar to the fluttering phenomenon of the aircraft wings. In extreme cases, it can lead to the collision between the blades and tower and may cause the catastrophic failure of wind turbines. Passive, active, hybrid and semi-active control methods were also employed to mitigate the unwanted vibrations of the blades. In addition, some researchers embedded shape memory alloy (SMA) materials into the blades to increase their damping [93–95] or strength [96] to reduce the deformations of the blades, and the geometrical configurations of the blades were modified to reduce the wind loads on the wind turbine [97]. However, compared to the control of the tower, studies on the blade vibration control are relatively scarce. Similar to the tower, only the structural control strategies for the in-plane and out-of-plane vibrations of the blades are reviewed in this section.

4.1. In-plane vibration control of blades

Zhang et al. [98] suggested using a roller damper installed at certain locations along the blades to mitigate the in-plane vibration of the blades, and three different layouts of the roller as shown in Fig. 23 were proposed. As shown, the vibrating energy of the blades was absorbed by a ball, a cylinder or a flywheel rolling in a circular tube. In the three possible layouts, the flywheel has a larger mass moment of inertia at the cost of less compact layout than that of the ball or cylinder with the same physical mass. Afterwards, Zhang et al. installed TLCD [99] and TLD [100] to enhance the damping of the blades in the in-plane direction. Extensive parametric studies were performed to evaluate the influences of the mass and frequency ratios, friction coefficient and mounting location of these dampers. Their results revealed that better control effectiveness could be obtained by increasing the mass ratio and installing the damper closer to the tip. However, as mentioned by Zhang et al. [98–100], the available space in the hollow blade reduces toward the tip, the installation of dampers in the blades is a trade-off problem in practical applications. On the other hand, the control effectiveness decreased with the decrement of the rotational velocity of the blades. The reason is that Zhang et al. [98–100] used a very small damper (the mass ratio between the damper and blade is less than 0.5%) and took advantage of the centrifugal acceleration generated by the rotating blades to enlarge the physical mass of the damper. When the rotational velocity of the blades decreased, the mass of the damper and hence the control effect decreased. Moreover, each blade was simplified as a two-DOF system, with one in the in-plane direction and another in the out-of-plane direction. It is obvious that the wind loads along the length of the blades are inevitably different, the estimation of the blade responses thus might not be accurate with this simplification. A similar idea was proposed by Basu et al. [101] using a circular liquid column damper (CLCD) which is circular tube partially filled with liquid that could move back and forth in the tube. In terms of energy dissipation mechanism, the roller damper and CLCD are different. The inherent damping of the roller damper is the friction between the surfaces of damper and circular tube, which likes the BVA and tuned rolling damper in the vibration control of the tower (refer to Section 3), while in the CLCD, the control effect is from the liquid passes through an orifice opening in the middle of the circular tube, which is similar to the damping mechanism of TLCD as discussed in Section 3.

Staino et al. [102], Staino and Basu [103,104] and Tao et al. [105] adopted an active control method to mitigate the in-plane vibration of the blades, and two active elements (actuators or tendons) were mounted on a frame supported by the nacelle as shown in Fig. 24. In which, the active elements and the supporting structure are shown in the thin (red) and bold lines respectively. As shown, a net control force acting at the tip of the blade in the in-plane direction was generated, and the reaction force was transferred along the supporting structure and finally to the nacelle. Numerical simulations demonstrated that this system could effectively reduce the in-plane response of the blades induced by wind loads, and it was also effective at different blade rotational velocities. However, the space inside the blades is even smaller than that in the nacelle, the installation of a complicated controller in the blades is thus a big challenge. Fitzgerald and Basu [106] used a prestressed cable connecting to the mass of an ATMD [107] and the tip of the blade as shown in Fig. 25. In this control system, two actions on the blade were generated when the ATMD moved due to the blade vibration. One was a control force of the ATMD acted on the blade to reduce its in-plane vibration. Another was that the cable had an inclined angle to the radial axis of the blade due to the movement of the mass of ATMD, the resultant force in the cable thus had a component opposing the in-plane loadings of the blade, which further reduced the response of the blade in the in-plane direction.

