Hindawi
Shock and Vibration
Volume 2024, Article ID 1076935, 18 pages
https://doi.org/10.1155/2024/1076935

Review Article

Review of Lightweight Vibration Isolation Technologies for Marine Power Devices

Yuanran Qiu,[1,2] Wei Xu,[1,2] Zechao Hu ,[1,2] Junqiang Fu,[1,2] and Mengxuan He[1,2]

[1]*Institute of Noise & Vibration, Naval University of Engineering, Wuhan 430033, China*
[2]*National Key Laboratory on Ship Vibration & Noise, Wuhan 430033, China*

Correspondence should be addressed to Zechao Hu; huzechao68@outlook.com

Received 29 August 2023; Revised 22 November 2023; Accepted 12 December 2023; Published 6 January 2024

Academic Editor: Jiaxi Zhou

Vibration induced by marine power devices (MPD) transmitting to the hull structure is one of the most important factors that cause ship vibration and underwater sound radiation. Vibration isolation technologies (VIT) are widely applied to reduce the vibration transmission. However, the overweight issue of VIT for marine power devices is a currently challenging engineering problem. The current reserve of lightweight and high-efficiency VIT for MPD and relevant theoretical and design research are seriously insufficient. This article first elaborates the causes of the overweight problem of VIT for MPD: (1) failing to grasp the quantitative law; (2) single vibration suppression mechanism. Then, it systematically sorts out the technical methods and application examples with potential to solve the overweight problem, such as dynamic optimization design, lightweight material method, novel intermediate mass structures, distributed dynamic vibration absorbers (DDVAs), locally resonant structures (LRS), particle damping (PD), quasizero stiffness isolators (QZSI), and active vibration control (AVC) technologies. Finally, the future development of lightweight VIT for MPD is prospected. It can be used as a reference for marine vessel vibration attenuation research and engineering design.

1. Introduction

The 21st century marks a new stage in human development of various ocean resources and utilization of strategic ocean space, highlighting the prominent role of oceans in promoting economic and social development and ensuring overall national security. Against the backdrop of accelerating the construction of a maritime power, promoting the high-tech development of marine vessel has become urgent [1–3].

Modern marine vessel is developing towards being high speed, large size, and lightweight, resulting in ever-increasing power output of propulsion devices, with a single machine power reaching tens of thousands of kilowatts and vibration level exceeding 110 dB [4]. This leads to increasingly obvious structural vibrations, which have many adverse effects: (1) structural noise generated by vibration is transmitted from the hull to the cabin, leading to deterioration of working and living conditions for crews and even endangering their health; (2) long-term exposure to alternating loads can cause fatigue damage to vessel's structure and equipment; (3) interference with precision instruments such as sonar can cause a decline in their performance; (4) increasing the underwater radiation noise of marine vessel, especially submarines, affecting acoustic stealth and reducing battlefield survivability [5].

Vibration induced by MPD transmitting to the hull structure is one of the most important factors that cause ship vibration and underwater sound radiation, as shown in Figure 1 [6]. Vibration reduction is a principal issue for marine vessel, and any techniques and applications that decrease vibration by even a few decibels are worth pursuing. Therefore, VIT for MPD are key requirements and challenging problems.

Due to the predominant influence of the "mass law" on the effectiveness of VIT, which states that the larger mass, the better vibration isolation effectiveness (VIE) [7–10], current MPD primarily adopt integrated floating raft

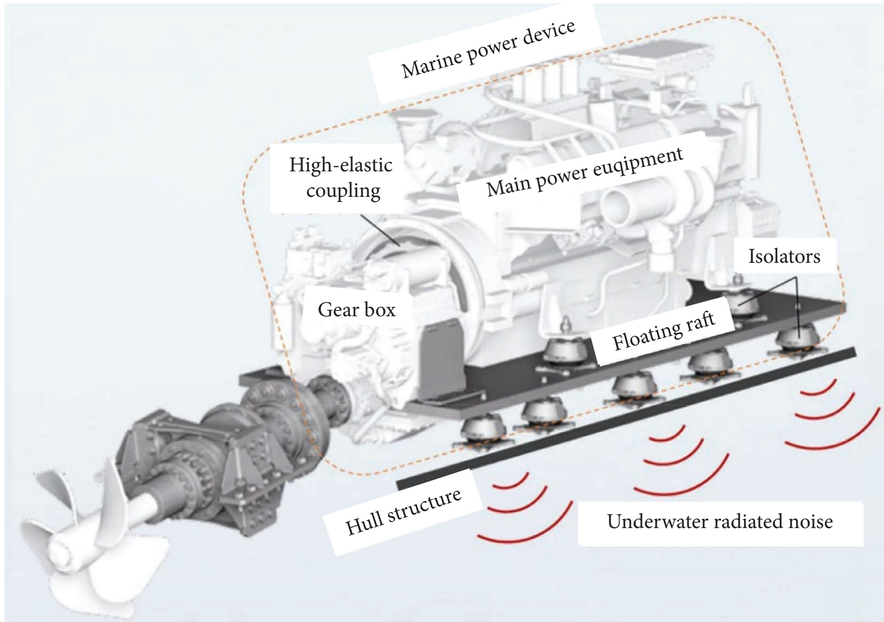


Figure 1: Vibration generation and transmission process of MPD [6].

vibration isolation systems (FRVIS) that weigh several hundred tons in order to ensure sufficient VIE. However, this imposes an increasingly heavy burden on the overall design and significantly affects the comprehensive achievement of overall indicators. The overweight problem of VIT for MPD is a real engineering challenge that urgently requires solutions.

In this paper, it explains the etiology of overweight problem in current VIT first. Then, it reviews the technical approaches with great potential to address this issue systematically proposed by scholars recently. Finally, it summarizes the future development trends of lightweight VIT for MPD, and the structure and main content of the paper is shown in Figure 2.

2. The Etiology of Overweight Problem

2.1. Failure to Grasp the Quantitative Law Governing the Relationship between Structural Quality and VIE. Currently, FRVIS are widely used in MPD. Numerous scholars have conducted extensive research on the relationship between the mass ratio and VIE of FRVIS, indicating that VIE of FRVIS is directly proportional to the quality of floating raft (FR), i.e., if better VIE is desired, the mass of FR should be as large as possible, and FR should remain “rigid” within the frequency range of interest [7]. However, practical engineering experiments show no significant improvement in VIE, resulting in an excessively high ratio of structural quality. The quantitative design method for FR is obviously absent.

2.2. Single Vibration Suppression Mechanism Is Incapable of Addressing the Challenge Posed by Low-Frequency Spectral Vibrations Induced by Light-Weighting. The application of FRVIS has significantly improved the overall VIE across the entire frequency range. However, its vibration suppression mechanism is single, relying solely on the elastic properties of material and inertial properties of FR to reduce vibration transmission. When FR generates standing waves, the VIE will be greatly reduced. Light-weighting leads to a decrease in the stiffness of FR, resulting in more low-frequency standing waves. Traditional energy dissipation methods like FRVIS require a large mass and size to effectively suppress these low-frequency standing waves due to their large wavelengths and strong penetration properties. Therefore, it is difficult to achieve efficient VIE under light-weighting conditions.

3. Potential Lightweight Technologies and Its Applications

Faced with the overweight problem of FRVIS for MPD, structural dynamic optimization during the design stage is considered as the fundamental and ultimate solution. However, under the current function-oriented design specification constraints, there is limited room for structural optimization to achieve weight reduction. Consequently, researchers have turned to explore new materials, structures, and mechanisms as alternative methods to realize light-weighting.

3.1. Dynamic Optimization Design. Dynamic optimization design towards FR based on structural dynamics principles can be achieved through various means such as optimizing structural parameters, shapes, and frequencies without adding any subsystems. It will enhance VIE and increase the light-weighting level. Methods of structural optimization design include modal control, topology optimization, size optimization, shape optimization, and others.

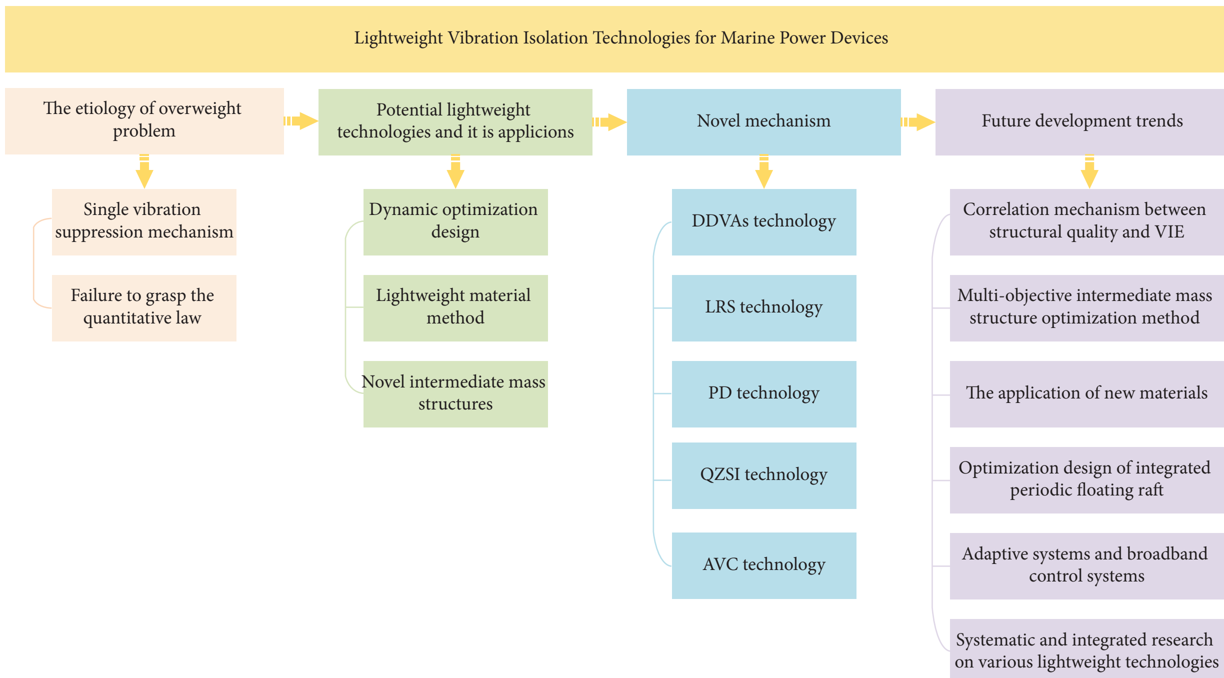


Figure 2: The structure and main content of the paper.

Hu [11] conducted a structural optimization design study on a large-scale FR (dimensions: 14.4 m × 5.2 m × 1.2 m; weight: 43.2 t) aiming at reducing vibration transmission. The modal control method was used to increase the first-order elastic mode of the FR in the vertical direction from 16.5 Hz to 25.4 Hz. These improvements effectively avoided low-frequency resonance by shifting away from the excitation frequencies of the shaft system, and mounted equipment on the raft and vibration transmitted to the hull were reduced by more than 5.0 dB after optimization in the frequency range of 15 Hz–80 Hz.

The size and weight of FR have further increased, reaching tens of meters and hundreds of tons [12]. It is difficult to optimize the FR due to various practical constrains. Therefore, there are few studies on optimizing large-scale FR, and most studies focused on small-sized FR. Zhu [13] conducted an optimization design on a small raft (dimensions: 2.4 m × 1.6 m × 1.2 m) using the variable density method. There is little difference in the VIE of the raft before and after optimization, but the weight of the raft is greatly reduced by 17%. With the help of the finite element method and optimization algorithm, Wang et al. [14] established a topological optimization model of an FR designed for a ship air compressor. After normalization, an FRVIS that satisfied the optimization constraints was obtained. The first-order natural frequency of the FR was increased from 170 Hz to 174 Hz. The simulation results confirmed that the optimized FR still exhibits high-efficiency VIE even under 20% mass reduction condition.

3.2. Lightweight Material Method. The emerging development of new materials provides an opportunity to realize lightweight VIT.

