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Review

# Review of floating wind turbine damping technology

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ABSTRACT

As the world's need for renewable energy has grown in recent years, the possibility of creating and collecting deep-sea wind energy has become a research hotspot. Floating wind turbines need damping devices to provide a stable working state and structural safety. Damping systems are often used for offshore floating constructions based on various operating principles and locations. Damping technology of various sorts is continually being researched for various demands, such as floating body size, form, and operating circumstances. To react to complex and changeable external circumstances, new perspectives on damping method categorization and selection are required. The conclusion was reached by classifying and comparing, tuned liquid column dampers are often employed in operational conditions. Dampers with power sources perform well in extreme conditions, such as Magnetorheological dampers. Rotational inertia dampers can greatly decrease torque but have yet to be widely employed in floating wind turbines. The purpose of this study is to review the latest improvements in offshore damping technology. The research results will provide characteristics and design references for future vibration damping of floating offshore wind turbines.

## 1. Introduction

In recent years, with the gradual promotion of the global "carbon neutrality" goal, clean energy has increasingly become the leading choice for energy supply (Nathwani and Kammen, 2019). Offshore wind energy is also outstanding for its high average wind speed and capacity. As a result, the offshore wind market has grown from 2.2 GW in 2016 to 6.1 GW in 2020, result in its market share in global new installations from 4% to 7% (Shouman, 2020). However, with the development of offshore power generation technology, extreme weather conditions have become one of the inevitable problems (Hutchins et al., 2019). A variety of extreme loads often accompany major natural disasters. For example, typhoons are often accompanied by tsunamis, and submarine volcanic eruptions can bring earthquakes and tsunamis (Gill and Malamud, 2014). The occurrence of these disasters has caused considerable losses to offshore wind turbine.

A large number of engineering cases show the terrifying power of extreme weather. In November 1989, the Seacrest drilling rig in the Gulf of Thailand was hit by a typhoon with a central wind speed of 46.3 m/s, and the maximum wave height exceeded 14 m, which eventually caused the platform to capsize, and 91 people died (Fazeres et al., 2019). Extreme weather is also a threat to onshore wind turbines. Storm Anatole struck the North Sea and northern Europe on December 3–4, 1999. The storm's effects included extensive forest damage, deaths, hundreds of injuries, power outages, disruption to transportation, and storm surge flooding on Denmark's west coast. At the time of the storm, Denmark was firmly committed to wind energy, and about ten onshore wind turbines were destroyed in the wind (Kettle, 2021). During 2004–2005, three consecutive Category 5 hurricanes (Ivan, Katrina, and Rita) hit the Gulf of Mexico Central (GOM). They damaged many drilling and production rigs, including Noble Jim Thomson (NJT) drilling semi-submersible (Zhang et al., 2008). Typhoon "Sudlo" hit Taiwan on August 7–8, 2015, causing the towers of 2.0 MW wind turbines to collapse (Fakour et al., 2016).

Unlike other types of wind turbines, floating wind turbines (FOWT) are more susceptible to loads such as wind and waves. It faces a complex load condition, as shown in Fig. 1 (Clement et al., 2021), and its dynamic responses are difficult to predict. In order to study the response state of FOWT in extreme environments, it is often necessary to determine the combined load characteristics and action (Lamei and Hayatdavoodi, 2020). Appropriate damping technology can effectively protect the structure and operate the state of FOWT. Researchers have reviewed damper structures suitable for local locations (Rahman et al., 2015) and summarized the working principles of damping techniques suitable for wind turbines (Ghassempour et al., 2019). Dampers' design and failure process are closely related to the limited states (Miyamoto et al., 2010). Therefore, different limit states must be improved for floating structures by selecting different damping systems (Zapoměl et al., 2012; Tubaldi et al., 2016).

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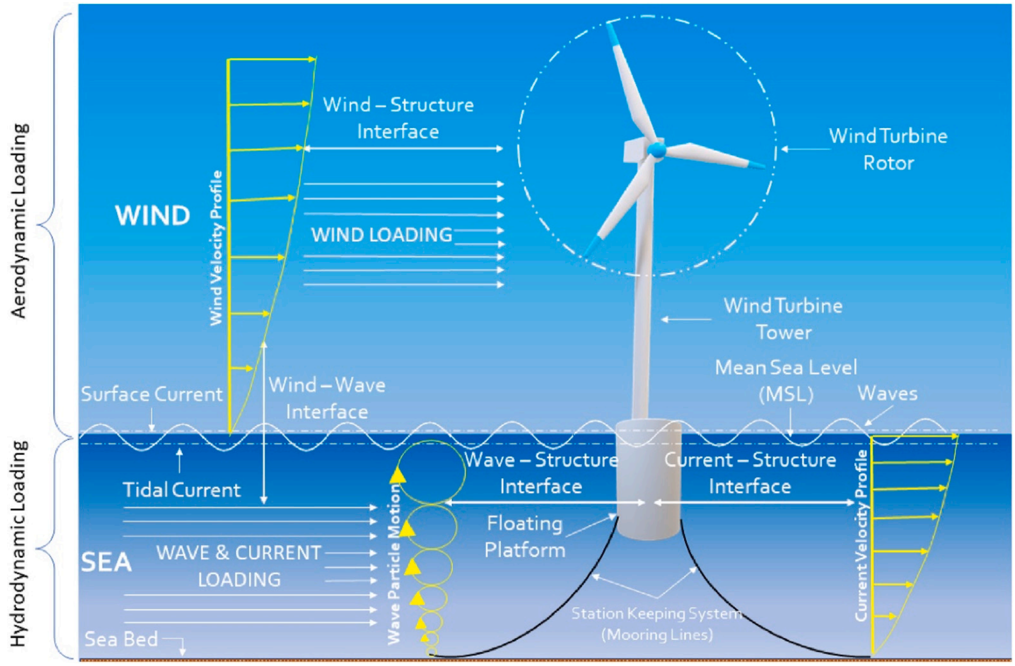


**Fig. 1.** Environmental Loads of OWT (Clement et al., 2021).

In addition to the environmental loads, the limit state of the floating structure is another significant factor (Fallais et al., 2016; Hong et al., 2020), which broadly governs the operating characteristics and strength of the damping system (Fallais, 2015; Zargar et al., 2017). Moreover, the limit state of the floating body is also affected by environmental loads (Saranyasoontorn and Manuel, 2005; Agarwal and Manuel, 2007). In order to standardize the effects of these extreme loads during the design phase of offshore structures, the Eurocodes, which are definite by Det Norske Veritas (Norway) and Germanischer Lloyd (Germany), describe different operating conditions for offshore wind turbines. The unit is divided into four limit states (Frieze et al., 2004) Serviceability Limit State (SLS), Ultimate Limit State (ULS), Accidental Limit State (ALS), and Fatigue Limit State (FLS). The extreme limit state means that the structure reaches the maximum bearing capacity and loses its resistance to excessive yielding, structural deformation, or overall imbalance. The fatigue limit state refers to the failure of a structure due to the accumulation of damage under cyclic loading. The accidental limit state refers to the maximum bearing capacity of the structure under accidental loads. The service limit state is the maximum permissible value for each indicator of a structure under typical loads.

In order to ensure the safe operation of the FOWT at different limit states, researchers are actively searching for suitable damping techniques. This paper will analyze and summarize the damping techniques suitable for FOWT in the following four ways. The framework of this study is shown in Fig. 2, and the highlights of the study are as follows:

1. Firstly, we present a comprehensive summary of the influence of damping technology, the limited state of the floating structure, and the interaction between environmental loads;
2. Secondly, we divide the newest offshore damping technologies by application scenario;
3. Thirdly, we evaluate and summarize offshore damping technology;
4. Finally, we summarize the potential directions and priorities for future technologies;

The rest of the paper is structured as follows: Section 2 analyzes the offshore environmental loads of offshore wind turbines, Section 3.1 reviews the offshore damping technology suitable for FOWT, Section 3.4 summarizes the technical characteristics of damping technology, and Section 4 discusses future research directions.