MR dampers were also adopted to provide the control forces to mitigate the in-plane vibrations of the blades as shown in Fig. 26 [108]. As shown, one end of the MR damper was connected to the blade and another end was connected to the supporting frame. The control forces were generated based on the input voltage of the damper and the differences between the displacements and velocities at points A1 and A2 as shown in the figure. The influences of the number and mounting location of MR damper were investigated. It should be noted that extreme wind was considered in Ref. [108]. Under the normal operating conditions, the displacements and velocities at these two points might not be obviously different considering the distance between points A1 and A2 was relatively small (1.5 m in Ref. [108]). Moreover, the additional frame installed in the blades would increase the stiffness and mass of the blades, the influence of which on the structural responses was neglected in Ref. [108]. Since the rotational velocity and stiffness of the blades and the tension of mooring cables in the floating offshore wind turbine change over time, the wind turbine is a time-variant system. Dinh et al. [109] and Arrigan et al. [110] installed semi-active TMDs in each blade, nacelle and on the spar platform (in Ref. [109] only) to control the structural responses of the wind turbine in the in-plane direction, and STFT method was adopted to track the real time dominant frequency of the system.

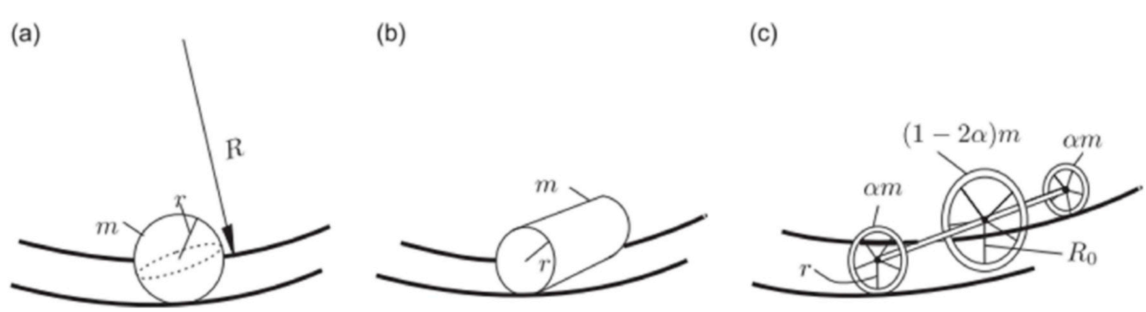


Fig. 23. Possible layouts of roller damper (after [98]).

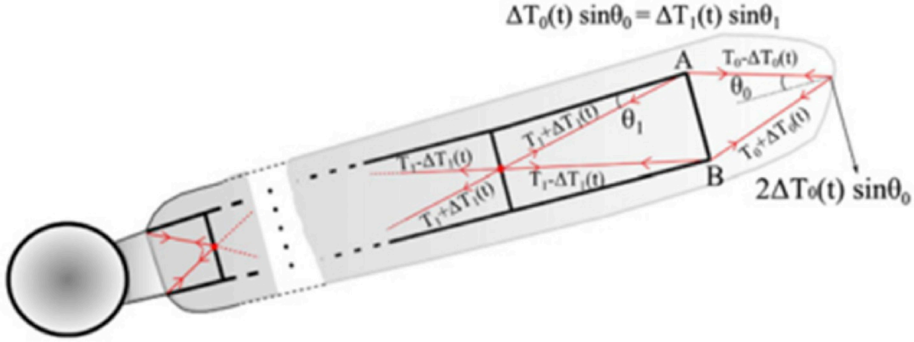


Fig. 24. Active control of the blade in-plane vibration using active tendons (after [102–104]).