Alloy materials have characteristics of high strength, heat resistance, and good corrosion resistance. In the shipbuilding industry, replacing ordinary Q345B steel with alloy materials for raft production has been attempted. Compared with Q345B steel, titanium alloy materials can reduce weight by about 42.2% and aluminum alloy materials by about 65.6%. However, these attempts had to be abandoned due to insufficient technical maturity.

Composite materials have characteristics of high strength-to-weight ratio, high modulus-to-weight ratio, high corrosion resistance, light-weighting, and excellent damping properties which enable them to be used independently as structural materials. Yang et al. [15] utilized carbon fiber-reinforced composite materials to manufacture FR, the carbon fiber raft was 20%–30% lighter than the fiberglass one on average, and the damping properties were 1-2 orders of magnitude better than those of metallic materials. Therefore, the carbon fiber-reinforced composite material not only achieved lightweight request but also improved the VIE of the raft. Li et al. [16] designed and manufactured both steel and composite material raft to carry out comparative studies. The results showed that the acceleration vibration level difference of the composite material raft can be increased by 6.9 dB under the same mass conditions. Mu [17] applied composite materials to the foundation of VIT and found that the composite material foundation achieved an improvement in VIE with less material usage, thus increasing the lightweight level.

3.3. Novel Intermediate Mass Structures. The traditional FR for MPD is a frame structure mostly made of metal materials, with a low level of multifunctional integration. It is difficult to balance the requirements of high-efficiency VIE and lightweight level. Therefore, new design concepts and intermediate mass structures need to be considered and adopted. Many scholars have actively tried various new intermediate mass structures, including periodic floating rafts (PFR) and distributed rigid vibration isolation structures (DRVIS).

3.3.1. PFR. When elastic waves propagate in a structure with a periodic geometry, they undergo continuous reflection and attenuation between periods, resulting in frequency passbands and stopbands for the transmission of elastic waves, where some frequencies are allowed to transmit, while others are blocked [18]. This characteristic is advantageous in overcoming the limitations of traditional FR, realizing more effective vibration control with smaller mass, and providing a new approach for low-frequency spectral vibration control induced by light-weighting. Therefore, it is regarded as a potential effective VIT to achieve light-weighting and high-efficiency VIE. Typical PFR proposed by experts include truss-type, curved beam-type, chiral-type, honeycomb-type, and others.

(1) Truss-Type PFR. The application of truss-type PFR in MPD first emerged in the 1980s. The French navy adopted this structure on their “Triomphant” class submarines [19]. In 1997, Bondaryk [20] designed a truss-type cabin raft. All the submarine’s MPD are elastically mounted on the truss-type PFR. Experimental results demonstrated that truss-type PFR can enhance the VIE of the system to 50 dB.

In current research, truss-type PFR have demonstrated good performance in reducing mechanical vibration [21–23]. Zhang [24] designed a prototype of “cradle” truss-type PFR (dimension: 2 m × 1.6 m × 1.15 m; weight: 432 kg), as shown in Figure 3. Compared with a traditional frame structure FR (dimension: 2.055 m × 1.5 × 1.15 m; weight: 392 kg) under the same installation and excitation conditions, the experimental results showed that the “cradle” truss-type FRVIS increased the vibration level difference by 3–9 dB, significantly improving the vibration transmission characteristics in the frequency range of 200–400 Hz. Utilizing the characteristics of periodic structures and waveform conversion function, new truss-type PFRs are proposed by Cheng et al. [25], Zhou [26], and Wen et al. [27], as shown in Figure 3, and the entire system can reduce vibration transmission over a wider frequency band. Truss-type PFR exhibits good adaptability and operability in reducing mechanical vibration transmission and have the potential for further light-weighting.

(2) Curved Beam-Type PFR. The curved beam has the ability to transmit both bending waves and longitudinal waves and has a special conversion effect on bending and longitudinal waves. Its bandgap characteristic can attenuate the propagation of elastic waves, so it has been applied on the design of highly-efficient FR [28–30].

Huang et al. [31] first proposed the concept of curved beam-type PFR, aiming to achieve a wide bandgap within the lower frequency range. Cheng [32] designed and manufactured a curved beam-type PFR as shown in Figure 4 and explored the VIE performance using both finite element and experimental methods. The results showed that the curved beam-type PFR had better VIE than traditional FR under various excitation conditions under equal mass condition. Kuang [33] proposed an optimized newly curved beam-type PFR based on the work of Cheng. The simulation results demonstrate that curved beam-type PFRs exhibit favourable bandgap characteristics, making them suitable for practical FR structures. Therefore, the use of curved beam-type PFR will increase the lightweight level of VIT.

(3) Chiral-Type PFR. Chiral structures possess a form of tensile-compressive structure based on internal concave deformation and rotational deformation mechanisms and are widely used in fields such as aerospace, architecture, and marine engineering due to their outstanding mechanical performance and cell microstructure design-ability [34–37].

Huang et al. [38] first introduced the bandgap characteristics of periodic chiral structures into the design of FR and proposed the chiral-type PFR based on wave transformation and vibration localization. This design incorporates the bandgap and passband mechanisms generated by the periodic structures to enhance the VIE. Shiyin et al. [39] conducted in-depth research on the dynamic characteristics of chiral-type PFR as shown in Figure 5. Finite element simulation results showed that the chiral-type PFR had obvious VIE in the frequency range above 250 Hz, especially above 500 Hz, indicating that the VIE of chiral-type PFR is mainly reflected in the mid-to-high frequency.

Unlike traditional rafts, chiral-type PFR have inherent vibration isolation capabilities, which can greatly enhance the VIE performance in the mid-to-high frequency range. Moreover, the structural rigidity of the chiral-type PFR is much greater than that of the curved beam-type and truss-type PFR.

(4) Honeycomb-Type PFR. The periodic honeycomb-type structure with high porosity and low density which can avoid severe anisotropy is widely used to isolate vibration. Therefore, honeycomb-type PFR is an effective measure to realize high-efficiency VIE, light-weighting, and low cost [40–43].

Yang and Xia [44] proposed a honeycomb-type PFR based on the negative Poisson’s ratio effect. This innovative design offered improved VIE and versatility in vibration isolation applications. Xia and Yang [45] established traditional frame structure raft and honeycomb-type FR through the finite element method, as shown in Figure 6. The results showed that in the frequency range of 10–35 Hz, the VIE of honeycomb-type raft was 4 dB higher than that of the traditional frame structure raft; in the frequency range of 60–100 Hz, the VIE increased by 10 dB and the weight of the honeycomb-type PFR was reduced by 37.7% compared with the traditional raft, demonstrating outstanding VIE performance and huge potential for weight reduction.

In conclusion, the emergence of PFR is a new development in FR design. However, current research on PFR

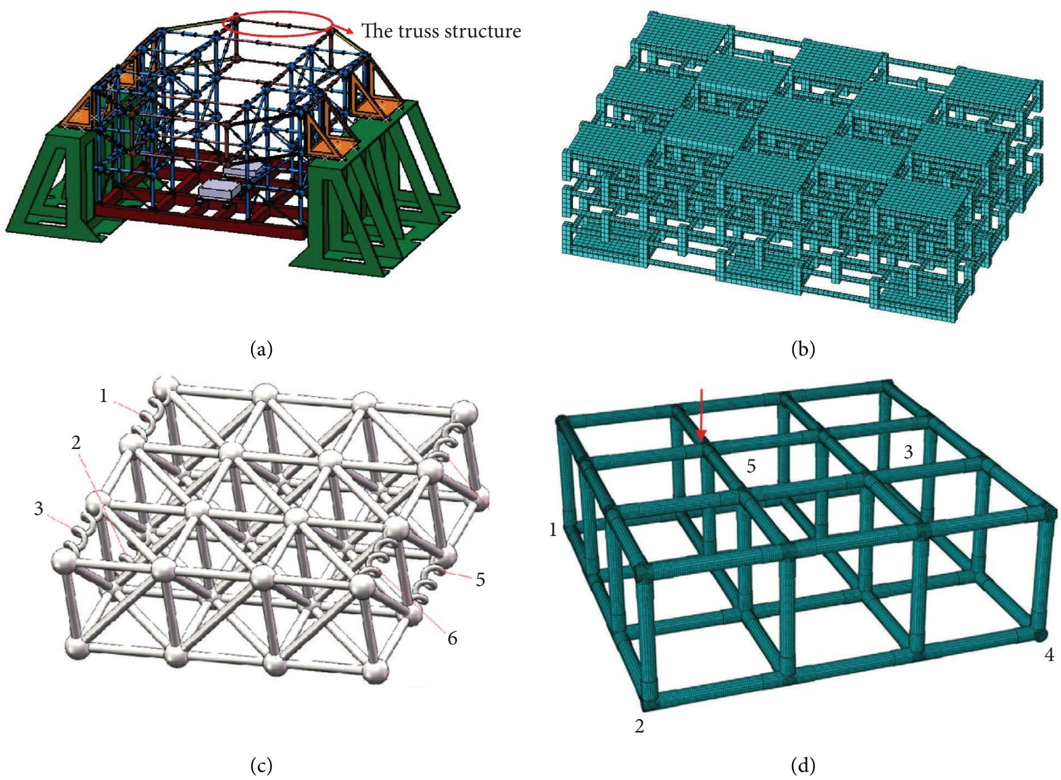


Figure 3: Truss-type PFR. (a) "Cradle" truss-type PFR [24]. (b) Truss-type PFR designed by Cheng et al. [25]. (c) The edge horn screw truss-type PFR [26]. (d) Carbon fiber-reinforced plastics truss-type PFR [27].

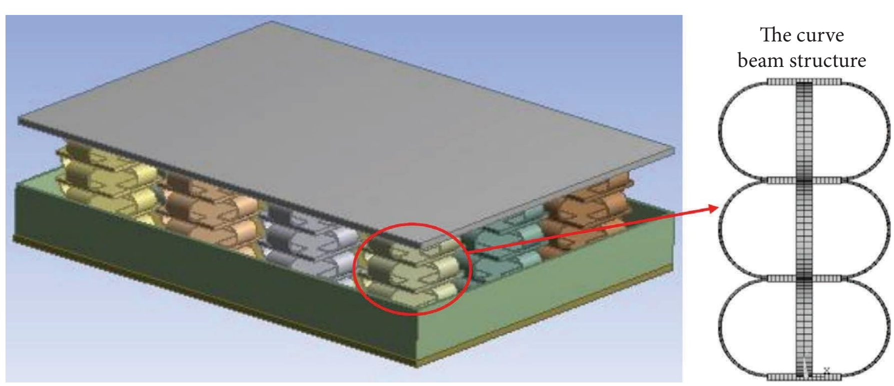


Figure 4: Curved beam-type PFR [32].

mainly focuses on the vibration isolation mechanisms. To achieve the ultimate goal of engineering application of PFR, further in-depth research is needed and multiple comprehensive optimization measures should be attempted to design more superior PFR. It is foreseeable that the application of PFR will elevate the lightweight level of VIT for MPD to a new height.

3.3.2. DRVIS. When traditional FRVIS cannot be used on MPD due to overall condition constrains, DRVIS can be used as a replacement. Compared with FR, the dynamic characteristics of DRVIS are closer to the rigid body with a larger impedance over a wide frequency range, which is beneficial for improving the VIE.

Zhang [46] and Yang [47] used the impedance method and the mobility matrix theory method, respectively, to verify that the VIE of DRVIS is better than traditional FRVIS in the entire frequency range under the same mass conditions.

DRVIS is widely used in practical engineering given its superior VIE performance. The United States applied DRVIS to isolate the diesel engine unit of the oceanographic survey vessel "Bigelow," as shown in Figure 7 [48]. The diesel engine unit weighs 15.7 t, and the total weight of vibration isolation devices is 6 t, accounting for 38% of the equipment mass. The VIE of the system in the range of 31.5 Hz to 8 kHz is 34 to 58 dB.

