

# Typical dampers and energy harvesters based on characteristics of ferrofluids

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**Abstract:** Ferrofluids are a type of nanometer-scale functional material with fluidity and superparamagnetism. They are composed of ferromagnetic particles, surfactants, and base liquids. The main characteristics of ferrofluids include magnetization, the magnetoviscous effect, and levitation characteristics. There are many mature commercial ferrofluid damping applications based on these characteristics that are widely used in numerous fields. Furthermore, some ferrofluid damping studies such as those related to vibration energy harvesters and biomedical devices are still in the laboratory stage. This review paper summarizes typical ferrofluid dampers and energy harvesting systems from the 1960s to the present, including ferrofluid viscous dampers, ferrofluid inertia dampers, tuned magnetic fluid dampers (TMFDs), and vibration energy harvesters. In particular, it focuses on TMFDs and vibration energy harvesters because they have been the hottest research topics in the ferrofluid damping field in recent years. This review also proposes a novel magnetic fluid damper that achieves energy conversion and improves the efficiency of vibration attenuation. Finally, we discuss the potential challenges and development of ferrofluid damping in future research.

**Keywords:** ferrofluid characteristics; damping applications; ferrofluid viscous dampers; ferrofluid inertia dampers; tuned magnetic fluid dampers (TMFDs); vibration energy harvesters

## 1 Introduction

In 1965, Stephen [1] from National Aeronautics and Space Administration (NASA) successfully prepared stable ferrofluids for the first time, after which many of the properties of ferrofluids were investigated, including their levitation characteristics [2, 3], rheological properties [4, 5], magnetization characteristics [6], magnetoviscous effect [7, 8], magnetocaloric effect [9, 10], and magneto-optic effect [11, 12]. Ferrofluids have a wide range of industrial applications such as seals [13–15], dampers, sensors [16, 17], lubrication [18–20], biomedicine [21], and finishing [22, 23]. Although the statistics are incomplete, there are more than 170 applications for ferrofluids, many of which cannot utilize other materials. The applications of

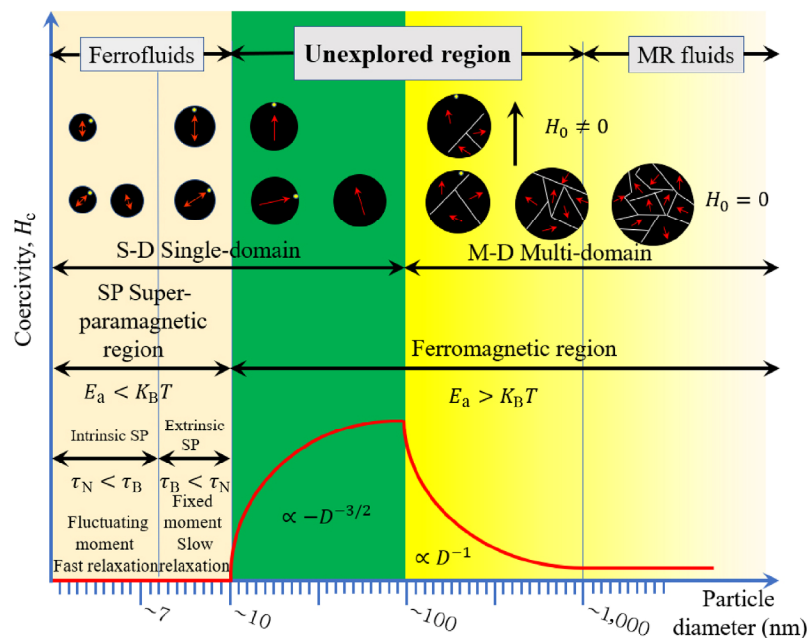
ferrofluids are mainly divided into mature commercial applications [24] and emerging applications under development [25]. Among these, the use of ferrofluids to reduce vibration is relatively mature. Because ferrofluids are gradually being used in a wider range of fields, new applications will accelerate the development of ferrofluids to reduce vibration.

Ferrofluids, which are also known as magnetic fluids (MFs), are a new type of functional materials. They are stable colloidal solutions formed of solid magnetic particles with diameters on the nanometer scale that are uniformly dispersed in base carrier liquids [26, 27]. MFs exhibit fluidity and magnetism, which can be controlled by a magnetic field [28]. In 1966, Rosensweig [29] discovered the stable levitation phenomenon for a magnetic body immersed in a

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magnetizable fluid, and provided a calculation method for buoyancy. Since then, many scholars have conducted studies on the levitation characteristics of MFs. At present, the estimation of the levitation force mainly focuses on cylindrical and spherical permanent magnets [30]. Three years after the discovery of the levitation characteristics of MFs, another important property of MFs was discovered, which is called the magnetoviscous effect. In 1969, Rosensweig et al. [31] and Mctague [32] observed that the viscosities of MFs varied with the magnetic field. The microscopic explanation for this phenomenon is that ferromagnetic particles are arranged in the direction of the magnetic field and even form chains or network structures. These structures increase the viscosity resistance during the flow of MFs, and the macroscopic manifestation is an increase in the apparent viscosity. Magnetorheological fluids (MRFs) were first invented

by Rabinow [33] in 1948. MRFs can easily be confused with ferrofluids. MRFs are composed of micrometer-sized ferromagnetic particles. Because of their large size, these particles are identified as magnetic multidomains and are not significantly affected by Brownian (thermal) motion [34]. Therefore, these particles tend to aggregate and deposit. Thus, MRFs are unstable. In contrast, MFs are composed of nanometer-sized ferromagnetic particles. Because of their small size, these particles are considered to be single magnetic domains and are subjected to Brownian motion. Hence, they do not aggregate, even in the absence of magnetic fields [35]. As a result, the stability of MFs is better than that of the MRFs. There is no clear dividing line for the particle sizes of MRFs and MFs, as shown in Fig. 1 [36]. MRFs exhibit stronger shear viscosities and yield stresses than MFs, as shown in Table 1 [37–39]. Because of the interesting