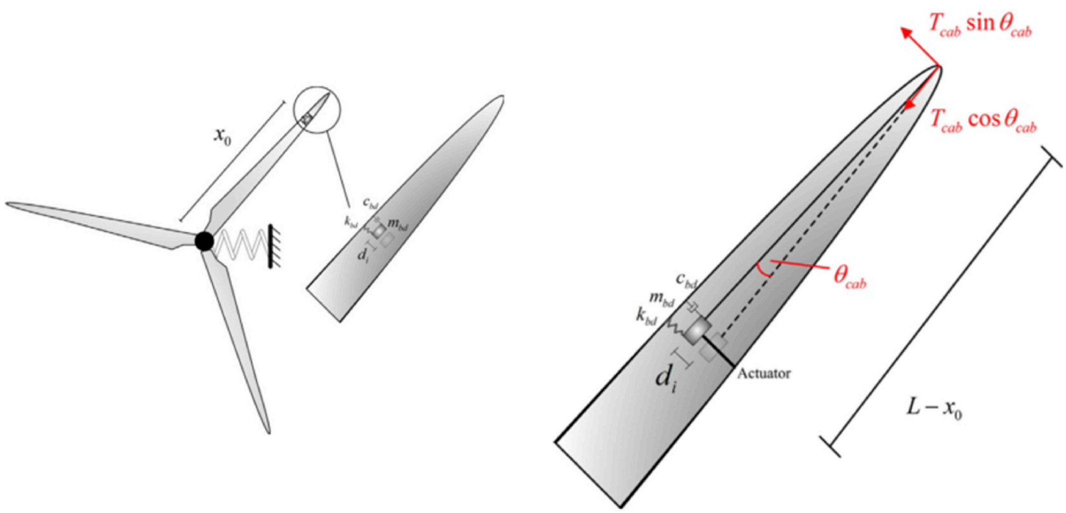


Fig. 25. Cable connected ATMD inside the blade (after [106]).

4.2. Out-of-plane vibration control of blades

The out-of-plane responses of the blades are significantly related to the aerodynamic damping resulting from the relative velocity between the wind and blades, which depends on the wind speed, rotational velocity and geometrical characteristics of the blades. A few studies on mitigating of the blade out-of-plane vibration were reported. Considering the limited space inside the blades, Zuo et al. [111] installed MTMDs in the blades and tower instead of using a single TMD [112,113] to control the out-of-plane vibration of the blades and tower. In Ref. [111], the parked and operating conditions and the number of TMDs were studied. Although the control effectiveness of MTMDs slightly decreased compared to a single TMD installed at the tip of the blade and the top of the tower, the reliability of the control system was however significantly improved in case some of the dampers do not function well. Ju and Sun [114] used an input shaping to reduce the out-of-plane vibration of the blades induced by the changes of pitch angle. In this control system, a second impulse was applied to the structure at a specific time to reduce or cancel the residual vibration caused by an impulse input. More recently, Fitzgerald et al. [115] proposed a wavelet-based individual blade pitch control strategy based on the modification of the conventional linear quadric regulator (LQR) control algorithm. In which, the local energy distribution over the frequency bands were obtained by the wavelet analysis of the response of the blades in the out-of-plane direction, which was then used to design the pitch controller by updating the weighting matrices applied to the response energy and the control effect. This new controller was demonstrated to have better control effectiveness compared to the standard LQR and proportional integral controllers. Similar to the in-plane vibration mitigation of the blades, the rotational velocity of the blades and the stiffness of the blades and nacelle may vary with time. To more accurately capture the time-dependent frequency of the wind turbine, semi-active TMDs in the blades were used by Arrigan et al. [116] to control the out-of-plane vibrations.

5. Conclusions

Multi-megawatt wind turbines built with large rotor and slender tower are susceptible to the external dynamic excitations such as wind, wave and earthquake loads. Extensive numerical, experimental and analytical studies have been performed in order to control the adverse vibrations of wind turbine tower and blades. In this paper, previous studies on this topic are reviewed and discussed. Following conclusions are obtained:

1. Previous studies on the wind turbine vibration control mainly focused on the tower, and many passive, active, hybrid and semi-active methods have been proposed by different researchers. Among them, the passive control devices such as TMDs, TLCDs and TLDs were most widely used since these methods have simple configurations and do not need external power source. The studies on the vibration mitigation of the tower by adopting active control methods are limited. The reason might be that the required external power and complicated control algorithm make these methods not very practical. Recently, attentions on the hybrid and semi-active control methods (normally ATMD and MR damper), which