Qiu et al. [49] applied DRVIS to solve the difficult vibration isolation problem of a large-scale marine steam

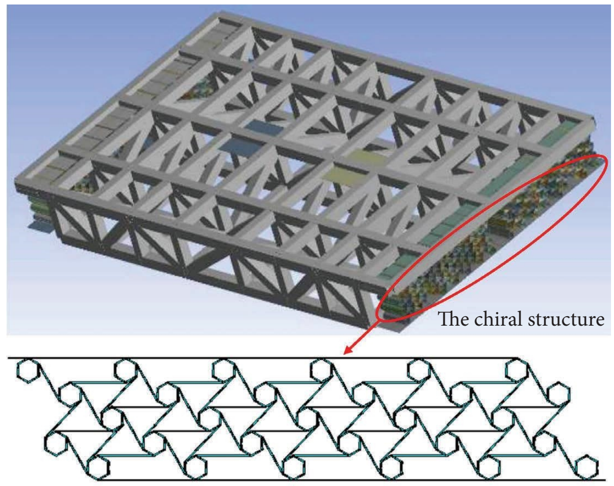


Figure 5: Chiral-type PFR [39].

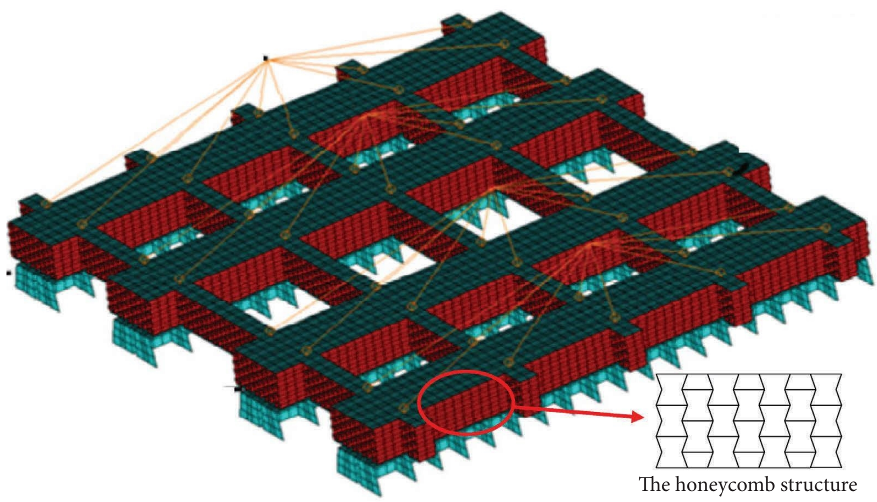


Figure 6: Honeycomb-type PFR [44].

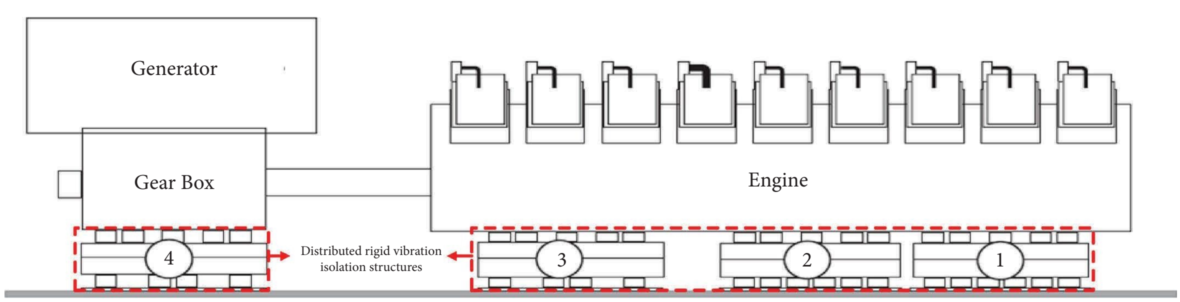


Figure 7: DRVIS applied in the oceanographic survey vessel: Bigelow [48].

turbine generator with high vibration isolation requirements and outstanding contradiction in overall available weight and space resources, as shown in Figure 8(a). The weight of the vibration isolation device accounted for only 15% of the equipment mass. Experimental results showed that the vibration acceleration attenuation of the entire frequency range was obvious, and the vibration level of foundation is close to the background level. The Australian Navy used DRVIS to isolate the main engine of submarines to reduce the contribution of low-frequency structural vibration to the overall acoustic signal of submarines, as shown in Figure 8(b) [50].

DRVIS, as a new intermediate mass structure, has enormous potential to solve the contradiction between lightweighting and high-efficiency VIE. However, the

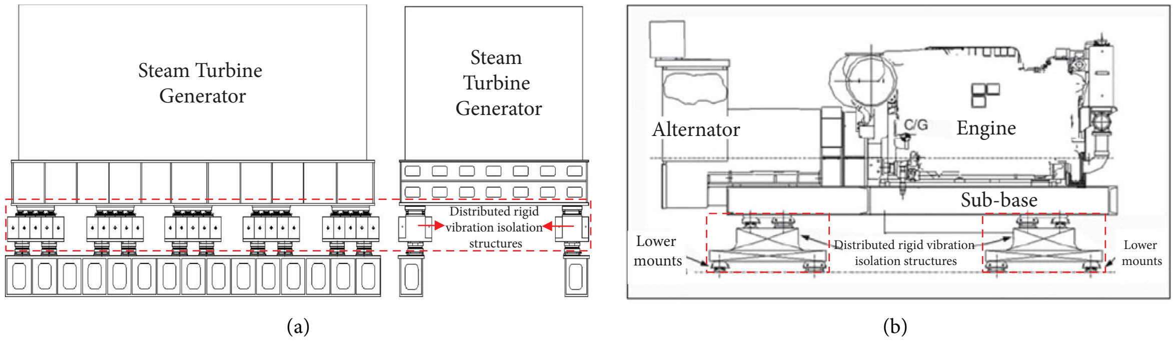


FIGURE 8: Applications of DRVIS [49, 50]. (a) DRVIS applied in a steam turbine generator. (b) DRVIS applied in Collins class submarine.

quantitative relationship between VIE and mass ratio has not yet been mastered, and further theoretical and experimental research is needed to achieve the goal of smaller mass ratio and high-efficiency VIE.

4. Novel Mechanism

The current vibration suppression mechanism of VIT for MPD is rare; DDVAs technology, PD technology, LRS technology, QZSI technology, and AVC technology have low-frequency broadband and high-efficiency VIE, which have shown strong application prospects in the vibration and noise control for large-scale lightweight structures in the aerospace field recently. They are regarded as potential means that can be applied on VIT design for MPD to increase the lightweight level.

4.1. DDVAs Technology. Many scholars have conducted research on controlling the vibration of flexible structures by installing DDVAs with different tuning frequencies on the surface shown in Figure 9. Studies indicate that DDVAs technology can effectively reduce broadband vibration. Therefore, the applications of DDVAs can solve the problem of low-frequency vibration control caused by structural light-weighting and make lightweight VIT possible.

Research on DDVAs technology began in the aerospace industry, which is more sensitive to light-weighting. In the mid-1980s, Fuller et al. [51–54] from Virginia Tech Vibration and Noise Center in the USA conducted extensive works on the applications of DDVAs to reduce vibration and noise in commercial aircraft cabins and rocket fairings.

In the mid-1990s, Fuller et al. [51] established a simplified analytical structural acoustics model of a propeller aircraft to study the potential vibration and interior noise reduction of DDVAs. The experimental results showed that globally detuning DDVAs to minimize an interior acoustic cost function gives attenuations of the order of 6–10 dB of the blade passage frequency interior noise when properly configured over a wide frequency band. The concept of globally detuning also provides a reference for using DDVAs to control other large-scale flexible structures under wide-band or random excitation. In a recent study on the payload compartment of a rocket fairing, the total weight of the fairing is about 750 kg and each dynamic vibration absorbers (DVAs) weighs 12.5 kg. The total weight of the four absorbers accounts for 6.67% of the total weight of the fairing, indicating that DDVAs have the advantages of low additional mass.

In order to reduce the internal acoustic levels in the 50–160 Hz frequency band of a simulated rocket's cylindrical shell, Esteve and Johnson [55] used 13 uniformly DDVAs with tuning frequency of 112.5 Hz along the circumference inside the circular shell and 5 Helmholtz resonators (equivalent to acoustic absorbers) with inherent natural frequencies of 61 Hz, 82.4 Hz, 102.5 Hz, 136.6 Hz, and 149.6 Hz uniformly around the cavity, as shown in Figure 10. An overall reduction of 7.7 dB in the frequency range of 50–160 Hz was obtained through DDVAs weighting only 2% of the cylinder mass, demonstrating the effectiveness of DDVAs in controlling low-frequency vibration noise of structures with small additional mass.

Yang et al. [56] formulated a plate with DDVAs mounted to study the control mechanisms in different frequency bandwidths and the coupling properties due to the introduction of absorbers. In his study, 4 dominating modes were selected as the control target. For each mode, it is found that 3 DVAs can provide a desired band control performance. The genetic algorithm was used to determine the optimal location of each DVA. The experimental results showed that an apparent reduction was achieved at each targeted mode, with reduction ranging from 7.3 to 19.0 dB, and the weight of 12 DVAs used accounted for only 8% of the plate weight. The capability of DDVAs technology to achieve a broadband vibration reduction was demonstrated.

On the basis of DDVAs, Idrisi et al. [57] and Wagner et al. [58] further developed continuous DDVAs that consist of an elastic layer of elastic media with embedded mass inhomogeneities, mechanically replicating mass-spring-damper systems. Experimental results showed that coupling between the masses of multiple dynamic absorbers contributes to more effective control of the noise radiation of the wall structure in a wider frequency band (0–500 Hz), with a total additional mass of less than 10% of the main structure only.

The applications of DDVAs in MPD can effectively address the issue of deviation in tuning frequencies caused by variations in devices speed and aging of isolators, thereby broadening the absorption frequency band. DDVAs have been employed to suppress the longitudinal vibration

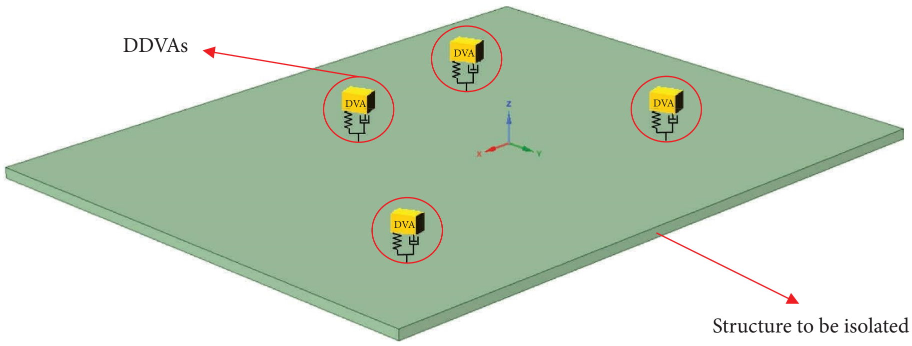


Figure 9: Schematic of DDVAs technology.

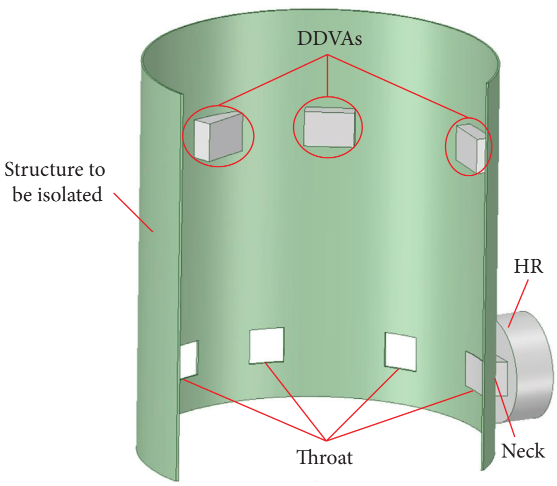


Figure 10: The cylinder shell with DDVAs and HR mounted [55].

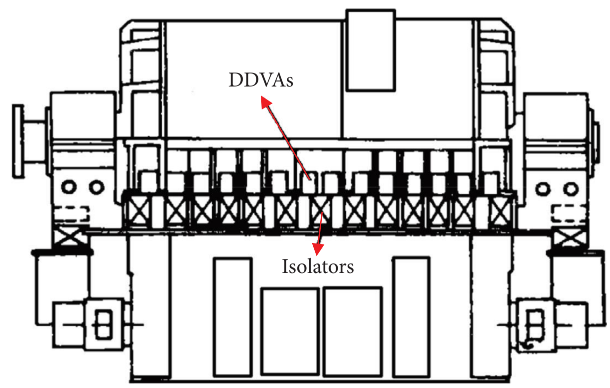


Figure 11: Naval propulsion motor with DDVAs mounted [62].

transmission of shipboard devices and structures [59–61], but applications on FRVIS are relatively less common.