**Fig. 1** Schematic of size region of particles in ferrofluids and MRFs ( $H_0$ : Magnetic field intensity;  $E_a$ : Anisotropy energy;  $K_B T$ : Thermal energy;  $\tau_N$ : Néel relaxation time;  $\tau_B$ : Brownian relaxation time). Reproduced with permission from Ref. [36], © The Society of Rheology, Inc. 2019.

**Table 1** Comparison of MRFs and ferrofluids [37–39].

Characteristic	MRF	Ferrofluid
Particle characteristic length	1–10 $\mu\text{m}$	10 nm–1 $\mu\text{m}$
Magnetization characteristic	Superparamagnetism or ferromagnetism	Superparamagnetism
Saturation magnetization	1,000 kA/m magnitude	100 kA/m magnitude
Typical matrix viscosity	0.01–100 Pa·s	1–100 mPa·s
Typical yield stress	50–100 kPa	10–100 Pa

features of MRFs, MRF dampers are predominantly used in applications where vibration control or the transfer of force is required, such as tool vibration [40], civil buildings and bridges, suspension systems, and aircraft landing gear [41].

Based on the characteristics of MFs mentioned above, many dampers using MFs have been proposed. In 1967, NASA designed a ferrofluid viscous damper [42] to reduce the oscillations of a radio astronomy explorer (RAE) satellite. This was the first successful use of a magnetic fluid damper (MFD) in the aerospace industry. Since then, research into the use of MFs to reduce vibration has attracted considerable attention. From the 1970s to the beginning of the 21st century, research [43–45] has mainly focused on the MF viscous damper, which can be adjusted to change the viscous damping force and thus absorb vibration energy. In 1978, a viscous-fluid inertia damper that utilized the levitation characteristics of a ferrofluid was created and used to dampen the rotary shaft of a stepping motor [46]. Subsequently, scholars have conducted research on the levitation force [47, 48] and energy dissipation [49, 50]. An MF dynamic absorber was proposed based on a related theoretical study [51], which could reduce the vibration of flexible overhanging structures on spacecraft. In 1994, Iusan and Stanci [52] applied the first ferrofluid levitation principle to sensors. Subsequently, various MF dynamic absorbers based on this first levitation principle were designed and structurally optimized [53]. At the beginning of the 21st century, ferrofluids were used in tuned liquid dampers (TLDs) owing to their controllable flow to improve the energy dissipation efficiency. Scholars have studied the motion of MFs in tuned magnetic fluid dampers (TMFDs) to enhance their energy consumption efficiency [54–56]. In recent years, an increasing number of vibration energy harvesters based on the levitation characteristics of ferrofluids have been developed to obtain electrical energy from low-frequency vibrations [57, 58].

In 1980, Raj and Moskowitz [59] reviewed the application of magnetic liquid technology to damping phenomena. Ten years later, they discussed successful commercial applications of ferrofluids, including damping [24]. Five years after that, they added new

applications such as gauges, sensors, and ferrofluid stepper motors in a review of the recent advances in ferrofluid technology in the 1990s [60]. Some review articles on MFs briefly mention the MF damping [61–63]. In 2017, Azzawi et al. [64] presented a review of the damping in ferromagnetic thin films and multilayers. In the same year, Huang et al. [65] summarized the typical ferrofluid damping devices, including vibration isolators, dampers, and dynamic vibration absorbers. Khairul et al. [66] introduced the advanced applications of tunable ferrofluids in energy systems and harvesters. They confirmed that the interest in the development of miniaturized systems and microelectromechanical systems has increased. Unlike previous review articles, this review paper classifies the damping principles of MFDs based on the characteristics of MFs and summarizes the development of MFDs from the 1960s to the present, especially the most popular studies in the past decade, namely those related to TMFDs and vibration energy harvesters.

This review paper first introduces the principles of MF damping, and then classifies typical MFDs and energy systems from the 1960s to the present, according to the principles of vibration reduction. Compared to previous reviews, this review article considers new studies on TMFDs and vibration energy harvesters in detail. The main issues with promising research directions for MF damping, such as energy harvesting, biological damping, and magnetic particle damping, are pointed out. We hope that this paper will enlighten beginners and inspire explorers in this field.

## 2 Basic principles and characteristics of ferrofluids

Ferrofluids are a category of liquids, and their motion follows the laws of hydrodynamics [67, 68]. Ferrofluids also exhibit magnetism; therefore, their behaviors are controlled by a magnetic field, and their magnetic properties obey the laws of electromagnetism [69]. The basic components of ferrofluids are non-magnetic liquids and solid ferromagnetic particles, with two basic assumptions made about solid-phase particles. The first assumption is that all solid-phase

particles are spherical and have the same size. The second assumption is that although the solid-phase particles in ferrofluids are very dense, their total volume is less than 10% of that of the ferrofluids. Thus, they are considered a sparse phase [70].