## 2. Environmental conditions

For the FOWT, the operational condition is strongly dependent on the external environmental conditions. Environmental conditions are influenced by many factors such as loads, limit states, etc. The environmental conditions are divided into two main types according to the level: operational conditions and extreme conditions. The operating conditions are the loads and limit states to which the FOWT is subjected in its normal operating condition. The extreme conditions refer to the load and limit state conditions to which the FOWT is subjected in extreme operating conditions. The choice of damping is influenced by variables including the size and direction of the external load. These variables relate to the posture and wear damage of floating structures (Smilden et al., 2017). The limit state influences the safe load range and damping application circumstances (Li et al., 2020). Therefore, this subsection will focus on the limit states of the FOWT under different environmental conditions.

### 2.1. Operational conditions

Under conventional operating conditions, the FOWT is threatened by fatigue loading in real-time. Fatigue loads have an impact on structural life and fatigue processes, so researchers have studied fatigue loading extensively. The amplitude of fatigue stresses on FOWT should be within the floating structure's permissible design range (Malliotakis et al., 2021). Fatigue loads may cause the float to enter either the serviceability limit state (SLS) or the fatigue limit state (FLS) (Park, 2020). Fatigue loads influence limit state change at all times, so this condition need offshore damping systems with quick reaction times and all-direction damping.

Many locations in the FOWT are highly sensitive to fatigue loading. Specific fatigue loads can cause damage to a particular location. Zou et al. (2021) analyzed the damage to the reverse balance flange in an FOWT tower by cyclic loading and assessed the degree of damage at different locations of the flange. Sang et al. (2018) studied the fatigue-prone locations of wind turbine foundations under turbulent wind action to provide effective guidance for the design of semi-submersible FOWT. Gueydon et al. (2014) found that second-order wave forces

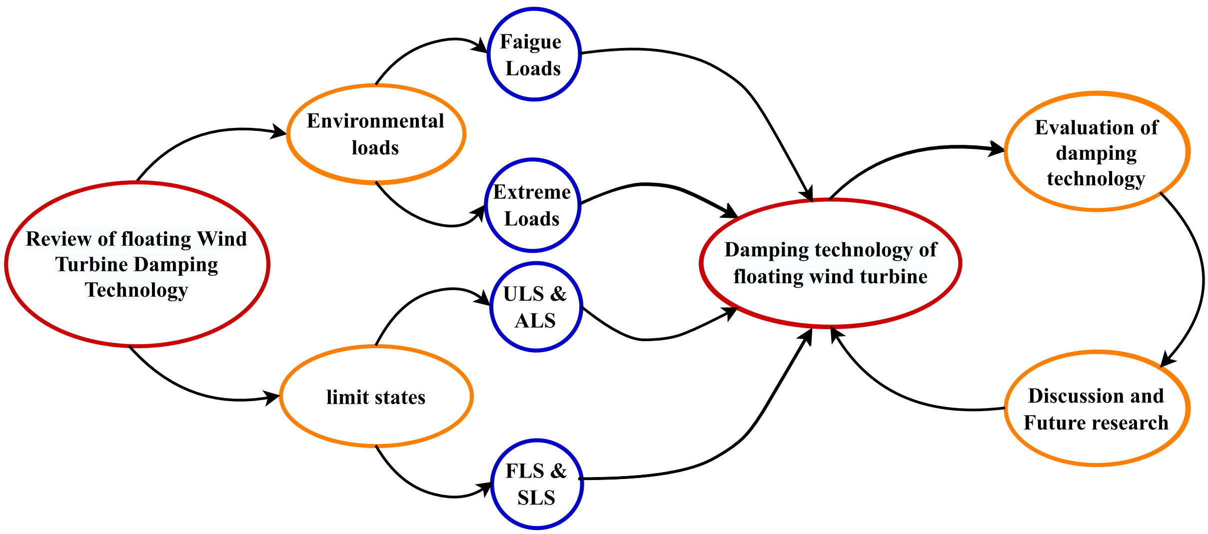


**Fig. 2.** Framing map of the review.

have a significant effect on the fatigue damage of tower structures, and second-order waves can exacerbate the wind–wave coupling effect.

In order to describe the effects of fatigue loading in detail, researchers have introduced FLS and SLS. Al-Ramthan and Aubeny (2018) evaluated the design process of an offshore floating structure suction caisson using a SLS. The effects of parameters such as period, amplitude, and stiffness were considered in the model. Finally, a good evaluation model was obtained. Kvåle and Øiseth (2017) designed and installed monitoring on a bridge to investigate a pontoon's SLS. The influence of environmental parameters on the response state was obtained experimentally. Li et al. (2018) investigated the FLS of a new type of floating wind turbine. Experiments were also conducted on structural ultimate and fatigue damage loads, and the new hybrid platform was found to have superior performance. Jalbi et al. (2018, 2019) considered SLS, FLS, and inherent frequency to optimize the caisson foundations for FOWT and found that the optimized caissons performed well. Thöns et al. (2012) considered parameters such as hot spot stresses and natural frequency in a model in order to study the FLS and SLS of offshore wind turbine converter support structures. This evaluation model reveals the characteristics of the structure through testing.

The fatigue loads on floating wind turbines are mainly cyclical wind and wave loads. This leads to the generation of periodic motions in floating turbines (Duan et al., 2016). In order to accurately describe the load characteristics of the FOWT under FLS and SLS, scholars have carried out modeling studies of periodic wind and wave loads. Jensen et al. (2011) predict the extremes of wave and wind-induced loads, and models have been developed based on first-order reliability methods (FORM) and Monte Carlo simulation (MCS). The new model can reduce the prediction time and effectively improve accuracy. Xu et al. (2019a) investigated the effect of non-linear wave effects on floating wind turbines, and the float motion and structural response under linear and non-linear irregular waves were compared. The results of the study demonstrated the importance of the non-linear wave model. Chen and Basu (2019) studied the modeling of wave–current interactions in FOWT and considered a new mechanical model in the structural dynamics analysis of blades and towers. The study results show that the model has a high accuracy when the tidal current may opposite to the surface waves. Marino et al. (2017) researched the elastic response and fatigue load conditions of an offshore wind turbine foundation under different wind and wave effects. It was found through simulations that the effects of fatigue loads and aerodynamic loads should be considered. Li et al. (2018) simulated the short-term fatigue of FOWT tower foundations with random wind–wave loading. The damage prediction model substantially improved the prediction accuracy by considering factors such as duration, wind direction, and period. Zhang et al. (2019) proposed an optimization model for FOWT structures based on reliability analysis, which can effectively assess the reliability of structures based on Monte Carlo simulation methods with Latin hypercube sampling and finite element models. Researchers consider various influencing factors and load parameters in their models. Studies of wind and wave loads have shown that such loads directly affect the operating conditions of floating structures.

For this section, periodic wind and wave loads will cause both FLS and SLS limit states. Kvittem and Moan (2015) found that wave period has a significant effect on tower damage in semi-submersible wind turbines. Li and Zhang (2020) study found that cyclic loading caused more severe fatigue damage to the tower base and tower top. For both FLS and SLS limit states, the dampers should be installed in areas where fatigue is serious (e.g. tower top & tower base).

### 2.2. Extreme conditions

In extreme conditions, the safety of the FOWT is threatened by extreme environmental loads. FOWT extreme loads are unreasonable load values and unconventional forms of loading that are beyond their design allowances and usually cause irreversible damage to the FOWT structure. Such loads, including tsunamis, hurricanes, earthquakes, and ice floe impacts, occur in many forms. The Ultimate Limit State (ULS) and the Accidental Limit State (ALS) is caused by these loads. Due to the large magnitude, short duration, and high economic damage caused by extreme loads, this situation requires offshore damping technology with an extensive damping range, adjustability, and safety.

Under extreme loads, FOWT will be exposed to irreversible damage. These accidental damages can cause serious safety incidents and economic losses. MacNicoll et al. (2020) found that heavy storms can cause serious damage to the mooring system of a FOWT. Xu et al. (2019a) studied the structural damage of FOWT after stopping in extreme weather and found that wind loads caused the most significant damage to blades and towers at this time. Zhang et al. (2013) tested the performance of a 10MW tension-leg platform (TLP) type FWTS under extreme loads, and showed that the improved TLP effectively solved the tendon brake problem. Xiong et al. (2018) found that extreme winds caused additional damage to the gearbox of the FOWT, and that faster pitch speeds could help to reduce this damage.