In a study conducted by Wu et al. [62], 32 DDVAs with evenly spaced tuning frequencies and a mass ratio of 0.01 were applied on a naval propulsion motor mounting system, as shown in Figure 11. The tested results revealed that the DDVAs exhibited a bandwidth of approximately 5 Hz. Zhang et al. [63] studied the vibration characteristics of FRVIS with DDVAs mounted. The results demonstrated a significant improvement in the performance of VIE with DDVAs mounted. The absorption frequency band was effectively expanded with DDVAs of different tuning frequencies mounted.

DDVAs technology with small additional mass can effectively solve the problem of vibration noise suppression with multiple frequency spectra and wide bandwidth. Its effectiveness has been theoretically and experimentally verified in the aerospace field. In solving the overweight problem of VIT for MPD, DDVAs technology has strong technical feasibility and broad engineering application prospects.

4.2. LRS Technology. Recently, the concept of "Locally resonant" and other new proposals in the field of physical acoustics have provided new opportunities for low-frequency vibration reduction. A typical LRS is shown in Figure 12. LRS has the characteristic of regulating the propagation of elastic waves within the structure and can realize the property of generating bandgaps under small-size conditions. The bandgap characteristics of LRS depend on the resonant subunits contained in LRS and are independent of the dimension parameters of LRS. This means that low-frequency broadband vibration reduction effects can be achieved by altering dimension parameters of LRS [64].

Liu et al. [65] first proposed and fabricated the LRS to block low-frequency sound waves, in which centimeter-sized lead balls coated with a 2.5 mm layer of silicone rubber were used as subwavelength resonant microstructures and periodically embedded in an epoxy matrix as shown in Figure 13(a). However, the use of microstructures made of high-density metal materials and cut-out materials inevitably brings about the problems of increased total mass and low manufacturing efficiency, which limits its engineering application.

The rapid development of resin additive manufacturing (3D printing) technology has enabled the efficient production of small-sized and complex precision microstructures, which has greatly promoted the engineering application of LRS. Li et al. [66] used 3D printing technology to fabricate a locally resonant plate and achieved both vibration isolation and energy harvesting functions by attaching piezoelectric element and control circuits on the resonant microstructures, as shown in Figure 13(b). Therefore, 3D printing technology has freed the selection and design of materials from the constraints of traditional

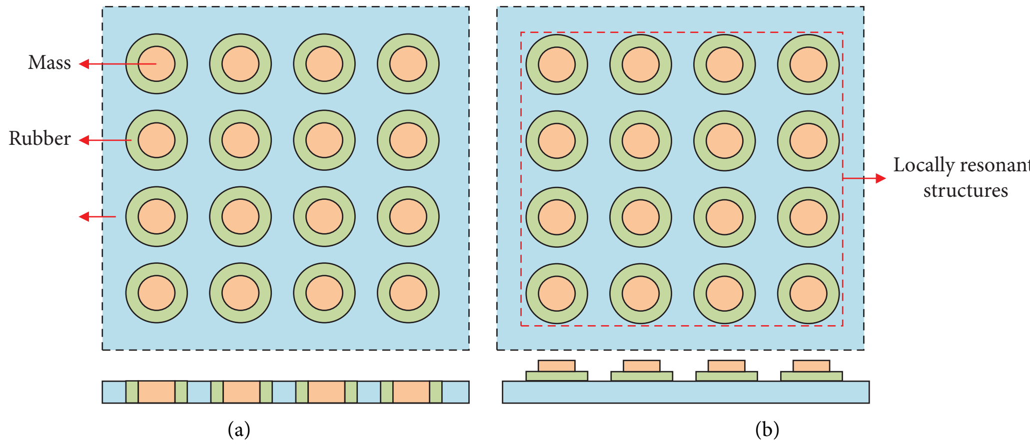


Figure 12: LRS technology [64]. (a) Resonators embedded in the base structure. (b) Resonators attached on the surface of the base structure.

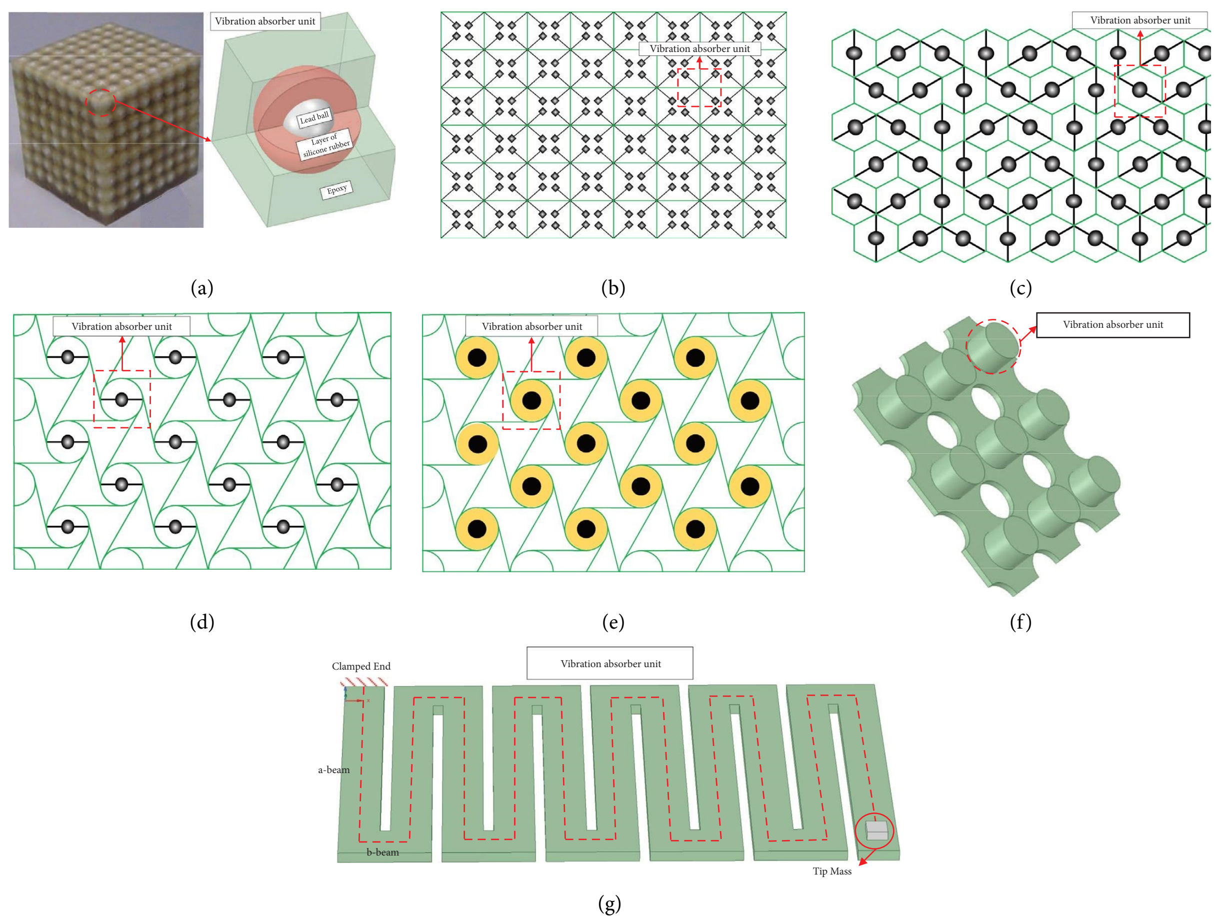


Figure 13: Different resonant microstructures proposed by scholars. (a) Lead ball coated with silicone rubber LRS proposed by Liu et al. [65]. (b) A cantilever-type LRS proposed by Li et al. [66]. (c) A honeycomb core-type LRS proposed by Yu and Lesieutre [67]. (d) A chiral honeycomb lattice beam-type LRS proposed by Hu et al. [68]. (e) A chiral beam-type LRS proposed by Zhu et al. [69]. (f) A trampoline-type LRS proposed by Abdeljaber et al. [70]. (g) A linear zigzag-type LRS proposed by Bilal et al. [71].

manufacturing processes and can better exert the powerful wave control function of the LRS.

However, the application of fully resin-printed LRS is difficult in situations where high structural static bearing capacity and environmental adaptability are required so that it cannot be used in many engineering fields. The embedded LRS design provides a solution to this problem. Yu and Johnson [67] further used 3D printing technology to manufacture a honeycomb sandwich panel with high static strength and embedded low-strength resonant microstructures, as shown in Figure 13(c), in them to form a locally resonant panel that can isolate external vibrations. In Zhao's [68] research, 3D printed subwavelength-scale microstructures were embedded into a chiral honeycomb base structure, as shown in Figure 13(d), to form a lightweight meta-structure which can suppress vibrations with different polarizations at target frequencies. These embedded designs not only consider the static load-bearing capacity of the structure but also achieve efficient VIE performance.

The working frequency of LRS is closely related to the design of resonant microstructures. To address the low-frequency vibration isolation issues that are of utmost concern in marine engineering, the resonant frequency of the microstructure can be reduced by increasing the resonant mass or decreasing the microstructure stiffness, thereby enabling the structure to operate in the corresponding low-frequency range. Zhu et al. [69] fabricated a chiral-lattice-based elastic metamaterial beam with multiple embedded local resonators composed of tungsten and rubber columns to achieve broadband vibration suppression without sacrificing its load-bearing capacity, as shown in Figure 13(e). In order to achieve low-frequency bandgap, the mass of resonant microstructure had to be increased, which is not conducive to improve the lightweight level of the VIT. Reducing the equivalent stiffness of the resonant microstructure can shift the bandgap to low frequency, thereby achieving low-frequency vibration isolation function while maintaining the structure's lightness at the same time. The cantilevered zigzag microstructure design, as shown in Figure 13(f), proposed by Abdeljaber et al. [70] and the pillar-hole microstructure design, as shown in Figure 13(g), proposed by Bilal et al. [71] both reduce the equivalent stiffness of the resonant structure by optimizing its geometric configuration, thereby achieving low-frequency vibration isolation.

In the field of marine engineering, the utilization of LRS's bandgap characteristics enables the achievement of vibration reduction of marine structures and equipment [72]. LRS was proposed to solve the low-frequency sound and vibration control problems for marine piping systems [73]. According to the low-frequency mechanical vibration generated by the power devices on the ship, a single-phase spiral-shaped LRS is designed and analyzed [74], as shown in Figure 14. The experimental results show that the spiral LRS has good adaptability and flexibility for broadband frequency, and the frequency band of vibration isolation can cover from 15 Hz to 45 Hz. Particularly, the frequency band of vibration isolation is not limited by the weight of the MPD. Qin [75] introduced LRS to attenuate the vibration of marine structure foundation, as shown in Figure 15. The experimental results show that the frequency response of the base can be effectively reduced by 20% with only 0.02 mass ratio ($m_{\mathrm{LRS}}/m_{\mathrm{base}}$).

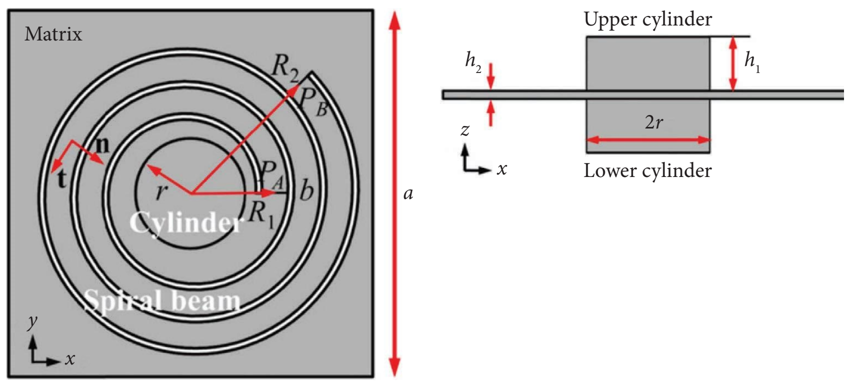
LRS technology, with its artificially designable subwavelength microstructures and disruptive dynamic equivalent properties, has provided a new approach for low-frequency vibration control of MPD and is regarded as a potential means to achieve lightweight and highly efficient low-frequency VIE. However, in order to produce significant bandgaps in LRS, there is a phenomenon of excessive mass ratio in the design of LRS in existing studies which does not meet the requirements of practical engineering. Therefore, it is necessary to develop a parameter optimization method for LRS with the goal of lightweight and highly efficient VIE to promote the lightweight development of LRS and broaden their application prospects.