### 2.1 Bernoulli equations

Neuringer and Rosensweig [71] first proposed the momentum equation for ferrofluids in 1964. The biggest difference between the mechanics equation of ferrofluid mixed flow and that for a general two-phase mixed flow is that the equation for ferrofluids contains a magnetic field action term [35]:

$$\rho_f \frac{dV}{dt} = \rho_f g - \nabla p^* + \eta_H \nabla^2 V + \mu_0 M \nabla H \quad (1)$$

where  $\rho_f$  is the density of the ferrofluid,  $V$  is the velocity of the ferrofluid,  $\eta_H$  is the viscosity of the ferrofluid,  $g$  is the local acceleration due to gravity,  $p^*$  is the composite pressure, and  $t$  is the time.

The following five assumptions are made.

- 1)  $\rho_f$  is a constant.
- 2) The magnetization vector,  $M$ , of the ferrofluid is parallel to the magnetic field intensity,  $H$ .
- 3) The flow of the ferrofluid is isothermal.
- 4) The temperature in the ferrofluid flow field is much lower than the Curie temperature.
- 5) The flow of the ferrofluid is steady.

The generalized Bernoulli equation of ferrofluids is as Eq. (2) [35]:

$$p^* + \frac{1}{2} \rho_f V^2 + \rho_f gh - \mu_0 \int_0^H M dH = C \quad (2)$$

where  $h$  is the distance from the reference surface in the  $g$  direction, and  $C$  is a constant.

### 2.2 Magnetoviscous effect

A certain orderly arrangement of the magnetic moments of molecules in a magnetic medium is called magnetization. The most important physical property of MFs is their magnetization. In contrast to paramagnetic substances, the magnetization process of MFs is affected by both kinematics and thermodynamics. Therefore, the magnetization equation [72] is as Eq. (3):

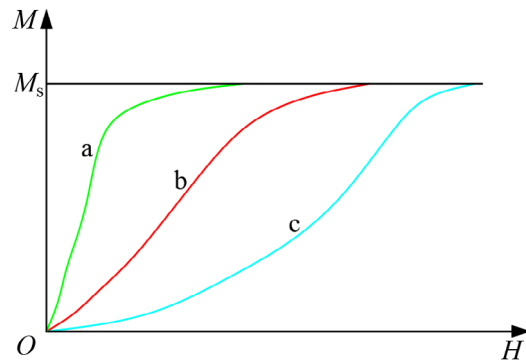
$$\frac{dM}{dt} = \Omega \times M - \frac{1}{\tau} (M - H) - \frac{1}{6\eta_H \phi} M \times (M \times H) \quad (3)$$

where  $\phi$  is the volume fraction of magnetic particles in the MF,  $\tau$  is the Brownian time of rotating particle diffusion, and  $\Omega$  is the flow vorticity of the ferrofluid.

The change in the viscosity of an MF under a magnetic field is called the magnetoviscous effect. In 1969, Rosensweig et al. [31] first proposed the concept of the magnetoviscous effect and studied the changes in the viscosities of different types of MFs under a magnetic field. The viscosity of an MF is generally influenced by the following factors: the viscosity of the carrier liquid,  $\eta_0$ ; saturation magnetization of MF,  $M_s$ ; magnetic field intensity,  $H$ ; temperature,  $T$ ; and shear rate,  $\gamma$ . The function form is  $\eta = \eta(\eta_0, M_s, H, T, \gamma)$ . Figure 2 shows the magnetization curves of ferrofluids based on a theoretical analysis [73].

### 2.3 Levitation characteristics

Because the magnetic field is distributed symmetrically around a permanent magnet, the pressure in the ferrofluid is symmetrically distributed. When a permanent magnet is located at the center of a container, the pressure exerted on the permanent magnet is balanced. However, when the permanent magnet deviates from the center of the container, it is no longer symmetrical. The solid-phase particles in the ferrofluid are single magnetic domains; therefore, when the ferrofluid concentration is not very high, there is no interaction between the solid-phase



**Fig. 2** Magnetization curves of ferrofluids (a. Newtonian flow ferrofluids; b. non-Newtonian flow ferrofluids ( $\gamma > 0$ ); c. non-Newtonian flow ferrofluids ( $\gamma = 0$ )). Reproduced with permission from Ref. [73], © Beihang University Press 2011.

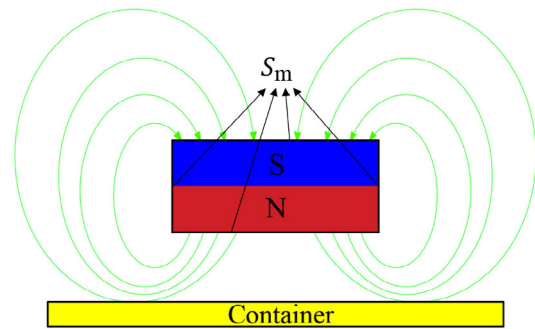
magnetic particles. However, in the presence of an external magnetic field, it exhibits superparamagnetism. The Langevin function [74, 75] can be used to express the magnetization law of ferrofluids. When the permanent magnet is close to the bottom surface, the magnetic flux lines barely enter the low-magnetic-conductivity medium; thus, they are compressed on the bottom surface, as shown in Fig. 3. This compression of the magnetic flux increases the pressure on the lower part of the magnet and generates buoyancy that opposes the effect of gravity on the permanent magnet. Similarly, it is difficult for the permanent magnet in the ferrofluid to approach the container wall. Therefore, the permanent magnet receives a restoring force, which forces it to the center. Thus, it can be stably suspended in the ferrofluid and does not easily move randomly in a three-dimensional space. This is a second type of levitation.