To characterize the effects of extreme loads, the researchers have introduced ULS and ALS. Benassai et al. (2014) investigated the mechanical properties of the FOWT suspended chainline mooring system in the ULS. Hørte et al. (2017) investigated a reliability model for mooring systems to calibrate the reliability of mooring systems in the ULS and the ALS. The new model was found to be more accurate by comparison with other methods. Kim et al. (2019) investigated the ALS of a ship hull under iceberg impact. The shortcomings of the ice load model were identified through simulation, which was analyzed and discussed. Prabowo et al. (2017) investigated a ship hull collision's ULS. Kim et al. (2022) developed a five-legged suction bucket support structure to solve the ULS of FOWT. Finally, the scour risk of the structure was evaluated experimentally. Wilkie and Galasso (2017) developed a ULS and probability model for the arrival of FOWT under solid storms. The failure rate of the FOWT was assessed by comparing the model with experimental data. Xu et al. (2019b) investigated the ULS design process for a shallow water FOWT, optimized and compared mooring system solutions with experimental data, and gave engineering recommendations.

Many researchers have investigated the unexpected loads that lead to these limit states. Wang et al. (2021) studied the failure of mooring systems of deepwater semi-submersible platforms under extreme sea conditions. Through hydrodynamic simulations, an effective mooring analysis method was proposed. Jin et al. (2005) studied the effect of impact action on offshore platforms. Damage assessment indexes were obtained through simulation, and a feasible and reasonable repair and reinforcement solution was provided for the damaged platform. Zhang and Sclavounos (2021) investigated the extreme effects of non-linear waves on floating wind turbines. Expressions for higher order wave loads were derived through model analysis. Karimirad (2013) studied the structural response of a mooring system under severe weather. The damping and inertia forces of the mooring line were found to have a significant effect on the tension response through simulation analysis. Liao et al. (2022) developed a wave impact CFD method for semi-submersible platforms to investigate green water events. Experimental data optimized the accuracy of the model. Sun et al. (2018) investigated the effect of wave–current interaction on surge height. It was experimentally concluded that wave height and energy spectrum could be changed using wave–current interaction. Koks et al. (2020) modeled the damage of extreme storms. The damage was estimated by analysis and modeling of disaster data. Vazirizade et al. (2022) proposed a reliability estimation method for marine platforms with dynamic loads applied in the time domain. The reliability and failure rate under different load states were analyzed using simulations. Kaynia (2019) reviewed techniques for seismic resistance of offshore wind turbines and found that they are particularly susceptible to vertical seismic excitation. The results of the review show that the seismic resistance of offshore wind turbines depends on the damping technology's performance. Gelagoti et al. (2019) investigated the seismic performance of a 10 MW offshore wind turbine under seismic loading. Experiments showed that jacketed FOWT performed more stably under cyclic loading. Currently, studies of extreme loads are based on experiments or software simulations, and it will affect structures' safety directly.

For this section, transient or random extreme loads can cause both ALS and ULS limit states. Li et al. (2019) found that extreme loads at low locations are mainly influenced by wind, while extreme loads at high locations are more closely related to wave forces. Ma et al. (2020) studied the extreme susceptibility of FOWT mooring cables to break under extremely coherent gusts. Ullah et al. (2020) investigated that extreme gusts can cause blade damage and break. For both ALS and ULS limit states, damping techniques should be installed in areas where the extreme load is serious (e.g. Mooring systems & floating foundations & blades).

## 3. Damping technology

The previous sections demonstrated how closely the limit state and load connect to the choice of damping technique. The design and inspection of marine structures should take due account these limitations. Limit states can be used to categorize existing offshore damping strategies (Guglielmino et al., 2005). This section aims to find suitable damping techniques for the different limit states of the FOWT and will divide the damping technology by considering the working mechanism, technical details, and frequency coverage.

### 3.1. Damping technology for FLS & SLS

Considering the three aspects above, this section provides an overview of damping techniques suitable for FLS and SLS. Currently, most offshore damping techniques can effectively solve this problem. For the offshore operating scenario of a wing-beam FOWT. Zhang and Høeg (2020) proposed the use of tuned liquid column dampers (TLCDs) to mitigate tower-side vibrations and wing-beam rolling motions. It was found that TLCDs can effectively reduce the vibration amplitude and resonant frequency of offshore platforms. The TLCD is a U-shaped tubular device with an interior filled with water or similar liquid (see Fig. 3(a)). The internal liquid is adjusted to mitigate the vibrations of the floating body using the liquid level and storage capacity. A new hybrid damping system, SMA-MRF, was designed by Zareie et al. (2019) to mitigate seismic loads in response to severe environmental loads at sea. It was found that this damping system has simple activation conditions and is effective in mitigating variable loads. As shown in (Fig. 3(b)), the structure consists of a shape memory alloy (SMA) and a magnetorheological fluid (MRF), an innovative material capable of returning to its original shape after large deformations and an intelligent fluid that can change its viscosity through a magnetic field. Combining the advantages of these two techniques, Hokmabady et al. (2019) introduced magnetorheological tuned liquid column gas dampers (MR-TLCGD) for offshore structural vibration problems. The study results show that MR-TLCGD provides better vibration damping than tuned liquid column gas damper (TLCGD) systems.

Manuel (2022) studied the vibration damping effects of the solid heave plate of a column-type wind turbine. The hydrodynamic coefficients of the models are evaluated and compared through multiple forced vibration and attenuation tests. Finally, a dimensionless model is proposed to evaluate the safety margin of the design. The device includes a linear motor, guide rails, air bushings, piston rods, and loading cell (see Fig. 3(c)). This structure significantly reduces the mechanical friction generated by heave plates. To improve the vibration problems of FOWT structures in typhoons and storms, Lian et al. (2018) introduced an eddy current tuned mass damper (EC-TMD) system on top of the structure. The linear damping of the EC-TMD system is shown to have a strong vibration damping capability through testing. As shown in (Fig. 3(d)), the EC-TMD system consists of a mass block, four steel cables, several permanent magnets (PM), a copper plate (conductive metal), and a steel plate located under the magnetic field. Analysis of the experimental data shows that the influencing factors such as clearance, PM layout, and magnetic field strength significantly affect damping.

For floating wind turbines, Ghafari et al. (2022) developed a hybrid floating platform based on Wavestar. The effect of the diameter and damping coefficient of the wavstar on the vibration damping effect was tested. The structure includes a semi-submersible platform, deck, connecting arm, and wavestar (see Fig. 4(a)). Experimental results show that the device has good results in the range of wave height (5 ∼10 m) and wave period (T = 5 s and $T$ = 6 s). In order to mitigate the vibration fatigue process on offshore platforms, Leng et al. (2021) proposed a vibration isolation system based on magnetorheological elastomers (MREs). The system uses a semi-active fuzzy controller (SFC) to control real-time vibration. As shown in Fig. 4(b), the system includes a vibration isolation layer, a control unit, and a sensor network. The case study shows that the SFC-MRE vibration isolation system can provide adjustable stiffness and damping characteristics to mitigate wave excitation significantly. To solve the vibration damage problem