4.3. PD Technology. PD technology is a vibration reducing method by placing a limited sealed cavity filled with an appropriate amount of particles at locations where structural vibration is significant, as shown in Figure 16. The vibration energy is transferred and absorbed through friction, impact, and collision between the particles and the cavity wall, as well as between the particles themselves. The outstanding advantages of PD technology include low additional mass and excellent VIE, which is beneficial for lightweight design; minimal alteration to the original structure and easy to install; a wide vibration reduction frequency band and good energy dissipation effect towards characteristic line spectrum; stable damping characteristics that are not easily affected by aging or extreme environmental conditions.

PD technology was first used to control the severe vibration generated during the flight of weight-sensitive aerospace equipment. In a research conducted by the Pratt and Whitney Rocketdyne, PD was used to solve the high-cycle fatigue of the liquid oxygen inlet duct of the space shuttle main engine. The experimental results showed that a reduction in the amplitude of over fivefold was achieved under static loading conditions. It was also successfully used in the vibration control of Delta IV components. 10 lb of particles achieved an equivalent amount of acoustic amplitude attenuation as 300 lb of blankets wrapped around the vehicle body, demonstrating its potential in lightweight vibration isolation [76].

PD technology is widely applied in mechanical engineering. Kielb et al. [77] conducted a study on the VIE of aluminum beams with PD. Seven through-holes with a diameter of 2 mm were opened on the aluminum beam, and different types of particles such as tungsten-based alloys, cobalt oxide alloys, and iron-based alloys were filled in the holes to conduct preliminary tests. The results showed that the VIE of PD was very significant, and the weight of the filled particles accounted for only 5% of the beam. Tao et al. [78] designed a new particle-damped two-stage isolation system, which integrate PD into the intermediate mass structure. The research results showed that installations of PD can significantly reduce the vibration response transmitted to the foundation. Therefore, replacing part of the intermediate structure mass with PD can help improve the VIE performance and provide room for light-weighting.

The application prospects of PD technology in civil engineering have also been demonstrated. Lu et al. [79] conducted experiments on the VIE performance of PD under earthquake excitation based on a five-story steel frame, and the results showed that the PD significantly reduced the displacement and acceleration response of the primary structure. The mass ratio of PD to the primary structure was only 2.8%. Ogawa et al. [80] applied PD to



(a) (b)

FIGURE 14: Schematic diagram of single-phase spiral-shape LRS unit applied in the marine power system [74]. (a) Top view. (b) Front view.

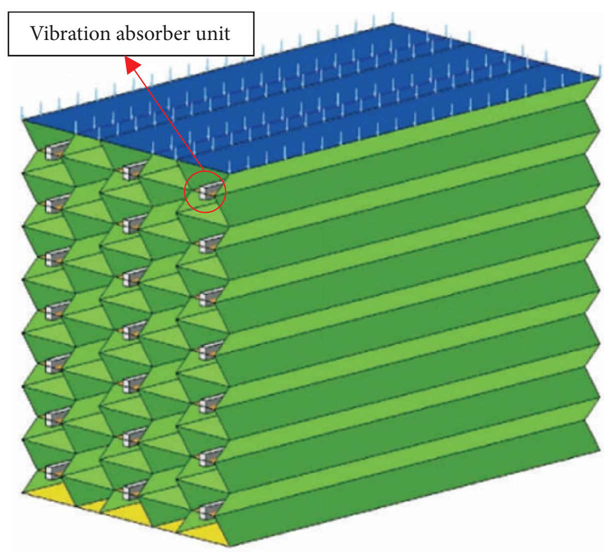


FIGURE 15: Marine mount structure with LRS mounted [75].

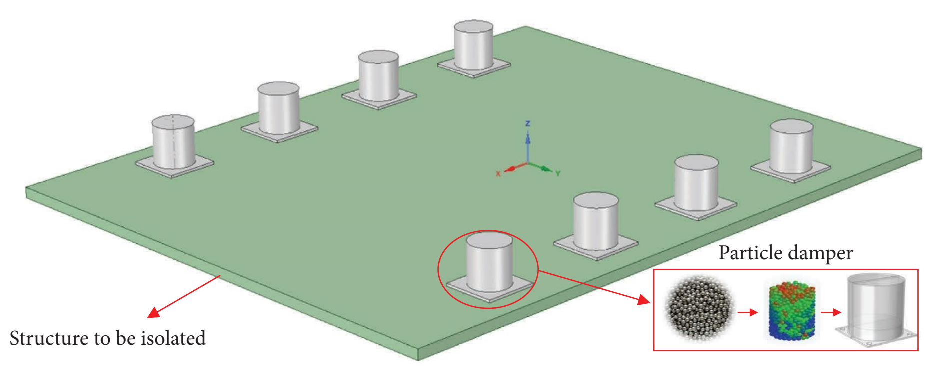
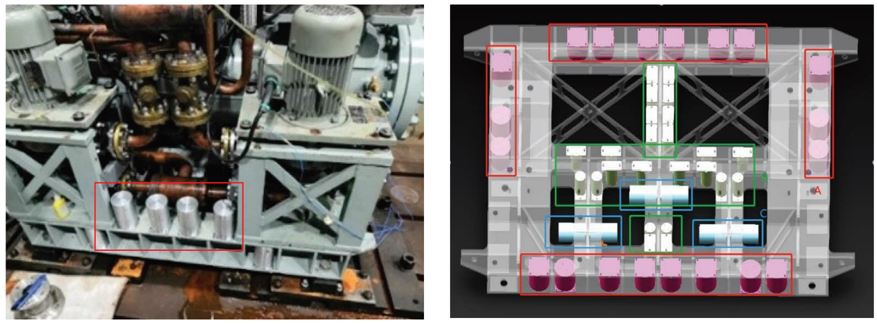


FIGURE 16: Schematic of PD technology.

control wind-induced vibration in a cable-stayed bridge pylon, and Naeim et al. [81] applied PD to tall buildings, which withstood the test of the 2010 Chile earthquake.

In the context of marine applications, PD technology has also shown high potential and value. Wang et al. [82] designed a novel particle-damped FR for a ship air conditioning unit as shown in Figure 17, which had good low-frequency VIE and played a role in line spectrum control. Meanwhile, it provided overall damping to structure, achieving the goal of reducing vibration in the entire frequency range.

Zhang [83] integrated PD technology with the VIT for a large-scale MPD, as shown in Figure 18. The tested results showed that PD had a good absorption effect on the



(a) (b)

Figure 17: PD technology applied in a ship air conditioning unit [82]. (a) Air conditioning unit with PD mounted. (b) The layout scheme of PD.

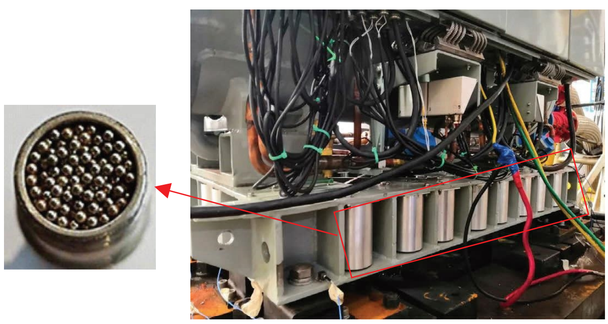


Figure 18: A large-scale MPD with PD mounted [83].

characteristic line spectra of MPD, with 6 spectra significantly reduced in 10–200 Hz. The weight of PD installed is only 2% of the MPD, fully verifying the engineering application value of PD in the design of VIT for MPD.

In summary, PD technology is an effective way to achieve high-efficiency VIE under the lightweight condition. However, current research on PD mainly focuses on the study of energy dissipation mechanisms, and there is a lack of quantitative research on the relationship between the mass, filling ratio, material, vibration absorption frequency, and VIE. Therefore, how to apply PD technology to achieve lightweight and efficient VIE has not yet been mastered.

4.4. QZSI Technology. Faced with the low-frequency vibration isolation problem induced by MPD, QZSI, consisting of elastic components with positive and negative stiffness, possesses zero stiffness at the static equilibrium position and large stiffness when the deflection is relatively large [84]. Hence, QZSI have attracted significant attention and regarded as useful practical solutions for their excellent isolation performance in the low-frequency range.

QZSI was first proposed by Alaguzhev to improve isolation performance using negative stiffness as a corrector [85]. A kind of QZSI consisting of a vertical spring and two oblique springs that are either linear, linear with prestress, or softening nonlinear with prestress, as shown in Figure 19(a), was designed by Carrella. It is shown that QZSI can outperform the linear system provided that the system parameters are chosen appropriately [89, 90]. Xu proposed a QZSI by employing the magnetic mechanism in parallel with the vertical coil spring as shown in Figure 19(b) to deal with the low-frequency vibration isolation problem [86]. Zhou designed a QZSI with the cam-roller mechanism. Experimental results show that the cam-roller mechanism with negative stiffness lowers the starting isolation frequency and enhances the isolation efficiency and suppresses the resonant response, leading to an excellent low-frequency vibration isolation performance [91].

However, many existing conceptual designs for QZSI are too bulky to be used in engineering, and the solution for a compact design is still lacking. In view of the limitation and complexity of ship space and the problem of low-frequency vibration isolation, Wang designed an QZSI with small volume and simple structure for marine vessel in which the bulking circular plate is taken as the negative stiffness as shown in Figure 19(c) [87]. Simulated and experimental results indicated that the isolation efficiency was improved greatly. However, many existing conceptual designs for QZSI are too bulky to be used in engineering, and the solution for a compact design is still lacking. Wang designed a spacing-saving QZSI shown in Figure 19(d) and experimentally verified the superior vibration isolation performance [88].

In solving the overweight problem of VIT for MPD, mounting systems equipped with QZSI have huge potential. Although many QZSIs have been proposed by scholars at home and abroad, most of them focus on the theoretical study of negative stiffness mechanism and innovative design of negative stiffness mechanism, and there are few studies on experimental research and applications on MPD. Further experimental study and applications on the practical MPD mounting system are necessary.