In another case, the permanent magnet is placed at the bottom of a container filled with a ferrofluid. Here, the magnetic flux barely enters an object with a low magnetic conductivity. Therefore, when an object is close to the permanent magnet at the bottom, the magnetic flux from the permanent magnet is compressed, as shown in Fig. 4, and the pressure on the bottom surface of the object increases. Under the static process, the first-order buoyancy and Archimedean buoyancy of the object can balance the force of gravity; thus, it can be stably suspended in the ferrofluid. This is the first type of levitation characteristic.

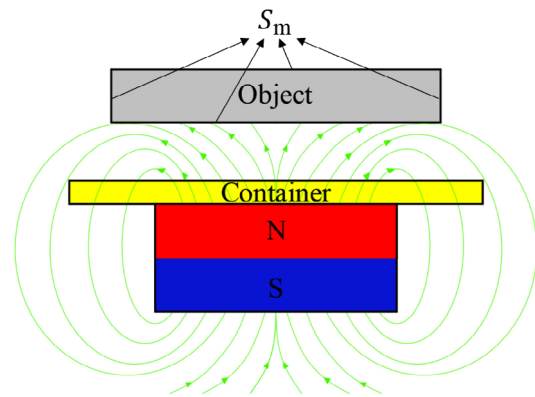
Equation 4 [76] can be used to calculate the levitation force of any magnetic or non-magnetic object immersed in a ferrofluid under a magnetic field:

$$F_m^* = \oint_{S_m} \left[ \left( -\int_0^H B dH + H_n B_n \right) \mathbf{n} + H_t B_n \mathbf{t} \right] da \quad (4)$$

where  $\mathbf{B}$  is the magnetic induction intensity, and  $B$  is its magnitude,  $\mathbf{H}$  is the magnetic field intensity, and  $H$  is its magnitude,  $S_m$  is the surface of an object immersed in the ferrofluid,  $da$  is a surface area element,  $\mathbf{n}$  is the normal unit vector at the interface,  $\mathbf{t}$  is a tangential unit vector at the interface,  $B_n$  is the normal component of  $\mathbf{B}$  perpendicular to the surface  $S_m$ , and  $H_n$  and  $H_t$  are the normal and tangential components of  $\mathbf{H}$ , respectively.



**Fig. 3** Magnetic field distribution of permanent magnet in container.



**Fig. 4** Magnetic field distribution of permanent magnet under container.

### 3 Typical dampers and energy harvesters of ferrofluids

Table 2 shows that unlike other types of dampers, an MFD has the advantages of a long life [42], no leakage [77], sensitivity to the inertial force [51], a simple and compact structure [46], etc., all of which promote the continuous extension and broadening of the application fields of MFDs.

#### 3.1 Ferrofluid viscous dampers

The magnetization characteristics of ferrofluids enable them to achieve positioning and accurate flow under the control of a magnetic field. The magnetoviscous effect makes the viscous shear force and damping of the ferrofluids controllable. These two important characteristics form the foundation on which ferrofluid viscous dampers can suppress vibrations.

Lite and Beltracchi [77] proposed two types of ferrofluid viscous dampers without mechanical coupling to suppress the torsional vibration of rotating

**Table 2** Comparison of different dampers.

Category	Applied range	Damping force	Damping efficiency	Advantage	Disadvantage
Ferrofluid damper [78, 79]	Amplitude = 1–18 mm Frequency = 1–20 Hz	0–130 N	Energy dissipation = 0–3.3 N·m	Simple mechanical configuration Low heat generation Widely used	Susceptible to external magnetic fields
Viscous damper [80–82]	Amplitude = 5–20 mm Frequency = 1–50 Hz	0–1,000 N	Displacement attenuation rate = 53.5%–68%	Stable performance High energy dissipation capacity Wide range of frequency applications	Leakage
Viscoelastic damper [83–85]	Amplitude = 0.2–2 mm Frequency = 0.1–1 Hz	0–4,000 N	Energy dissipation = 0–12.4 N·m	High energy dissipation capacity Wide range of amplitude adaptations	Greatly affected by temperature
Friction damper [86, 87]	Amplitude = 1.75–4.5 mm Frequency = 2–7 Hz	Moment = 0–200 N·m	Energy dissipation = 0–55 N·m	High energy dissipation capacity Easy to install and maintain Simple and compact configuration	Short life Easily damaged material Low reliability
Eddy current damper [88–90]	Amplitude = 0–200 mm Frequency = 0.2–0.8 Hz	$(0-3.6) \times 10^5$ N	Damping density = $24.9 \text{ MN}\cdot\text{s}/\text{m}^4$	No contact with the vibration structure Stable performance Adjustable and controllable damping	Complex structure Limited applications
Metallic damper [91–93]	Amplitude = 0–20 mm Frequency = 0–1 Hz	$(0-5) \times 10^4$ N	Hysteresis energy = 0–6000 N·m	Low manufacturing costs Stable hysteresis performance Resistance to temperature changes High reliability High energy dissipation capacity	Difficult to control Not sensitive to micro-vibration

equipment. However, the ferrofluid in an annular chamber is distributed unevenly, which leads to the mass of the rotating system being out of balance. Therefore, it cannot be used in high-speed rotating equipment that requires a certain degree of accuracy, such as motors. To suppress the resonance of the motor, Raj and Moscovitz [94] injected a ferrofluid directly into the gap between the stator and the rotor. In this case, the internal space of the motor is limited, or the internal magnetic field is insufficient, and a damping device can be connected to the end of the motor shaft. Matsumoto [95] designed a damping device for a motor in which the damping efficiency was kept constant without being affected by thermal fluctuations. Ferrofluids are used not only in motors but also to improve the performances of solenoid valves [96]. In 1972, a low-volatile ferrofluid was successfully prepared and used in moving coil loudspeakers [97].