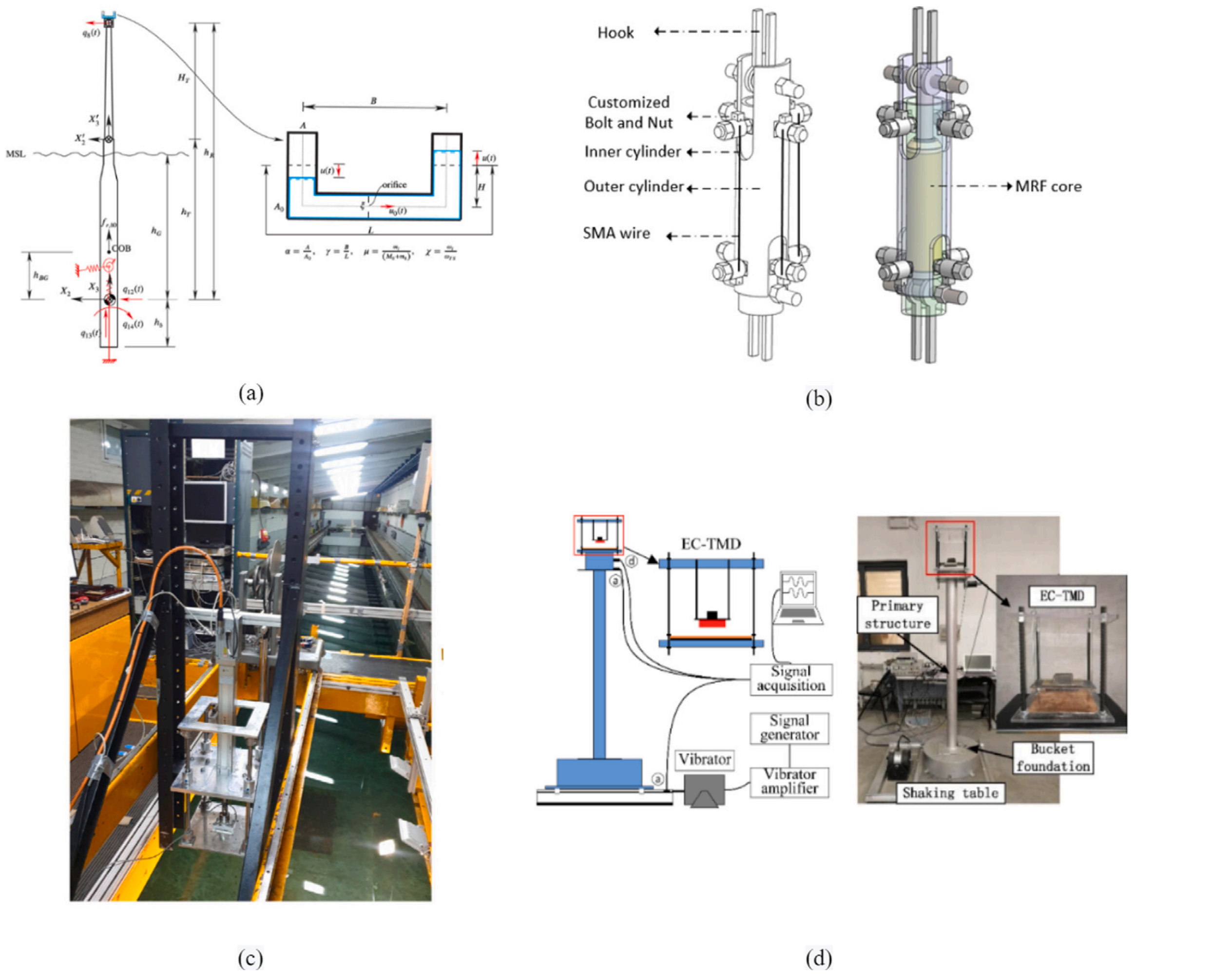


**Fig. 3.** Damping technology for FLS & SLS: (a) Tuned liquid column damper (Zhang and Høeg, 2020), (b) SMA-MRF damper (Zareie et al., 2019), (c) Solid heave plate (Manuel, 2022), (d) Eddy current tuned mass damper (Lian et al., 2018).

of single-pile offshore wind turbine towers under wind–wave excitation and seismic excitation, Zhao et al. (2018) tested the effect of a bi-directional tuned mass damper TMD (see Fig. 4(c)). The experimental results show that the damping performance of the TMD is closely related to the frequency content of the external excitation and is more effective in damping wind and wave loads. Aiming to solve the vibrations caused by wind–wave misalignment and vortices in offshore wind turbines, Sun and Jahangiri (2018) proposed a three-dimensional pendulum-tuned mass damper (3d-PTMD). (Fig. 4(d)) shows that the pendulum on top of the nacelle consists of a drogue and a mass sphere. Experiments have shown that the 3d-PTMD is more effective than the bilinear TMD in mitigating the bi-directional vibration of the FOWT under misaligned loading.

To address pitching vibrations caused by wind and wave forces, Azari et al. (2020) proposed a semi-active control system for floating offshore structures. The damping system uses hydrodynamic forces to regulate its damping ratio. The damping system contains STMD and Seesaw frame structures as shown in (Fig. 5(a)). Test results show that the semi-active damping system provides significantly higher suppression of vibrations. For long-term fatigue damage and sinking of offshore semi-submersible platforms, Ma et al. (2018) proposed the Tuned Heaving Plate Inertia (THPI) to control platform vibration. The THPI damping system is an additional inertial device between the SSP and the THP. The damping system consists of a float, a lifting plate, a truss, and a spring damping device (see Fig. 5(b)). Test results show that the THPI system gives better control performance than the FHP and THP systems. In the case of ensuring the safety and stability of the offshore platform, Wu et al. (2016) proposed a platform TMD. The TMD device consists of a frame, a mass block, two springs, four wheels, two tracks, and two buffers (see Fig. 5(c)). The structure was loaded with seismic waves, and experimental results showed that the buffered dampers effectively reduced the excessive vibrations caused by seismic waves. For the purpose of solving the problem of significant vibration of jacketed platforms under lateral loads such as wind and waves, Ghasemi et al. (2019) proposed the use of a shock-tuned mass damper (SMA-PTMD) to control platform vibration. The SMA-PTMD dynamic damper (DVA) consists of two parts, SMA-TMD and PTMD. The damping system consists of an SMA bar, cylinder, piston, and Plate (see Fig. 5(d)). Experimental results indicate that the SMA-PTMD has good damping performance, is easy to install, and is effective in controlling vibration on marine/land-based structures. As a classic floating wind turbine TMD technology, The TETRASPAR floating foundation was developed and tested. Thomsen et al. (2021) used orcaflex and openfast to build a dynamic model. The model considers the coupling effect of flexible and rigid bodies. The system includes the buoyant floater, ballasted keel and synthetic tethers (see Fig. 5(e)). Through the comparison of experiments and simulation results, the accuracy of the dynamic model is proved. As a means of reducing the pitch motion of semi-submersible wind turbines, Xue et al. (2022) proposes a tunable liquid multi-column damper (TLMCD). The damping force provided by TLMCD was experimentally tested, and the dynamic response of FOWT was simulated using OpenFOAM. The device can provide