4.5. AVC Technology. In the face of the low-frequency vibration control problem caused by MPD, traditional passive control technologies have difficulty achieving satisfactory VIE in the low-frequency range. We have to sacrifice space, weight, stability, and other factors to achieve low-frequency vibration isolation, resulting in the overweight weight problem of VIT. AVC technology has attracted more attention due to its superior low-frequency VIE and environmental adaptability. With the significant improvement in

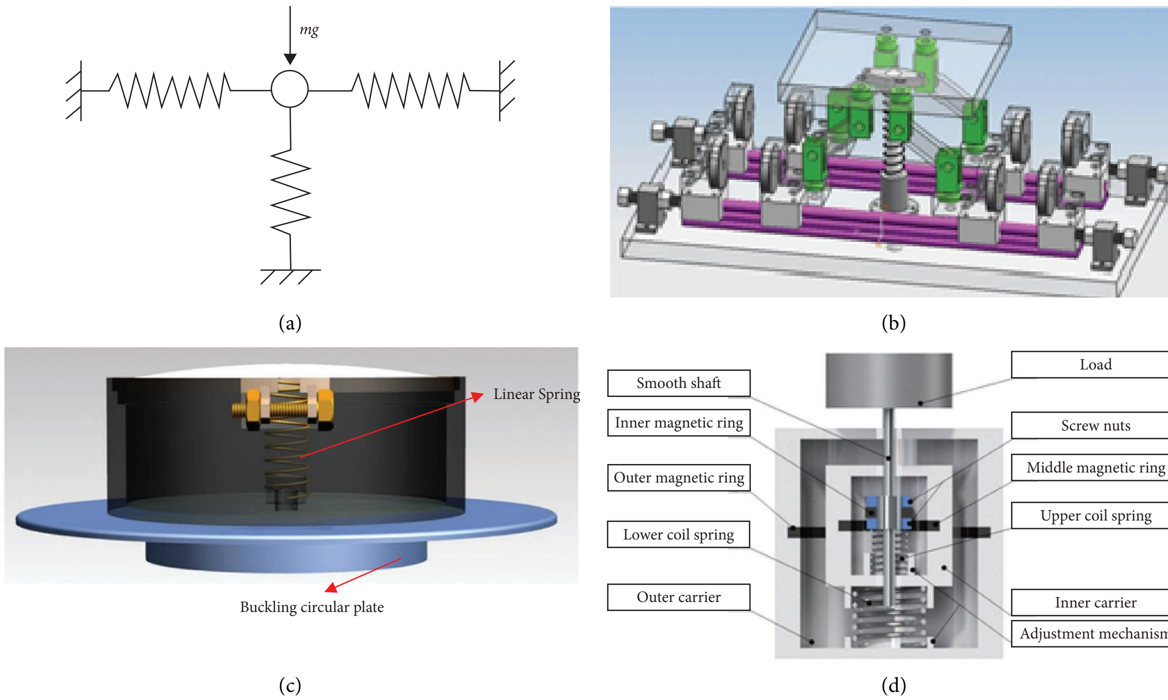


Figure 19: QZSI proposed by scholars at home and abroad. (a) A three-spring model of QZSI [85]. (b) A nonlinear magnetic QZSI [86]. (c) QZSI designed for ships [87]. (d) Two-stage nonlinear QZSI [88].

digital signal processing capabilities, more and more AVC systems are gradually being applied in MPD.

4.5.1. Active Distributed Dynamic Vibration Absorber Technology (Active DDVAs Technology). Active DDVAs can automatically change the structural parameters of absorber or drive the absorber's movable mass in a certain pattern through an actuator to achieve a wideband absorption effect according to the vibration state of the system controlled. Currently, commonly used active components include hydraulic, electromagnetic, piezoelectric, shape memory alloy, and others. Active DDVAs mounted at the foot positions of power equipment can effectively suppress the vibration transmission of equipment to the raft/hull. They can also be arranged in different directions to meet the requirements of multi-degree-of-freedom absorption if needed.

In 2010, the Dutch organization TNO utilized 6 special, high-efficient active absorbers mounted on three locations of a naval ship to control the vibration transmission [92], Yang et al. [93] installed 6 inertial electromagnetic active absorbers above the isolators of a type of tugboat diesel generator set, both of which achieve excellent vibration absorption.

In order to suppress the frequency-varying vibration of the FR mounting system, electromagnetic DDVAs (mass ratio: 0.05) were implemented. This arrangement successfully achieved effective control of the 9 Hz spectral vibration of the system [94]. Six active DDVAs (mass ration: 0.02) are retrofitted to a diesel generator set mounting system in a tugboat to determine the effectiveness in a realistic practical environment, as shown in Figure 20 [95]. Experimental results show that the combination of active DDVAs and mounting system is effective in reducing the global vibration on the frames below the generator, with vibration reductions of more than 10 dB, and the reduction in the acoustic pressure due to active DDVAs is up to 8 dB.

Active DDVAs technology has shown significant VIE for small-scale controlled objects, but for large-scale controlled objects such as MPD, it requires a large number of active DDVAs and sensors and will impose a huge computational burden on control algorithms. Therefore, further in-depth research is needed.

4.5.2. Active Vibration Isolation Technology (AVI Technology). In order to save installation space, various integrated hybrid vibration isolators combining active and passive components have been proposed successively for suppressing vibration transmitted from MPD to the hull.

BBN Technology Corporation [96] designed a hybrid vibration isolator integrating rubber isolators and electromagnetic actuators, as shown in Figure 21(a), to isolate a diesel engine. The line spectrum force transmitted to the foundation in 20–200 Hz was attenuated by 15–25 dB. Li et al. [97] proposed a hybrid vibration isolator with maglev actuator integrated in air spring as shown in Figure 21(b) for active-passive isolation of marine machinery vibration. The weight of marine machinery is about 5 t. 6 hybrid isolators weighing 30 kg each were used. The tested results showed that the most prominent 10–12 harmonics in the frequency range of 20–180 Hz were effectively attenuated by 10–30 dB after active control. Wu [98] used 4 hybrid isolators as shown in Figure 21(c), each weighing 92 kg to reduce the vibration of a 2.4 t marine 6135 diesel generator. In

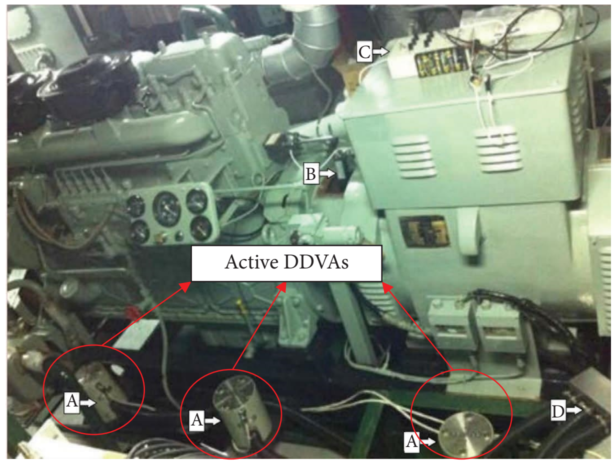


Figure 20: A diesel generator set mounting system with active DDVAs mounted [90].

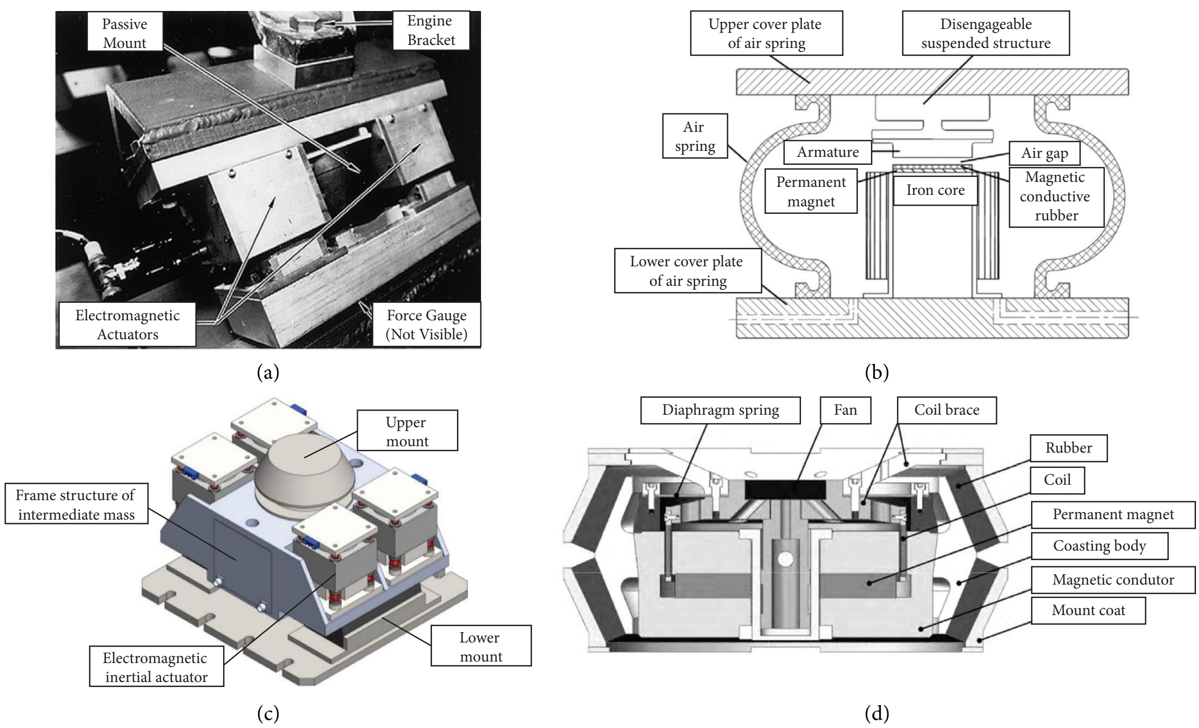


Figure 21: Different hybrid isolators. (a) Hybrid isolator integrating rubber isolators and electromagnetic actuators [86]. (b) Active-passive isolator composed of maglev actuator and air spring [91]. (c) Sensing-actuating integrated and active-passive hybrid isolator [87]. (d) Novel rubber-electromagnetic composite active-passive isolator [88].

0–800 Hz, the hybrid mean reduction was 46.0–57.9 dB under 15 tested conditions, and the total weight of isolators accounted for only 16% of the equipment. Ren et al. [99] proposed a compact active/passive hybrid vibration isolator composed of a low-frequency rubber isolator and linear electromagnetic actuator, as shown in Figure 21(d). The mean vibration level is attenuated more than 30 dB in 5–300 Hz.

AVI technology, as a supplement to passive isolation technology, can selectively isolate line spectrum vibration and improve the VIE. It will provide space for the lightweight VIT design.

5. Future Development Trends of Lightweight VIT for MPD

Recently, significant progress has been made in the field of vibration control technology for MPD through in-depth research on excitation sources, vibration transmission mechanisms, and control methods. Some of these technologies have already been applied to the actual marine vessel. However, research on lightweight VIT for MPD is still in its infancy. Currently, light-weighting is mainly achieved through structural dynamic optimization or the use of lightweight materials, but the overall level of light-weighting still needs to be improved. Through extensive research and experimental verification, many scholars have demonstrated that new structures and mechanisms such as PFR, DRVIS, DDVAs technology, LRS technology, PD technology, and AVC technology have lightweight and efficient VIE. These technologies have shown strong application prospects in various fields, so they are effective means to solve the overweight problem of VIT for MPD. In order to further reduce the vibration caused by MPD and continuously increase the light-weighting level, the following issues still deserve in-depth and meticulous research.

5.1. Research on the Correlation Mechanism between Structural Quality and VIE. In terms of theoretical research, it fails to gasp the quantitative relationship between structural quality and VIE. Therefore, it is necessary to establish a theoretical model close to the practical applications including complex excitation characteristics of MPD, study the quantitative relationship between structural quality and VIE performance, find the marginal performance, and provide guidelines for lightweight VIT design.

5.2. Research on Multiobjective Intermediate Mass Structure Optimization Method with High Efficiency VIE and Lightweight Functionality. Faced with overweight problem, structural dynamic optimization on intermediate mass structure during the design stage is considered as the fundamental and ultimate solution. Therefore, a comprehensive approach that combines methods such as size optimization, shape optimization, and topology optimization should be employed to achieve efficient VIE and light-weighting utilizing the emerging techniques such as neural networks and deep learning models.

5.3. Research on the Application of New Materials. The emerging development of new materials has provided an opportunity to achieve lightweight VIT. In the application of lightweight materials, deformation magnesium alloys and new composite materials have great potential. In addition, as a single material can hardly meet the lightweight requirements of the VIT for MPD to the greatest extent, it is necessary to study the design theory, methods, and corresponding processes of various material-mixed structures and adopt different materials in different parts to fully utilize the advantages of various materials. This integrated design theory and method of multiple materials will become a research hotspot in the lightweight VIT design.

5.4. Optimization Design of Light-Weighting, Load-Bearing, Vibration-Absorbing, and Vibration-Isolating Function-Integrated PFR. Faced with a single vibration suppression mechanism problem, the superior performance of PFR, DDVAs, PD, and AVC has been verified through theoretical and laboratory prototype testing, but practical applications on MPD are still in the exploratory stage. The main focus in the future is how to use multiple approaches and comprehensive optimization measures to design and promote their applications in engineering. In addition, to address the shortcomings of single-function and low integration of multifunctional PFR, the design concept of "light-weighting, load-bearing, vibration-absorbing, and vibration-isolating function-integrated PFR" is proposed. The integration of AVC technology, DDVAs technology, PD technology, and LRS technology into PFR will significantly improve the lightweight level of the FRVIS. Further in-depth research studies on the impact of various technology quality allocation on VIE under the goal of lightweight are well worth pursuing.