Ferrofluids show limited increases in viscosity even under a strong magnetic field. Thus, the viscous shear force is small, which means that they are suitable for applications with low damping efficiency, such as flexible brakes. At present, ferrofluid brakes

are either the contact-type [98] or non-contact type [99]. A contact-type brake has a fast response speed and large adjustable range of damping because of the direct contact between the rotating shaft and ferrofluid. However, when the shaft rotates, the power loss caused by the viscous shear force of the ferrofluid cannot be avoided. A non-contact brake can prevent this problem. In the 1990s, a large number of piston-type ferrofluid linear dampers appeared. The magnetic fields in these dampers are provided by external permanent magnets [44, 46, 100] or electromagnets [101]. To improve the damping force of a ferrofluid without reducing its fluidity, Zhou and Sun [79] proposed a smart colloidal damper with porous particles, whose damping capability could be controlled on demand. This damper not only increased the damping force but also provided a large stroke of up to 20% of its length, and it generated less than 4% of the heat produced by conventional dampers with the same energy dissipation capacity. A smart colloidal damper is a good candidate for developing advanced semi-active vibration-control systems. A miniaturized damper is required to reduce the shock of small

precision equipment, but its damping efficiency decreases with the size of the damper. Liu [102] proposed a porous elastic sheet damper with a ferrofluid to compensate for this defect.

Numerous studies have been conducted on the material itself, such as the magnetization characteristics [103] and magnetoviscous effect [104, 105] of ferrofluids. These studies [106, 107] confirmed that the performance of a ferrofluid viscous damper is significantly influenced by the viscosity of the material.

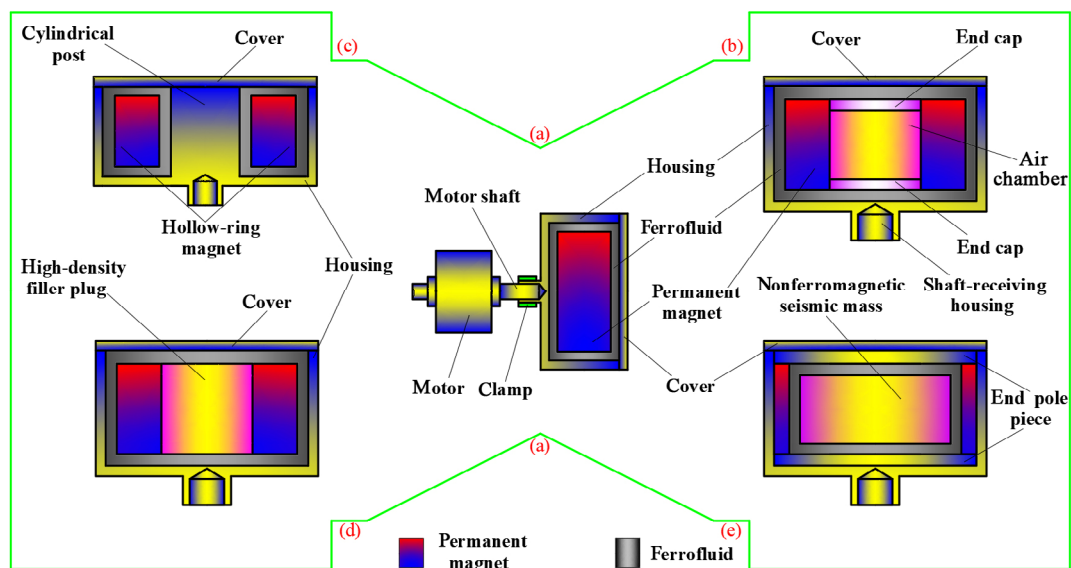
### 3.2 Ferrofluid inertia dampers

Since Rosensweig [29, 108] first discovered the levitation characteristics of ferrofluids in 1966, scholars from several countries have conducted extensive research on the two types of levitation characteristics and their applications [109, 110], and then gradually expanded these applications to the field of vibration engineering.

Moskowitz et al. [46] proposed a viscous-fluid inertia damper based on the second ferrofluid levitation principle to absorb the energy generated by a moving system, especially stepper motors and similar devices. A viscous-fluid inertia damper has a non-magnetic housing with a chamber, non-magnetic end cover, and seismic mass, as shown in Fig. 5(a). The space between the internal wall surface of the chamber and mass is filled with the ferrofluid. When the shaft oscillates, there is relative motion between the housing

and mass, and the ferrofluid generates a viscous shear force, which consumes vibration energy. The structures shown in Figs. 5(b)–5(e) show an improvement of the structure in Fig. 5(a). The seismic mass of the ring, as shown in Fig. 5(b), increases the buoyancy and decreases the weight to improve the bearing capacity of the damper. Figure 5(c) shows a damper with a housing with a central cylindrical post and hollow-ring permanent magnet, which provides an additional surface shear area for the ferrofluid to increase the dampening and bearing capacities. The difference between Figs. 5(c) and 5(d) is that the ring in Fig. 5(d) contains a high-density filler plug that increases the inertia of the mass. The damper in Fig. 5(e) is an inversion of the dampers shown in Figs. 5(a)–5(d).