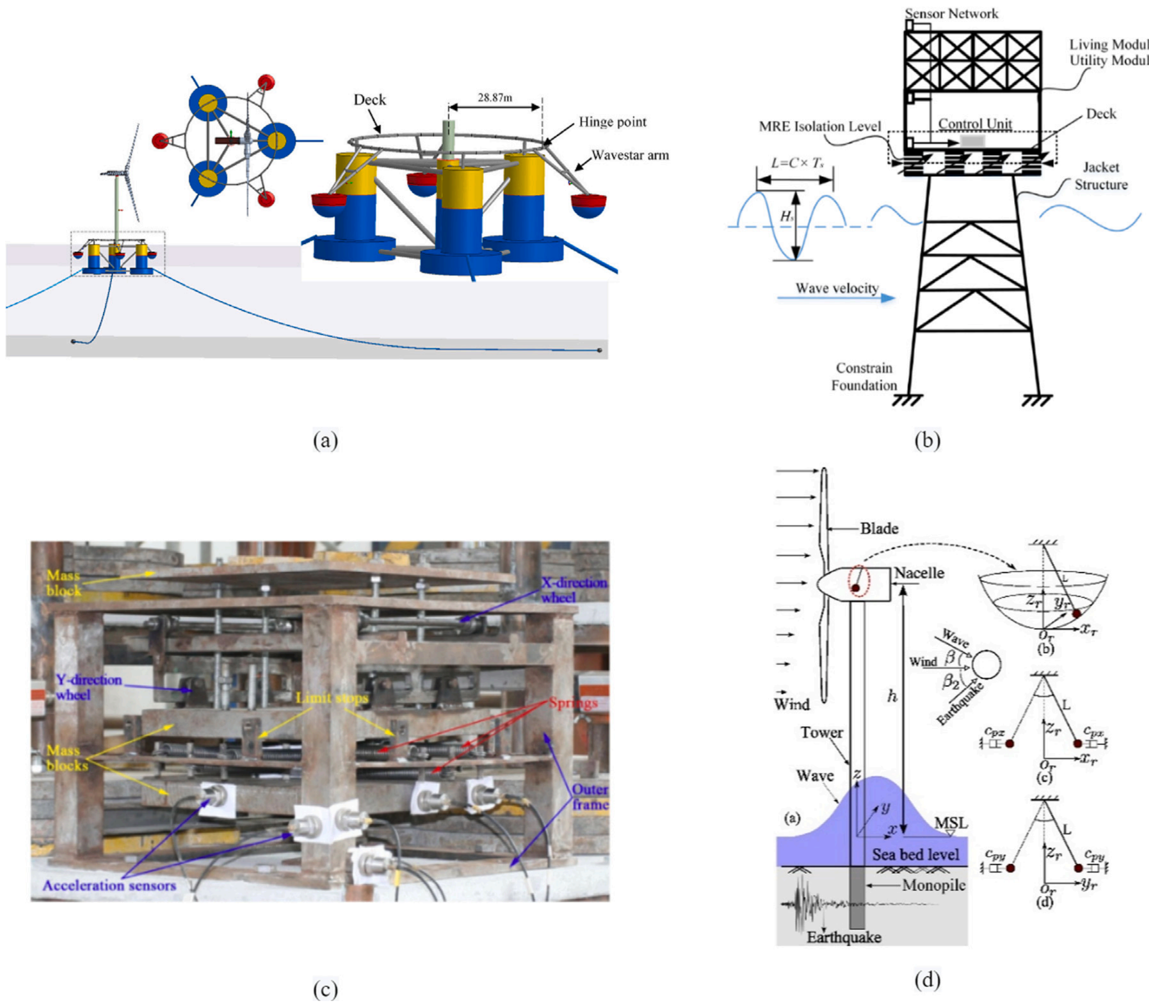


**Fig. 4.** Damping technology for FLS & SLS: (a) Wavestar hybrid floating platform (Ghafari et al., 2022),(b) magnetorheological elastomers (Leng et al., 2021), (c) bi-directional tuned mass damper (Zhao et al., 2018), (d) three-dimensional pendulum-tuned mass damper (Sun and Jahangiri, 2018).

damping forces in different directions by adjusting the liquid level height in different liquid columns (see Fig. 5(f)). Experimental results show that TLMCD has a significant effect on pitch motion control near the resonance period. In addition,Researchers have used aerodynamic damping to control FOWT. Cheng et al. (2016) studied the change in aerodynamic damping of the FOWT in steady and turbulent winds. Wen et al. (2022) found that aero-damping suppressed the pitch resonance vibration of the FOWT.

### 3.2. Damping technology for ALS & ULS

This section summarizes the damping techniques applicable to ULS and ALS. Many researchers have begun to focus on damping techniques suitable for such scenarios. Caterino (2015) proposed a vibration isolation system consisting of MR dampers and springs. The semi-active magnetorheological dampers (SA-MR) in the structure alter the mechanical behavior of the tower in real-time, aiming to reduce the impact of vibrations on the tower. As shown in (Fig. 6(a)), two sets of MR dampers and springs are mounted symmetrically on the bottom of the tower, and lateral vibration loads are simulated using the Actuator MTS. The experimental results show that the damping system effectively reduces the bending stresses exerted on the tower by strong winds. In order to solve the motion compensation problem for offshore wind turbine platforms and offshore oil platforms, Tian et al. (2019) designed a hybrid mechanism. After considering the constraints and redundancy of the mechanism motion, the motion trajectory optimization for waves is proposed. The system includes an energy accumulator and static platform (see Fig. 6(b)). Simulation experiments verify the algorithm to enable adequate motion compensation of the offshore platform. For the multimode jitter problem of cable-stayed bridges, Wen and Sun (2015) proposed a solution using active tuned mass dampers (ATMD) and sensors. The researcher explored the effects of different ATMD installation schemes while considering the effects of external loads. The experimental results show that distributed ATMDs combined with suitable control strategies can effectively mitigate wind-induced vibration in cable-stayed bridges. To relieve structural loads on floating wind turbines, Hu and He (2017) investigated the application of hybrid mass dampers (HMDs) with limits for vibration reduction in barge-type wind turbines. The researcher developed an active control model of the system, focusing on the effects of factors such as damper travel and power consumption. The nacelle's HMD includes a mass block, a spring, a damper, and a limiter (see Fig. 6(c)). The experimental results show that the active structural HMD control reduces vibration in offshore turbines. In response to the problem of increased wind turbine failures caused by the harsh offshore environment, Rezaee and Aly (2018) proposed a solution using a semi-active tuned mass damper (SATMD) and a magnetorheological damper system. The authors investigated a semi-active tuned mass damper (SATMD) in the nacelle and an externally supported magnetorheological damper system for the pylon. As shown in (Fig. 6(d)), the SATMD damper consists of two parts, the optimal spring, and the MR damper. Experimental tests show that the SATMD can effectively reduce the nacelle displacement response, but the rate of acceleration reduction is not ideal. To reduce

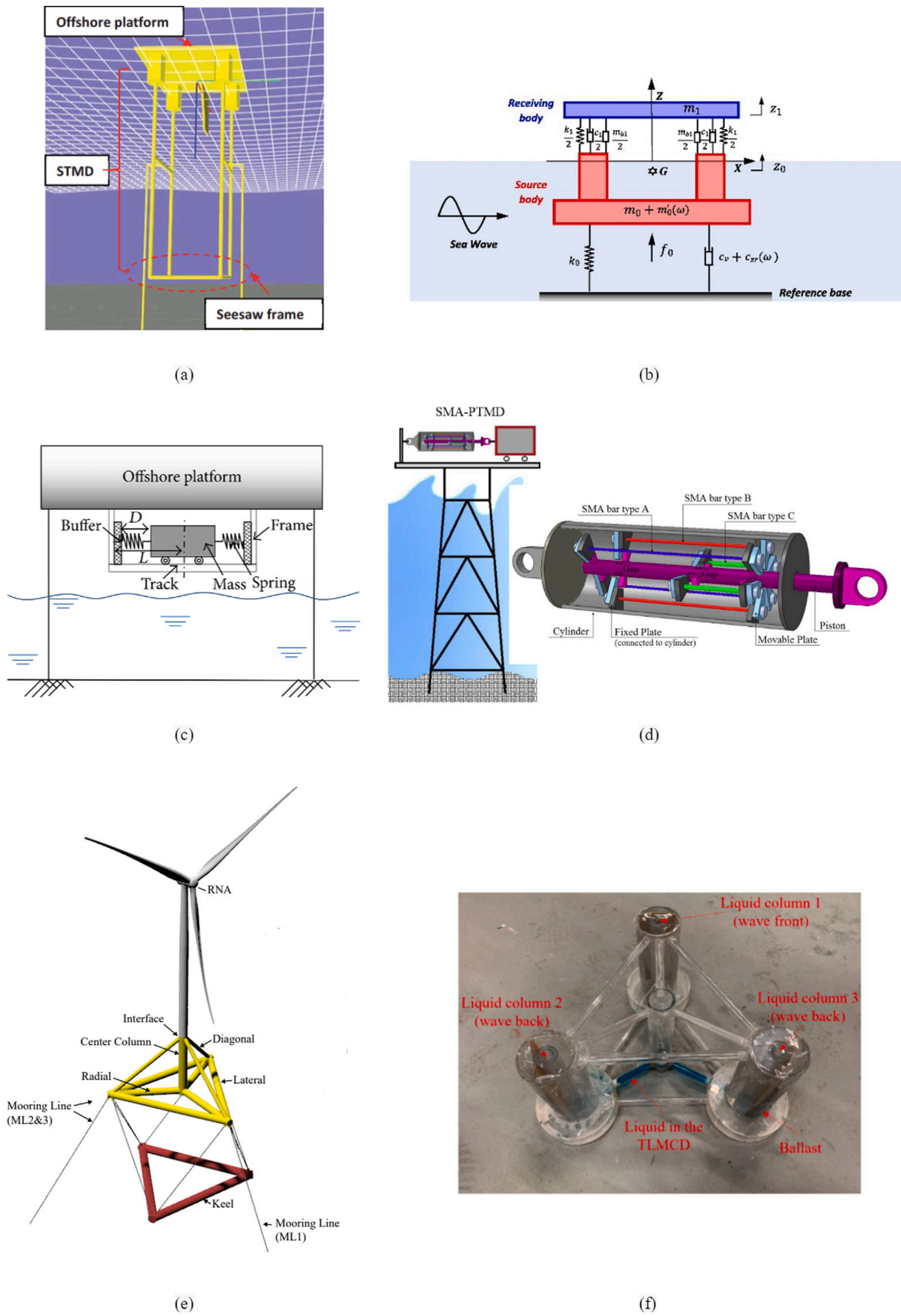


**Fig. 5.** Damping technology for ALS & ULS: (a) STMD and Seesaw damping system (Azari et al., 2020), (b) Tuned Heaving Plate Inertia (THPI) (Ma et al., 2018), (c) Platform TMD (Wu et al., 2016), (d) SMA-PTMD (Ghasemi et al., 2019), (e) TETRASPAR floating foundation (Thomsen et al., 2021), (f) Tunable liquid multi-column damper (Xue et al., 2022).