5.5. Research on Adaptive Systems and Broadband Control Systems. With the continuous improvement on the construction technology and widespread application of VIT, the impact of wideband vibration has gradually become prominent under the condition of effective suppression of line spectrum vibration caused by MPD. At the same time, with the continuous changes in operating conditions and environment, the vibration response characteristics caused by wideband excitation are also different. Therefore, seeking an efficient wideband vibration control system with adaptive capability is one of the urgent breakthroughs in AVC technology for MPD.

5.6. Systematic and Integrated Research on Various Lightweight Technologies. The various lightweight technologies are complementary to each other, and their advantages can be fully utilized through systematic and integrated methods for material selection, structural optimization design, and new principles. The systematic and integrated applications of various lightweight technologies are the fundamental approach to solve the overweight problem in VIT for MPD, and it is the main direction for the future development of lightweight VIT.

Abbreviations

MPD:	Marine power devices
VIT:	Vibration isolation technologies
VIE:	Vibration isolation effectiveness
FRVIS:	Floating raft vibration isolation systems
FR:	Floating raft
PFR:	Periodic floating rafts
DRVIS:	Distributed rigid vibration isolation structures
DDVAs:	Distributed dynamic vibration absorbers
PD:	Particle damping
LRS:	Locally resonant structures
QZSI:	Quasizero stiffness isolators
AVC:	Active vibration control
AVI:	Active vibration isolation.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to acknowledge the financial support for the research, authorship, and/or publication of this article from the National Science and Technology Major Project of China (J2019-II-0013-0033).

References

[1] L. He, W. Xu, W. J. Bu, and L. Shi, "Dynamic analysis and design of air spring mounting system for marine propulsion system," *Journal of Sound and Vibration*, vol. 333, pp. 4912–4929, 2014.

[2] Z. Wang and C. M. Mak, "Application of a movable active vibration control system on a floating raft," *Journal of Sound and Vibration*, vol. 414, pp. 233–244, 2018.

[3] H. Sun, K. Zhang, P. Zhang, and H. Chen, "Application of dynamic vibration absorbers in floating raft system," *Applied Acoustics*, vol. 71, no. 3, pp. 250–257, 2010.

[4] M. S. Yu, G. R. Huang, and T. X. Fu, "Development review on mechanical-noise control for submarine," *Journal of Ship Mechanics*, vol. 7, no. 4, pp. 110–120, 2003.

[5] L. He and W. Xu, "Naval vessel machinery mounting technology and its recent advances," *Acta Acustica*, vol. 38, no. 2, pp. 128–136, 2013.

[6] X. L. Xie, G. M. Dong, F. Lin, Z. Y. Zhang, and X. Y. Wen, "Development of vibration control technologies for marine power and gearing system," *Strategic Study of Chinese Academy of Engineering*, vol. 24, no. 6, p. 10, 2022.

[7] E. E. Ungar and C. W. Dietrich, "High-frequency vibration isolation," *Journal of Sound and Vibration*, vol. 4, no. 2, pp. 224–241, 1966.

[8] J. C. Snowdon, "Isolation from vibration with A mounting utilizing low- and high-damping rubberlike materials," *Journal of the Acoustical Society of America*, vol. 34, no. 1, pp. 54–61, 1962.

[9] J. C. Snowdon, "Mechanical four-pole parameters and their application," *Journal of Sound and Vibration*, vol. 15, no. 3, pp. 307–323, 1971.

[10] S. J. Zhu and L. He, "Study on the vibration isolation effect of double-stage vibration isolation systems," *Journal of Naval University of Engineering*, vol. 14, no. 6, pp. 6–9, 2002.

[11] Z. C. Hu, *Research on Vibration Reduction Methods and Mechanisms of Submarine Flexible Propulsion System in Low Frequency Range*, Naval University of Engineering, Wuhan, China, 2020.

[12] Y. R. Qiu, W. Xu, W. J. Bu, and W. Z. Qin, "Raft attitude control and elastic deformation suppression technique for large-scale floating raft air spring mounting system," *Journal of Vibration and Control*, vol. 28, no. 23-24, pp. 3457–3468, 2021.

[13] H. T. Zhu, *Topology Optimization Research and Vibration Characteristics Analysis of the Floating Raft Isolation System*, Dalian University of Technology, Dalian, China, 2019.

[14] F. Wang, H. Z. Shao, and H. Y. Cui, "Topology optimization weight loss research of the floating raft isolation system," *Ship Science and Technology*, vol. 41, no. 4, pp. 66–70, 2019.

[15] H. R. Yang, Y. Zhu, J. G. Zhang, and G. Z. Chen, "Research on vibration damping performance of CFRP raft with different connectors," *Composites Science and Engineering*, no. 11, p. 5, 2022.

[16] X. Li, G. B. Hu, K. T. He, J. H. Wei, and C. L. Lai, "The material truss design and optimization," *Ship Science and Technology*, vol. 44, no. 8, pp. 17–23, 2022.

[17] W. J. Mu, *Study on the Control Method of Composite Pedestal to Ship Equipment Vibration Transmission*, Harbin Institute of Technology, Harbin, China, 2018.

[18] R. Yang, Z. Wang, X. B. Li, W. Chen, and H. J. Wang, "Development and trends of naval floating raft vibration isolation systems," *Ship Engineering*, vol. 42, no. 7, p. 7, 2020.

[19] F. Zhang, S. H. Xu, and M. S. Yu, "A review of truss-type floating raft system," *Journal of Ship Mechanics*, vol. 14, no. 5, pp. 566–570, 2010.

[20] J. E. Bondaryk, "Vibration of truss structures," *Journal of the Acoustical Society of America*, vol. 102, no. 4, pp. 2167–2175, 1997.

[21] Y. Yong and Y. K. Lin, "Dynamic response analysis of truss-type structural networks: a wave propagation approach," *Journal of Sound and Vibration*, vol. 156, no. 1, pp. 27–45, 1992.

[22] M. Ruzzene, "Vibration and sound radiation of sandwich beams with honeycomb truss core," *Journal of Sound and Vibration*, vol. 277, no. 4-5, pp. 741–763, 2004.

[23] T. Kohrs and B. A. Petersson, "Wave propagation in light weight profiles with truss-like cores: wavenumber content, forced response and influence of periodicity perturbations," *Journal of Sound and Vibration*, vol. 304, no. 3-5, pp. 691–721, 2007.

[24] F. Zhang, *Acoustic Design Method and Noise Reduction Performance Analysis of Space Truss Raft System*, China Ship Research and Development Academy, Beijing, China, 2012.

[25] S. X. Cheng, Z. Y. Zhang, and H. X. Hua, "Analysis and experiment on vibration isolation characteristics of a periodic truss raft system," *Noise and Vibration Control*, vol. 31, no. 6, pp. 5–9, 2011.

[26] J. Zhou, *Structural Design and Analysis of Truss Type Vibration Isolation Floating raft*, Wuhan University of Technology, Wuhan, China, 2016.

[27] X. L. Wen, W. H. Li, Y. Fang, C. S. Song, and J. Zhang, "Design and vibration isolation performance of truss-type CFRP raft frame," *Shock and Vibration*, vol. 2019, Article ID 4281958, 10 pages, 2019.

[28] H. Xiuchang, J. Aihua, Z. Zhiyi, and H. Hongxing, "Design and optimization of periodic structure mechanical filter in suppression of foundation resonances," *Journal of Sound and Vibration*, vol. 330, no. 20, pp. 4689–4712, 2011.

[29] X. C. Huang, S. Y. Xu, H. X. Hua, and Z. Y. Zhang, "Research on dynamic properties and vibration isolation performance of curved beam periodic structure," *Journal of Shanghai Jiao Tong University*, vol. 47, no. 2, pp. 173–179, 2013.

[30] S. Lee, B. Mace, and M. Brennan, "Wave propagation, reflection and transmission in curved beams," *Journal of Sound and Vibration*, vol. 306, no. 3-5, pp. 636–656, 2007.

[31] X. C. Huang, S. Y. Xu, H. X. Hua, and Z. Y. Zhang, "Periodic floating rafts with curved beam structures based on wave shape transformation," Chinese Patent, CN 102748423 A, Beijing, China, 2012.

[32] S. X. Cheng, *Analysis and experiment on Vibration Isolation Characteristics of Floating Raft Composed of Periodic Structures*, Shanghai Jiao Tong University, Shanghai, China, 2012.

[33] C. Y. Kuang, *Design and Vibration Isolation Characteristics Research of a Floating Raft Constructed with Periodic Structures*, Shanghai Jiao Tong University, Shanghai, China, 2011.