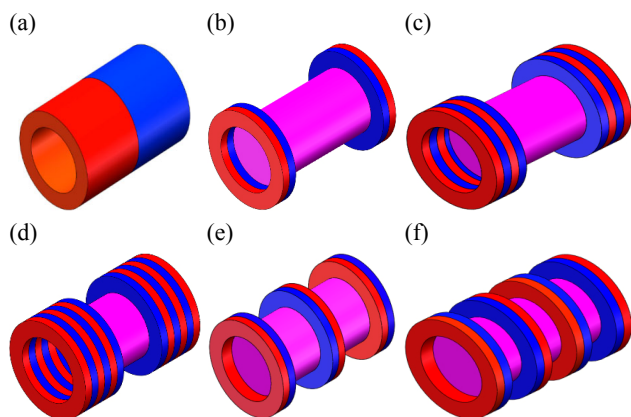
Bashtovoi et al. [51] investigated an MF dynamic absorber, which is an improvement based on the inertia damper that can be applied to spacecraft technology. It does not need to be filled with a ferromagnetic fluid, which greatly reduces the mass of the equipment. In addition, it can be very sensitive to small external inertial forces. This is also of great significance for the development of ferrofluid inertia dampers. Since the levitation phenomenon was first demonstrated, many studies have been conducted on the levitation force exerted on a complete cylindrical permanent magnet immersed in a ferrofluid. Yang and Liu [111] studied the levitation force of such a composite magnet because it has rarely been noted in previous



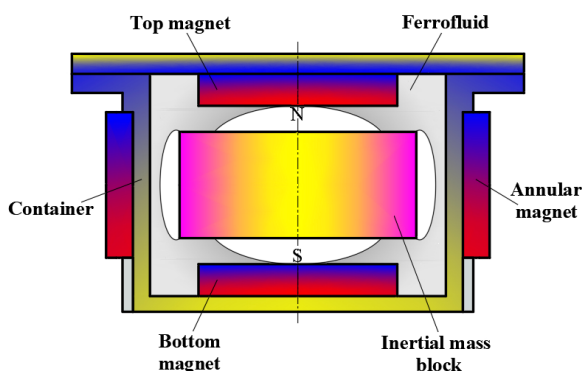
**Fig. 5** Schematics of viscous-fluid inertia dampers. Reproduced with permission from Ref. [46].

studies. They used analytical and numerical methods to calculate the levitation forces of different composite magnet structures, as shown in Fig. 6, and verified them experimentally. The experimental results showed that the levitation force on the composite structure was four times greater than that on the entire magnet. Although both calculation methods overestimated the levitation force, the numerical results were more accurate, with a maximum deviation of 14.2%.

In the 1990s, inertial devices using the first levitation characteristic of ferrofluids were proposed [52]. Dampers based on the second levitation principle of ferrofluids have some problems, such as the demagnetization or fragmentation of the permanent magnet, external interference, and unexpected eddy currents. To solve these problems, Yao et al. [53] designed a novel ferrofluid dynamic vibration absorber that consists of a copper inertial mass block, non-magnetic container with three permanent magnets, and quantity of ferrofluid, as shown in Fig. 7. Two



**Fig. 6** Schematics of composite magnet structures. Reproduced with permission from Ref. [111], IOP Publishing Ltd. 2018.



**Fig. 7** Model of the ferrofluid dynamic vibration absorber. Reproduced with permission from Ref. [53], © Elsevier Ltd. 2019.

sets of experiments were conducted. One set was used to investigate the influence of the mass of the ferrofluid on the levitation state of the inertial mass block, and the other was used to study the influence of the ferrofluid dynamic vibration absorber on the damping performance with or without the top magnet. They found that a vibration absorber based on the first levitation principle of ferrofluids had an excellent damping performance at a frequency of 1.18 Hz and an initial amplitude of 1 mm.

Ferrofluid inertia dampers based on levitation characteristics have compact structures and are sensitive to inertial forces; thus, they can potentially be used to reduce vibrations in spacecraft. Through many theoretical and experimental studies on the levitation force [112, 113], it is hoped that the performance of ferrofluid inertia dampers can be improved. In addition, a large proportion of vibration energy harvesters are based on levitation characteristics.

### 3.3 TMFDs

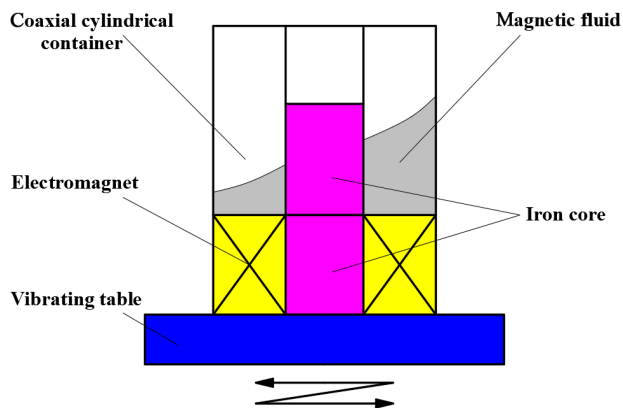
TLDs rely on the sloshing of liquids in containers to absorb the vibration energy. When the sloshing frequency of the liquid is consistent with the vibration frequency of the structure, the energy consumption reaches a maximum; however, the sloshing of the liquid in a traditional TLD cannot be controlled. MFs can be precisely controlled by changing the current in the electromagnet; thus, the damping efficiency of a TMFD is much better than that of a TLD.