the response of offshore platforms, Moharrami and Tootkaboni (2014) developed a mass damper (HBMD) utilizing hydrodynamic buoyancy. The damping system reduces platform vibration by adjusting buoyancy, inertial force, and fluid damping force. The structure consists of an HBMD and a connection spring (see Fig. 6(e)). Experimental results show that correct positioning and control of the damping system can effectively reduce the vibration response. An Adams dynamics model was developed for the dynamic characteristics of offshore floating raft structures (Geng et al., 2015). The researcher tested the response of the floating raft system under different damping and discussed the semi-active control strategy. The system includes a foundation, spring, draft, and controllable damper (Fig. 6(f)). It can be seen from the tests that the vibration isolation performance of the floating raft can be effectively improved by controlling the damping. To address the axial dynamic stresses in offshore risers, Zhang and Li (2015) proposed using winches to compensate for offshore floating bodies' floating and sinking motion. Therefore, the damping effect of the LQG controller was evaluated with the axial strain as the target. The experimental tests

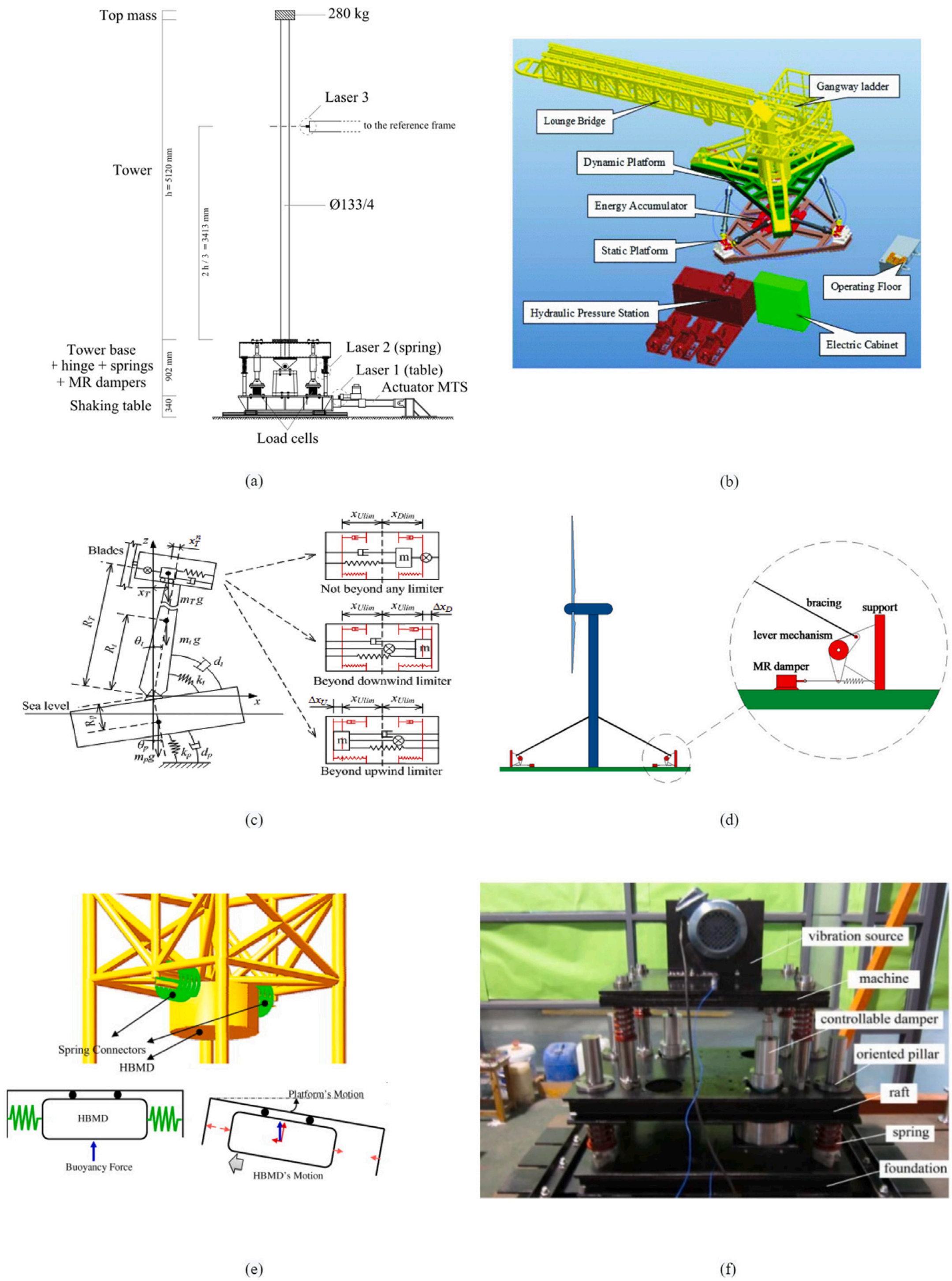


**Fig. 6.** Damping technology for ALS & ULS: (a) Semi-active magnetorheological dampers (Caterino, 2015), (b) Hybrid mechanism (Tian et al., 2019), (c) Hybrid mass dampers (Hu and He, 2017), (d) Semi-active tuned mass damper (Rezaee and Aly, 2018), (e) Hydrodynamic buoyancy mass damper (Moharrami and Tootkaboni, 2014), (f) Offshore floating raft structures (Geng et al., 2015).