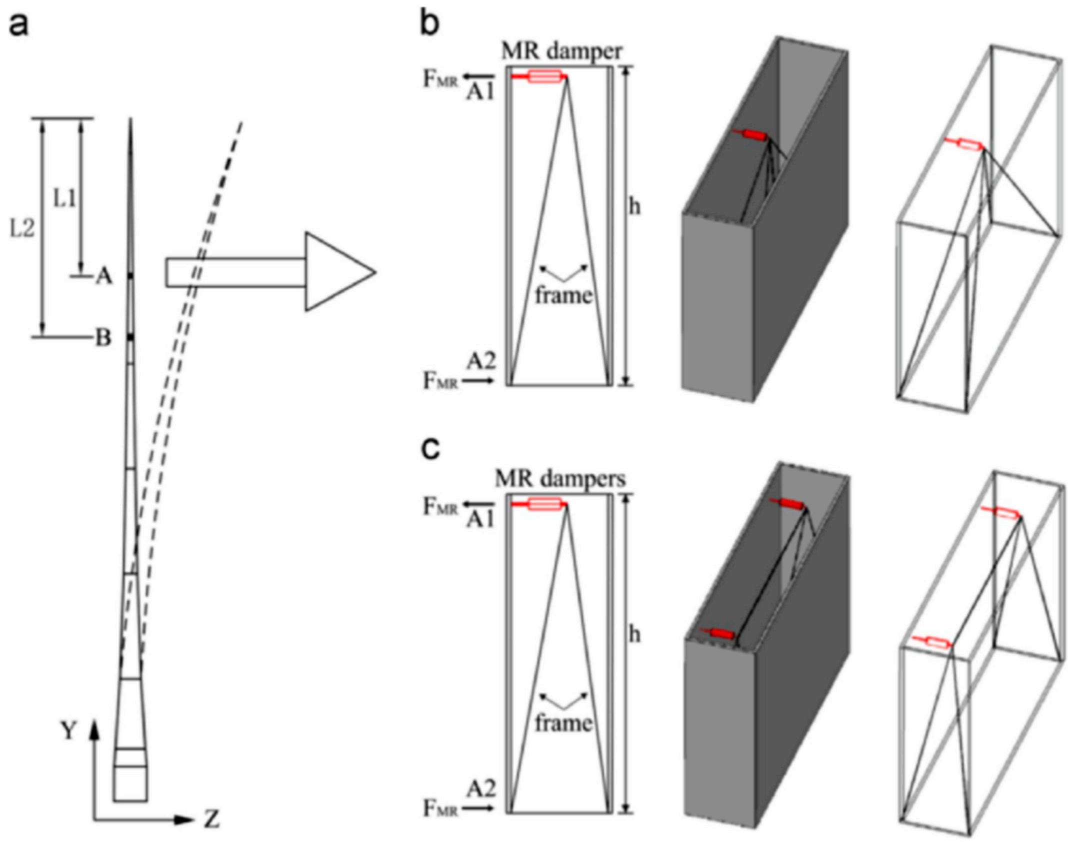


Fig. 26. Configuration of blade with MR damper (after [108]).

combines the advantages of the passive and active methods together, have been raised. The tower may damage under cyclic loads and the soil surrounding the pile foundation may lose part of its stiffness, the natural frequencies of the wind turbine are thus time-dependent. When the frequency of the damper in the passive and hybrid controls is tuned to a fixed frequency of the wind turbine, the control effectiveness of the passive and hybrid methods may be decreased or even amplified. To solve this problem, semi-active control can be a possible solution, in which the frequency of the damper can be adjusted based on the time-variant frequencies of the wind turbine. Moreover, the damping forces generated in the semi-control system can also be changed in accordance to the instantaneous responses of the wind turbine. In order to mitigate higher vibration modes of the wind turbine tower, multiple control devices should be installed along the height of the tower. By using this method, another two merits can be appreciated. One is that the robustness of this control system can be significantly improved, and the other is the installation of the control system is more straightforward due to the small mass of each damper.

2. Structural vibration control methods were also used to reduce the in-plane and out-of-plane responses of the blades, but the corresponding research works are relatively limited compared to the tower vibration mitigation. To achieve a better control performance, semi-active control technique was the most commonly adopted since the wind speed and rotational velocity of the blades always vary with time, and the vibration characteristics (e.g. vibration frequencies and aerodynamic damping) of the wind turbine are not necessarily fixed at deterministic values. Different from the wind turbine tower, the mitigation of higher vibration modes of the blades has not been investigated yet.
3. Although all these methods claimed being able to effectively mitigate the adverse vibrations of the wind turbine, most of the previous studies focused on the tower or the blades only, the interaction between the tower and blades was not considered in the structural response estimations or the wind turbine was simply assumed in the parked condition to investigate the effectiveness of the proposed control devices. In reality, the wind turbine is a complicated dynamic system which includes the aerodynamics, blade rotation, interaction between the tower and rotating blades and soil-structure interaction, etc. To more accurately investigate the control effectiveness, the influences of these parameters and the interactions between them should be considered simultaneously.
4. Most previous studies stayed at the conceptual level, their applicability in real engineering practice needs be studied especially considering the limited spaces in the nacelle and blades. Developing effective while applicable methods for wind turbine vibration control deserves more investigations.

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