In 1969, Zelazo and Melcher [114] first studied the dynamic behaviors of MFs in an oscillating container. In 1990, Sudo et al. [115] conducted experimental research on the behaviors of MFs in rectangular and cylindrical vessels that vibrated laterally under a horizontal magnetic field. In 1998, Abe et al. [116] proposed a TMFD and experimentally studied the sloshing characteristics of MFs under a dynamic magnetic field for the first time. Their results showed that when the excitation frequency was close to the natural frequency of the MF sloshing or the alternating magnetic force increased, the shear force increased correspondingly, and thus the damping efficiency improved. In 2002, Ohira et al. [117] presented a TLD that used a water-based MF. Four electromagnets were placed around the cylindrical container such that



the phase difference between the sinusoidal changing magnetic field and the model vibration could be adjusted when approaching the resonance frequency. This device significantly improved the damping performance of the TMFD.

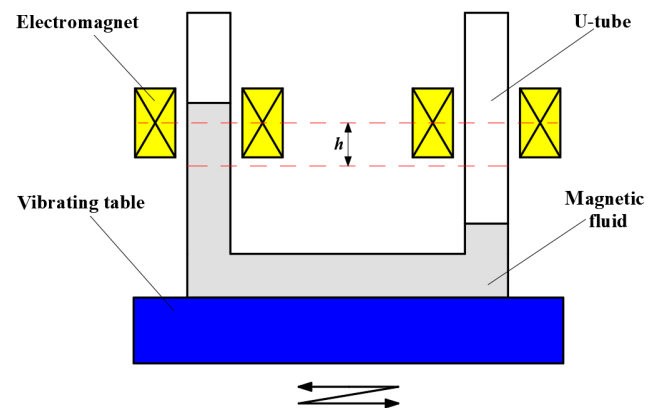
In 2007, Horie et al. [118] explained the unique damping characteristics of a TMFD by using a new analytical model. The upper and lower electromagnets were used to provide a vertical magnetic field when the dimensionless frequency ranges were 0.92–0.96 Hz and 1.01–1.02 Hz, respectively, and the resonance peaks of the structure decreased significantly. In 2008, Ohno et al. [119] set an electromagnet in a cylindrical container to study the damping characteristics of a TMFD. Their experiments showed that the TMFD could achieve a better damping efficiency when the maximum magnetic field intensity was 36 mT, and the optimal fluid depth was 18 mm. One year later, they [120] modified the TMFD based on the previous one, as shown in Fig. 8. It consisted of a coaxial cylindrical container with MFs, two iron cores, and one electromagnet. The iron cores were inserted into the container so that their bottoms coincided with the bottom of the container. The relationship between the length of the core and the frequency of the vessel vibration was investigated. The results showed that the damping characteristics of the TMFD improved significantly. Ohno and Sawada conducted a series of studies on TMFDs. In 2010, they found a relationship between the displacement amplitude of the MF and the pressure, and proved that the displacement of the MF was almost proportional to the pressure of the



**Fig. 8** TMFD with coaxial cylindrical container. Reproduced with permission from Ref. [120], © The Japan Society of Mechanical Engineers 2009.

fluid [54]. In 2011, they studied the variations in the axial and radial natural sloshing frequencies of a coaxial cylindrical container with an iron core inserted at different heights [56]. The rate of variation of the natural sloshing frequency increased remarkably when the end face of the inserted core was close to the surface of the MF.

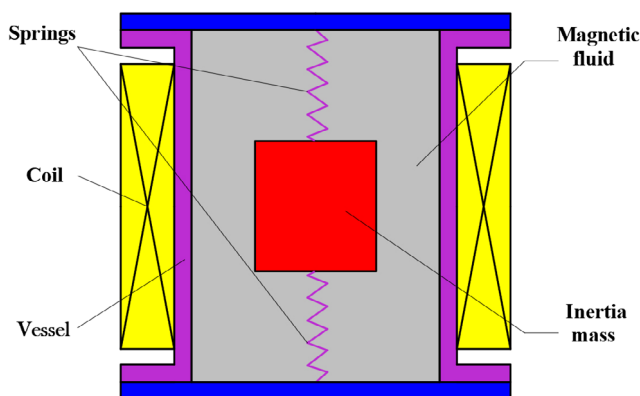
Tuned liquid column dampers (TLCDs) represent a branch of TLDs with structural differences. In 1989, Sakai [121] first proposed a TLCD, which is a passive device. This TLCD could suppress the vibrations caused by wind and earthquakes in high-rise buildings and other structures. It was composed of a U-tube container with a working fluid that exhibited efficient damping as the liquid moved in the column. In 2013, Masuda et al. [122] studied the influence of a magnetic field on the natural frequency of a TLCD with an MF using a U-pipe attached to an electromagnet. The height,  $h$  is defined as the distance between the free surface of the MF and the center of the electromagnet. When  $h$  is less than zero, the natural frequency of the system increases with the magnetic field. When  $h$  is greater than zero, the natural frequency of the system increases under a strong magnetic field, and decreases under a weak magnetic field. Unlike the model described in Ref. [122], the magnetic fluid-tuned liquid column damper (MF-TLCD) designed by Oyamada et al. [123] had two electromagnets installed on the left and right sides of the U-tube, as shown in Fig. 9. By studying how the magnetic field affected the natural frequency of the liquid column, it was found that the rate of change in the natural