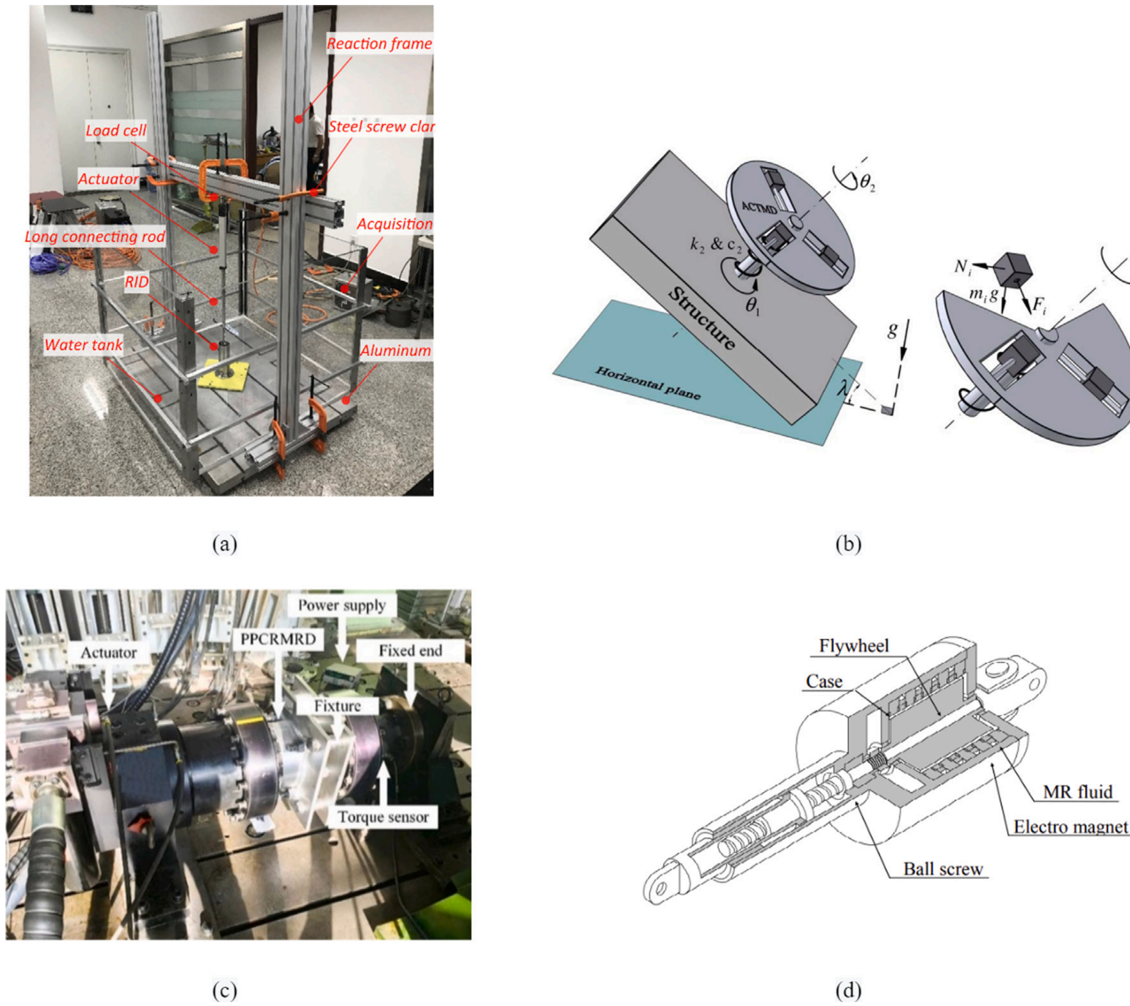


**Fig. 7.** Damping technology for rotational inertia: (a) rotational inertia damper (Ma et al., 2021), (b) Adaptive configuration tuned mass damper (Mohammadi-Ghazi et al., 2012), (c) magnetorheological fluid damper (Ito et al., 2015), (d) high-torque magnetorheological damper (Wei et al., 2020).

show that a reasonable control of the winch can significantly reduce the axial strain in the riser. Fitzgerald and Basu (2014) used ATMD to connect the mass block to the blade tip to solve the blade vibration problem. Chen et al. (2015) used MR dampers to dissipate energy inside the blade as a way to reduce the effect of external loads.

### 3.3. Damping technology for rotational inertia

In the future, rotational inertia damping technology could potentially be applied to the FOWT. In addition to being subjected to lateral and longitudinal vibrations, floating foundations are also subjected to torsional moments due to load asymmetries (Barj et al., 2014). The torques to which the structure is subjected can also cause structural deformation. In response to this problem, more and more rotational inertia dampers are being focused on and developed. To address the problem of torsional vibration on offshore platforms, Ma et al. (2021) designed a new rotational inertia damper to suppress vibration in the direction of rotation by generating a damping force. Fig. 7(a) shows that the RID consists of a ball screw assembly, a rotating tube, an outer tube, a radial bearing, two ball joints, and a set of turning plates. The results of the experimental tests show that the turning plates of the RID can generate significant damping forces in water. Mohammadi-Ghazi et al. (2012) proposed a design method for an adaptive configuration tuned mass damper (ACTMD). By continuously adjusting its operating state, it can cover most of the operating frequency range. As shown in Fig. 7(b)), the ACTMD structure consists of a base, a pivot, a spring, a turntable, and a moving mass block. The frequency of the ACTMD can be adjusted in real-time by moving the mass block at different positions. Through testing, it has been found that ACTMD can significantly suppress undesirable rotational vibrations in structures. For rotational vibration problems in multi-story buildings, Ito et al. (2015) proposed a rotating inertia mass damper using a filled magnetorheological fluid (MR fluid). The rotational inertia of this damper and the magnetorheological fluid each produce variable damping forces. The damping system consists of Flywheel, MR fluid, ball screw, and electromagnet (Fig. 7(c)). It was found that the response displacement of the structure was significantly reduced, and the acceleration of the vibration response did not increase. In order to improve the damping torque performance of the suspension system (Wei et al., 2020), a new high-torque magnetorheological damper (PPCRMRD) was proposed. (Fig. 7(d)) shows that the damping structure includes a shield, shift, Blade, MR valve, and Housing. The researchers tested the maximum damping torque and controllable damping torque of the PPCRMRD. The results show that the PPCRMRD can provide sufficient damping torque and a wide range of controllable damping torque. To alleviate FOWT's tower-side vibration problems, Zhang and Høeg (2021) the rotational inertia double tuned mass damper (RIDTMD) was installed in the nacelle. Through dynamic modeling and analysis, the working state and performance of RIDTMD can be effectively evaluated. Tests have shown that RIDTMD performance is consistently better than TMD except for large damping strokes.

**Table 1**
Working mechanism of FOWT's damping technology.

| Reference | Damping type | Energy consumption mechanism |
|---|---|---|
| (*Thomsen et al.*, 2021) | Fluid damping | When an object is in a fluid (liquid or gas) and has a relative motion to the fluid, the object is subject to the resistant force of the fluid. |
| (*Rezaee and Aly*, 2018) | Hysteresis damping | Dissipation of energy caused by hysteresis, energy in different phases partially cancels out |
| (*Wu et al.*, 2016) | Coulomb damping | Energy dissipation from two surfaces that friction each other. |
| (*Zareie et al.*, 2019) | Material damping | Dissipation of mechanical vibration energy into heat energy. |
| (*Ju and Sun*, 2014) | Aerodynamic damping | The aerodynamic load on the wind turbine is changed by adjusting the blade pitch angle. |
| (*Xue et al.*, 2022) | Energy-consuming devices | The vibration energy of the main structure is attracted to be dissipated in the system, thus damping the main structure. |

### *3.4. Evaluation of damping technology*

To facilitate the rational selection and design of damping systems for designers of offshore wind power projects. In this section, a detailed summary and evaluation of the above damping technologies are presented in terms of their working mechanism, technical details, and frequency coverage.

#### *3.4.1. Working mechanism*

It is known that common damping includes viscous damping, Coulomb damping, hysteresis damping, structural damping, aerodynamic damping, and fluid damping. Different field each have their own criteria for choosing and rating dampers. The energy absorption ratio and damping reaction rate are more important to the impact field (Liu and Wu, 2020). The ideal frequency ratio and the ideal damping ratio are sought after by periodic damping (Baduidana and Kenfack-Jiotsa, 2022). Hysteresis damping is proportional to the strain, whereas viscous damping is correlated with the system's excitation frequency (Dong et al., 2018). Coulomb damping primarily investigates friction coefficients and structural materials (Zareie et al., 2019). The fluid medium's density, viscosity, and velocity all influence the damping forces that it produces (Leng et al., 2021). Reasonable structural and damping qualities are especially crucial for damping technologies used on FOWT. The classification and energy dissipation mechanisms of the FOWT damping techniques mentioned in the previous sections are shown in Table 1.

#### *3.4.2. Technical details*

The degree of freedom, power source, stiffness, damping, adjustability, and other structural properties all have a substantial influence on the limit state. Damping approaches for FLS and SLS only need to concentrate on the degrees of freedom in the primary vibration modes. The unpowered damping system is already able to meet the requirements of FLS and SLS. It not only increases the safety of the structure but also reduces the cost of vibration isolation. The FLS and SLS damping systems can identify the stiffness and damping range at the design stage and do not need real-time adjustments. The more degrees of freedom in damping technology for ALS and ULS, the better the structural protection. According to system requirements, the damping system with the power source can withstand large-scale loads and modify damping and stiffness flexibly. Table 2 displays the complete parameters.

#### *3.4.3. Frequency coverage*

Currently, the FOWT vibrates at various frequencies in different operating conditions. Therefore, the three vibration areas of FOWT (1P, 2P, and 3P) should be the focus of dampening technology (Arany et al., 2016). The range of FOWT frequency bands is covered by 1P and 3P excitation, while the wind and wave are in the low-frequency range, as shown in Fig. 8. Several offshore damping techniques provide effective operating frequency ranges, as indicated in Table 3. As a result, another important design and selection factor is the damping system's frequency range. According to the data, the damping technique suggested by Lian et al. (2018) covers the frequency range with the fewest peaks, whereas Azari et al. (2020) covers the frequency range with the most peaks. Based on the frequency range data from the literature in Tables 2 and 3, we combine the operating ranges of the different dampers with Fig. 8. This will give the reader a better visualization of the effective frequency range of the dampers at different loads.