[34] B. Chen and S. Y. Xu, "Study on vibration band-gap characteristics of trigonal chiral structures," *Noise and Vibration Control*, vol. 33, no. 4, pp. 75–78, 2013.
[35] K. F. Tee, A. Spadoni, F. Scarpa, and M. Ruzzene, "Wave propagation in auxetic tetrachiral honeycombs," *Journal of Vibration and Acoustics*, vol. 132, no. 3, pp. 31–37, 2010.
[36] A. Spadoni, M. Ruzzene, S. Gonella, and F. Scarpa, "Phononic properties of hexagonal chiral lattices," *Wave Motion*, vol. 46, no. 7, pp. 435–450, 2009.
[37] F. Scarpa, S. Blain, T. Lew, D. Perrott, M. Ruzzene, and J. R. Yates, "Elastic buckling of hexagonal chiral cell honeycombs," *Composites Part A: Applied Science and Manufacturing*, vol. 38, no. 2, pp. 280–289, 2007.
[38] X. C. Huang, S. Y. Xu, H. X. Hua, and Z. Y. Zhang, "Periodic floating rafts with chiral structures based on wave shape transformation and vibrational localization," Chinese Patent, CN 102748420 A, Beijing, China, 2012.
[39] X. Shiyin, H. Xiuchang, and H. Hongxing, "A study on the isolation performance of trichiral lattices with gradient geometry," *Journal of Vibration and Control*, vol. 21, no. 16, pp. 3465–3475, 2015.
[40] M. Ruzzene and F. Scarpa, "Control of wave propagation in sandwich beams with auxetic core," *Journal of Intelligent Material Systems and Structures*, vol. 14, no. 7, pp. 443–453, 2003.
[41] F. Scarpa and G. Tomlinson, "Theoretical characteristics of the vibration of sandwich plates with in-plane negative Poisson's ratio values," *Journal Of Sound And Vibration*, vol. 230, no. 1, pp. 45–67, 2000.
[42] A. Honig and W. Stronge, "In-plane dynamic crushing of honeycomb. Part II: application to impact," *International Journal of Mechanical Sciences*, vol. 44, no. 8, pp. 1697–1714, 2002.
[43] A. Honig and W. Stronge, "In-plane dynamic crushing of honeycomb. Part II: application to impact," *International Journal of Mechanical Sciences*, vol. 44, no. 8, pp. 1697–1714, 2002.
[44] D. Q. Yang and L. F. Xia, "Vibration reduction mechanism and design method of floating raft with auxetic components," *Shipbuilding of China*, vol. 59, no. 3, pp. 144–154, 2018.
[45] L. F. Xia and D. Q. Yang, "Acoustics and vibration analysis of a double cylindrical shell with lightweight auxetic metamaterial ribs," *Journal of Vibration And Shock*, vol. 37, no. 18, pp. 143–149, 2018.
[46] W. Zhang, *Study on Performance of Vibration Isolation and Optimization of the Distribution Two-Stage Vibration Isolation System*, Shanghai Marine Equipment Research Institute, Shanghai, China, 2018.
[47] M. Y. Yang, *Study on Passive-Active Control Mechanism of Two-Stage Distributed Parameter Vibration Isolation Technologies*, Shandong University, Shandong, China, 2015.
[48] R. Fischer, L. Boroditsky, R. Dempsey, N. Jones, and M. Bahtiarian, "Airborne noise flanking of shipboard vibration isolation systems," *Sound and Vibration*, vol. 40, no. 12, pp. 19–23, 2006.
[49] Y. R. Qiu, W. Xu, Z. C. Hu, and S. W. Zhang, "Model-based design of a novel modular mounting system: light, compact, and efficient," *Advances in Mechanical Engineering*, vol. 14, no. 9, 2022.
[50] M. Winberg, C. Hansen, I. Claesson, and L. Xun, *Active Control of Engine Vibrations in a Collins Class Submarine*, Blekinge Institute of Technology, Australia, 2003.
[51] C. Fuller, J. P. Maillard, M. Mercadal, and A. H. Von Flotow, "Control of aircraft interior noise using globally detuned vibration absorbers," *Journal of Sound and Vibration*, vol. 203, no. 5, pp. 745–761, 1997.
[52] Y. M. Huang and C. R. Fuller, "Vibration and noise control of the fuselage via dynamic absorbers," *Journal of Vibration and Acoustics*, vol. 120, no. 2, pp. 496–502, 1998.
[53] Y. Huang and C. Fuller, "The effects of dynamic absorbers on the forced vibration of a cylindrical shell and its coupled interior sound field," *Journal of Sound and Vibration*, vol. 200, no. 4, pp. 401–418, 1997.
[54] C. R. Fuller and R. L. Harne, "Passive Distributed vibration absorbers for low frequency noise control," *Noise Control Engineering Journal*, vol. 58, no. 6, pp. 627–635, 2010.
[55] S. J. Esteve and M. E. Johnson, "Reduction of sound transmission into a circular cylindrical shell using distributed vibration absorbers and Helmholtz resonators," *Journal of the Acoustical Society of America*, vol. 112, no. 6, pp. 2840–2848, 2002.
[56] C. Yang, D. Y. Li, and L. Cheng, "Dynamic vibration absorbers for vibration control within a frequency band," *Journal of Sound and Vibration*, vol. 330, no. 8, pp. 1582–1598, 2011.
[57] K. Idrisi, M. E. Johnson, A. Toso, and J. P. Carneal, "Increase in transmission loss of a double panel system by addition of mass inclusions to a poro-elastic layer: a comparison between theory and experiment," *Journal of Sound and Vibration*, vol. 323, no. 1-2, pp. 51–66, 2009.
[58] A. Wagner, M. E. Johnson, K. Idrisi, and D. P. Bartylla, "An analytical model for the interaction of mass inclusions in heterogeneous (HG) blankets," *Journal of Vibration and Acoustics*, vol. 133, no. 6, 2011.
[59] Y. P. Cao and W. P. Zhang, "Using dynamic absorbers to reduce underwater structural noise due to longitudinal vibration of shafting," *Journal of Harbin Engineering University*, vol. 28, no. 7, pp. 747–751, 2007.
[60] X. D. Jin and X. M. Cheng, "Naval stern vibration and its decreasing by dynamic absorbers," *Journal of Shanghai Jiao Tong University*, vol. 31, no. 2, pp. 38–45, 1997.
[61] T. A. Smith and J. Rigby, "Underwater radiated noise from marine vessels: a review of noise reduction methods and technology," *Ocean Engineering*, vol. 266, pp. 112863–112915, 2022.
[62] C. J. Wu, D. P. Luo, S. Z. Yang, Y. F. Zhu, and Y. Y. Ma, "Design and application of multiple tuned mass damper for ships," *Journal of Vibration Engineering*, vol. 12, no. 4, pp. 584–589, 1999.
[63] K. Zhang, H. L. Sun, H. B. Chen, and P. Q. Zhang, "Power flow analysis of floating raft systems with dynamic vibration absorbers," *Journal of University of Science and Technology of China*, vol. 37, no. 1, pp. 13–19, 2007.
[64] X. Z Zhu, Z Chen, Y. H. Jiao, and Y. P. Wang, "Broadening of the sound absorption bandwidth of the perforated panel using a membrane-type resonator," *Journal of Vibration and Acoustics*, vol. 140, no. 3, Article ID 031014, 2018.
[65] Z. Liu, X. Zhang, Y. Mao et al., "Locally resonant sonic materials," *Science*, vol. 289, no. 5485, pp. 1734–1736, 2000.
[66] Y. Li, E. Baker, T. Reissman, C. Sun, and W. K. Liu, "Design of mechanical metamaterials for simultaneous vibration isolation and energy harvesting," *Applied Physics Letters*, vol. 111, no. 25, Article ID 251903, 2017.
[67] T. Yu and G. A. Lesieutre, "Damping of sandwich panels via three-dimensional manufactured multimode metamaterial core," *American Institute of Aeronautics and Astronautics Journal*, vol. 55, no. 4, pp. 1440–1449, 2017.

[68] G. Hu, H. Hu, Y. Wang, W. Zhao, and R. Zhu, "Isolating low-frequency vibration via lightweight embedded metastructures," *Scientia Sinica Physica, Mechanica, and Astronomica*, vol. 50, no. 9, Article ID 090010, 2020.

[69] R. Zhu, X. N. Liu, G. K. Hu, C. Sun, and G. Huang, "A chiral elastic metamaterial beam for broadband vibration suppression," *Journal of Sound and Vibration*, vol. 333, no. 10, pp. 2759–2773, 2014.

[70] O. Abdeljaber, O. Avci, S. Kiranyaz, and D. J. Inman, "Optimization of linear zigzag insert metastructures for low-frequency vibration attenuation using genetic algorithms," *Mechanical Systems and Signal Processing*, vol. 84, pp. 625–641, 2017.

[71] O. R. Bilal, A. Foehr, and C. Daraio, "Observation of trampoline phenomena in 3D-printed metamaterial plates," *Extreme Mechanics Letters*, vol. 15, pp. 103–107, 2017.

[72] L. M. Zhang and D. Q. Yang, "Review on the applied research of mechanical and acoustic metamaterials in ship engineering," *Chinese Journal of Ship Research*, vol. 18, no. 2, pp. 1–19, 2023.

[73] H. J. Shen, Y. F. Li, Y. S. Su, L. K. Zhang, and Y. B. Song, "Review of sound and vibration control techniques for ship piping systems and exploration of crystals applied in noise and vibration reduction," *Journal of Vibration and Shock*, vol. 36, no. 15, pp. 163–170, 2017.

[74] Y. D. Ruan, X. Liang, X. Y. Hua, C. Zhang, H. Xia, and C. Li, "Isolating low-frequency vibration from power systems on a ship using spiral phononic crystals," *Ocean Engineering*, vol. 225, Article ID 108804, 2021.

[75] H. X. Qin and D. Q. Yang, "Vibration reduction mechanism for phononic crystal cellular mount with auxetic effect," *Journal of Vibration Engineering*, vol. 32, no. 3, pp. 421–430, 2019.

[76] H. Panossian, "Non-obstructive particle damping: new experiences and capabilities," in *Proceeding of the 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Schaumburg, Illinois, May 2008.

[77] R. Kielb, S. F. Masri, P. R. King, H. Panossian, and F. Lieghley, "Advanced damping systems for fan and compressor blisks," in *Proceeding of the 34th AIAA/ASME/ASEE Joint Propulsion Conference & Exhibt*, no. 7, pp. 13–15, Cleveland, OH, USA, August 1998.

[78] Y. Y. Tao, L. Hu, Q. L. Yang, and R. Cui, "Experimental investigation on damping effect performance of double layer vibration isolation system with particle damping," *Modern Manufacturing Engineering*, vol. 09, pp. 1–6, 2018.

[79] Z. Lu, Y. Liao, and X. L. Lv, "Comparison study on damping performance between tuned mass damper and tuned particle damper," *Journal of Building Structures*, vol. 40, no. 12, pp. 163–168, 2019.

[80] K. Ogawa, T. Ide, and T. Saitou, "Application of impact mass damper to a cable-stayed bridge pylon," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 72, no. 1-3, pp. 301–312, 1997.

[81] F. Naeim, M. Lew, L. D. Carpenter et al., "Performance of tall buildings in Santiago, Chile during the 27 February 2010 offshore Maule Chile earthquake," *The Structural Design of Tall and Special Buildings*, vol. 20, no. 1, pp. 1–16, 2011.

[82] C. M. Wang, W. Q. Xiao, D. H. Wu et al., "Study on bandgap characteristics of particle damping phononic crystal," *Applied Acoustics*, vol. 166, pp. 107352–107363, 2020.

[83] Y. C. Zhang, *Theoretical and Experimental Study on the Low-Frequency Vibration Absorption Effect on Particle Damping in Vibration Reduction*, Naval University of Engineering, Wuhan, China, 2021.

[84] I. Kovacic, M. J. Brennan, and T. P. Waters, "A study of a nonlinear vibration isolator with a quasi-zero stiffness characteristic," *Journal of Sound and Vibration*, vol. 315, no. 3, pp. 700–711, 2008.

[85] P. Alabuzhev, A. Gritchin, and L. Kim, *Vibration Protecting and Measuring Systems with Quasi-Zero Stiffness*, Hemisphere Publishing, London, England, 1989.

[86] D. Xu, Q. P. Yu, J. X. Zhou, and S. R. Bishop, "Theoretical and experimental analyses of a nonlinear magnetic vibration isolator with quasi-zero stiffness characteristic," *Journal of Sound and Vibration*, vol. 332, no. 14, pp. 3377–3389, 2013.

[87] Z. R. Yang, Y. Wang, Z. M. Huang, and Z. S. Rao, "Characteristic analysis of a new high-static-low-dynamic stiffness vibration isolator based on the buckling circular plate," *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 40, no. 3, pp. 1526–1539, 2020.

[88] Q. Wang, J. X. Zhou, K. Wang et al., "Design and experimental study of a two-stage nonlinear vibration isolators with quasi-zero stiffness," *Communications in Nonlinear Science and Numerical Simulation*, vol. 122, Article ID 107246, 2023.

[89] A. Carrella, M. J. Brennan, I. Kovacic, and T. P. Waters, "On the force transmissibility of a vibration isolator with quasi-zero stiffness," *Journal of Sound and Vibration*, vol. 322, no. 4-5, pp. 707–717, 2009.

[90] A. Carrella, M. J. Brennan, and T. P. Waters, "Optimization of a quasi-zero stiffness isolator," *Journal of Mechanical Science and Technology*, vol. 21, no. 6, pp. 946–949, 2007.

[91] J. X. Zhou, X. L. Wang, D. L. Xu, and J. Zhang, "Experimental study on vibration isolation characteristics of the quasi-zero stiffness isolator with cam-roller mechanism [J]," *Journal of Vibration Engineering*, vol. 28, no. 3, pp. 449–455, 2015.

[92] B. Tom, B. Arthur, and V. Ruud, "Active vibration control for underwater signature reduction of a navy ship," in *Proceedings of the The 17th International Congress on Sound & Vibration (ICSV17)*, Cairo Egypt, July 2010.

[93] T. J. Yang, X. H. Li, M. G. Zhu, J. T. Du, X. G. Liu, and Z. G. Liu, "Experimental investigation of active vibration control for diesel engine generators in marine applications," *Journal of Vibration Engineering*, vol. 26, no. 2, pp. 160–168, 2013.

[94] B. Zhang, X. Wang, H. M. Wu, and B. T. Yang, "Optimization design of electromagnetic vibration absorber for ship vibration suppression," *Noise and Vibration Control*, vol. 40, no. 4, pp. 213–218, 2018.

[95] T. J. Yang, L. Wu, X. H. Li, M. G. Zhu, M. J. Brennan, and Z. G. Liu, "Active vibration isolation of a diesel generator in a small marine vessel: an experimental study," *Applied Sciences*, vol. 10, no. 9, pp. 3025–3035, 2020.

[96] E. F. Berkman and E. K. Bender, "Perspectives on active noise and vibration control," *Sound and Vibration*, vol. 31, no. 1, pp. 80–94, 1997.

[97] Y. Li, L. He, C. G. Shuai, and C. Y. Wang, "Improved hybrid isolator with maglev actuator integrated in air spring for active-passive isolation of ship machinery vibration," *Journal of Sound and Vibration*, vol. 407, pp. 226–239, 2017.

[98] L. Wu, *Application Research of Active and Passive Hybrid Vibration Isolation Technology for marine Diesel Generator Set*, Harbin Engineering University, Harbin, China, 2021.

[99] M. K. Ren, X. L. Xie, Z. W. Huang, and Z. Y. Zhang, "Novel rubber-electromagnetic composite active/passive vibration isolator," *Journal of Vibration and Shock*, vol. 40, no. 23, pp. 32–37, 2021.