## 4. Discussion and future research

As can be seen from the summary of the previous sections, various limit states need distinct damping systems. In order to advise the reader on damping techniques for different limit states, the authors have taken into account the operating mechanism, technical details, and frequency coverage and give the following advice: Tuned liquid column dampers are a good choice for FLS and SLS. In terms of operating mechanism, it is characterized by its structural simplicity and high reliability. In terms of technical details, it has a high degree of freedom and can be applied to floating platforms and nacelles, for example. In terms of frequency coverage, it has an adjustable operating frequency range. Magnetorheological dampers are a good choice for ALS and ULS. In terms of operating mechanism, it has a fast response time and high damping capacity. In terms of technical details, it has a high degree of freedom and a large number of positions to which it can be applied, etc. In terms of frequency coverage, it has an adjustable operating frequency range. In terms of frequency coverage, it has a wide and adjustable operating frequency range. In the three FOWT frequency ranges, damping solutions will work better. Rotational inertia dampers still need urgent research and testing, and there is presently insufficient information about them. This paper's primary goal is to update the development of offshore wind turbine dampening systems. The interaction between environmental loads, limit states, and damping systems must be figured out in order to build and design FOWT damping systems (Hayatdavoodi and Cengiz Ertekin, 2016; Christiansen et al., 2013). The benefits of the present technology are outlined in terms of structural and damping properties, and guidelines are discovered that may be used in the design process of the future. The following conclusions can be reached by reviewing and summarizing the pertinent literature:

1. Environmental loads, limit states, and damping technologies are closely related. The structure, degrees of freedom, operational position, and other characteristics of the damping system are significantly influenced by the limit state. The choice of damping system should take full account of the load conditions and damping characteristics.
2. Tuned liquid column dampers and magnetorheological dampers can provide damping forces for FOWT with different limit states. Both types of dampers offer good prospects for development and application. Moment of inertia dampers is an efficient way to cope with torsional damage, although there is not much reliable research on them yet.
3. Damping characteristics and frequency range are the main performance indicators of a damping system. The frequency range of the damping system should cover the dangerous vibration frequency range of the FOWT.

**Table 2**
Details of FOWT's damping technology.

| Reference | Damping DOF | Working position | Power source | Stiffness/Damping adjustability |
|---|---|---|---|---|
| (*Fitzgerald and Basu*, 2014) | 1 | Blade | Electric | No/No |
| (*Chen , Yuan , Li and Xu*, 2015) | 1 | blade | Electromagnetic | No/Yes |
| (*Zili Zhang*, 2020) | 5 | Nacelle | Electromagnetic | No/Yes |
| (*Yaqi Hu*, 2017) | 1 | Nacelle | Electric | Yes/Yes |
| (*Lian J*, 2018) | 6 | Nacelle | Electromagnetic | No/Yes |
| (*Sun C*, 2018) | 6 | Nacelle | No power | No/No |
| (*Ghasemi M R*, 2019) | 1 | Tower top | No power | Yes/No |
| (*Leng D*, 2021) | 2 | Tower top | Electromagnetic | No/Yes |
| (*Bin Zhao*, 2018) | 2 | Tower base | No power | No/No |
| (*Zareie S*, 2019) | 1 | Tower | Viscous | Yes/ Yes |
| (*Antonio M M*, 2022) | 1 | Platform | Electric | No/Yes |
| (*Hamid Reza Ghafari*, 2022) | 1 | Platform | Electromagnetic | No/Yes |
| (*Q Wu*, 2016) | 1 | Platform | No power | No/No |
| (*Thomsen et al.*, 2021) | 6 | Platform | No power | No/No |
| (*Xue et al.*, 2022) | 6 | Platform | No power | No/No |
| (*Caterino N*, 2015) | 1 | Platform | Electromagnetic | No/Yes |
| (*Tian C*, 2019) | 6 | Platform | Hydraulic | No/Yes |
| (*Rezaee M*, 2018) | 2 | Platform | Electromagnetic | Yes/Yes |
| (*Moharrami M*, 2014) | 6 | Platform | Electric | No/Yes |
| (*Geng C*, 2015) | 1 | Platform | Hydraulic | No/Yes |
| (*Azari M M*, 2020) | 1 | Mooring system | Electric | No/Yes |
| (*Ma R*, 2018) | 1 | Mooring system | No power | No/No |

**Table 3**
Characteristics and frequency range of damping technology.

| Reference | Frequency range | Linear/Nolinear | Effective status |
|---|---|---|---|
| (*Zili Zhang*, 2020) | 0.318–0.637 Hz | Nolinear | Tower side vibration and rolling motion |
| (*Lian J*, 2018) | 0.348–0.354 Hz | Linear | Top vibration in the X, Z direction |
| (*Leng D*, 2021) | 0.1–0.3 Hz | Nolinear | Deck displacement and acceleration |
| (*Bin Zhao*, 2018) | 1–1.7 Hz | Linear | Tower top displacement and tower vibration |
| (*Sun C*, 2018) | 0.24–0.32 Hz | Nolinear | The fore-aft and side-side directions of nacelle |
| (*Azari M M*, 2020) | 0–2 Hz | Linear | Pitch vibration of platform |
| (*Ma R*, 2018) | 0.04–0.127 Hz | Linear | Heave vibration of platforms |
| (*Q Wu*, 2016) | 2.5–4 Hz | Linear | Displacement of surge direction |
| (*Wenshou Zhang*, 2015) | 0.08–0.24 Hz | Nolinear | Axial dynamic stress response |
| (*HamidHamid Reza GhafariN*, 2022) | 0–0.24 Hz | Nolinear | Heave response of platform |
| (*Ruisheng Ma*, 2021) | 0.16–0.95 Hz | Nolinear | Excessive wave-induced vibration of platform |

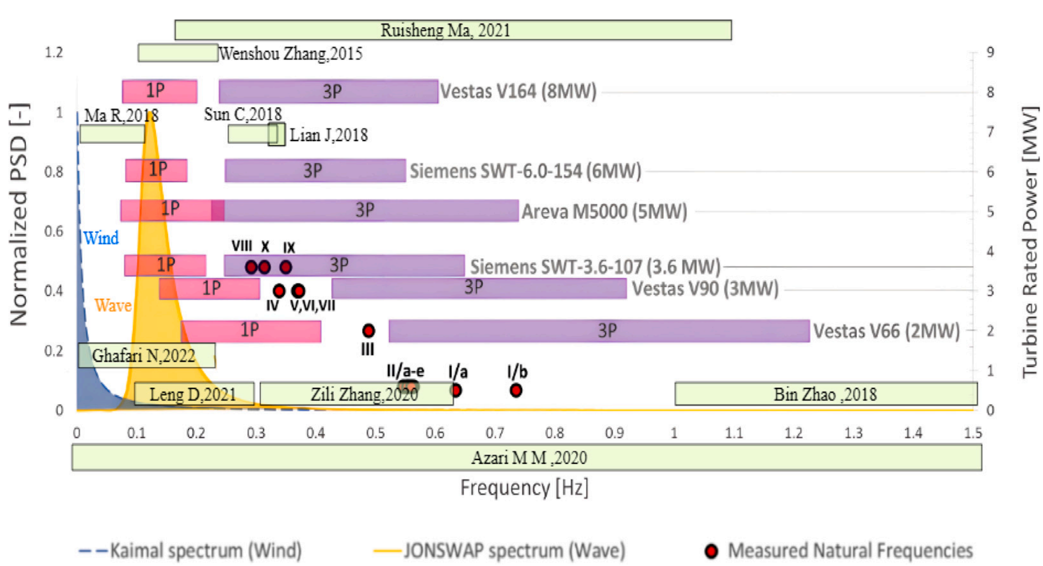


**Fig. 8.** Operating frequency range of FOWT (Arany et al., 2016).

Based on the aforementioned findings, further study and debate are still required to design various forms of FOWT damping system. Some of the problems where current research is lacking and insufficient include the following:

- Increasing the damping system's rigidity, damping, and frequency range adaptability. The damping system may be designed to handle a broader variety of loads and limit states by altering these parameters.

- There has not been enough investigation on FOWT limit state. Unreasonable travel parameters might result in secondary shocks and structural damage. The vibration range might be more effectively constrained by limiting devices.
- Multi-point distribution and joint control of multi-dimensional damping systems are worth investigating. At present, the working position of most damping systems is single, and the vibration reduction effect of complex structures is not significant enough. In order to avoid structural damage under extreme loads, the control strategy should be adjusted in time.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data in this article are publicly available.

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