**Fig. 9** MF-TLCD. Reproduced with permission from Ref. [123], © IOS Press and the authors 2014.

frequency was determined by  $h$  of the electromagnet and current. When the excitation frequency ranged from 1.05 to 1.4 Hz, the MF-TLCD exhibited a higher damping efficiency than the conventional TLCDC. In 2016, Kondo et al. [124] constructed three separate U-pipes and performed vibration experiments on each one. They found that when a magnetic field was applied, the shapes of the bottom and elbow of the U-pipe did not influence the natural frequency of the MF-TLCD. The damping performance of the MF-TLCD could be significantly improved using a U-pipe with an elbow with a large curvature.

Because of the magnetism and fluidity of MFs, MFDs have high sensitivity, and the damping force of an MFD can be adjusted by changing the magnetic field. Hence, MFDs are suitable for small-amplitude and low-frequency vibration reduction in space environments. In 2017, Yang et al. [125] designed a novel adjustable MFD, as shown in Fig. 10. Here, the cylindrical inertia mass, which is connected to two non-magnetic springs, is placed inside a sealed non-magnetic vessel filled with an MF. The experimental data confirmed that the damping force increased as the radius of the inertia mass increased and decreased as the gap between the inertia mass and the vessel increased. This damper is suitable for spacecraft structures with low-frequency vibrations and low-level damping. Based on previous work, Yang et al. [126] built a numerical simulation model of a cantilever beam and damper system, calculated the displacement and frequency of the freely supported beam, and analyzed the flow distribution of the MF in the damper. Their results showed that this type of damper is



**Fig. 10** Adjustable MFD. Reproduced with permission from Ref. [125], © IEEE 2017.

appropriate for controlling the vibration of a spacecraft. In 2019, Wang et al. [127] developed a magnetic spring-tuned mass damper that could absorb low-frequency vibration energy. By controlling the amount of ferrofluid and circumferential distribution of the fixed permanent magnet, the viscous damping of the MF could be adjusted as the damping coefficient changed from 0.0415 to 0.3642.

Because the sloshing of MFs can be controlled, the damping performances of TMFDs are significantly better than those of TLDs. Through extensive research on the sloshing behaviors of MFs [55, 128, 129], it is hoped that the damping performance of TMFDs can be further enhanced.

The typical dampers can be summarized as follows. Ferrofluid viscous dampers were the first ones proposed. They have large adjustment ranges for their damping forces and are generally used for vibration reduction in rotating equipment such as motors. In recent years, increasing attention has been paid to the vibration reduction of small precision equipment. Combining dampers with porous materials can ensure the damping performance while miniaturizing them. Ferrofluid inertia dampers are sensitive to small external inertia forces, and thus can be used for low-frequency and small-amplitude vibration suppression, such as in spacecraft. TMFDs are based on TLDs. They can dissipate more energy and are widely used for the wind-induced vibration of civil structures. Table 3 presents a brief comparison of the three kinds of ferrofluid dampers.

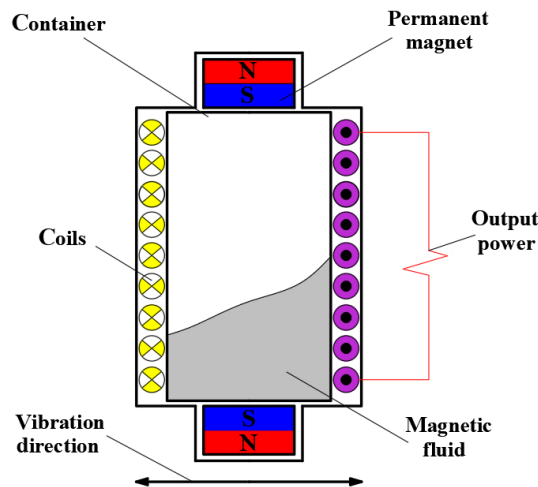
### 3.4 Vibration energy harvesters

In many fields, including wireless sensors and medical equipment, the use of energy harvesters to replace traditional internal energy sources (usually primary batteries) has attracted interest. Simultaneously, the appearance of various electricity generation methods for use in miniature devices, such as piezoelectricity [130, 131] and triboelectricity [132], is conducive to the development of energy harvesters.

In 2012, Bibo et al. [133] proposed the concept of vibration energy harvesters based on MFs. Figure 11 shows a microgenerator that converts the mechanical motion of an MF into electricity under the influence of a magnetic field. They studied how magnetic

**Table 3** Comparison of three kinds of ferrofluid dampers.

Category	Researcher	Year	Type	Application	Innovation
Ferrofluid viscous damper	Litte and Beltracchi [77]	1970	Passive	Suppress the torsional vibration of low-speed rotating equipment	Without mechanical coupling
	Price and Kruse [98]	1990	Active	Flexible brakes	Contact type
	Matsumoto [95]	1993	Passive	Suppress the torsional vibration of a motor	Eliminated the influence of thermal fluctuations
	Raj and Moscovitz [94]	1995	Passive	Suppress the resonance of a motor	Injected ferrofluid directly into the gap
	Calarasu et al. [99]	1999	Active	Flexible brakes	Non-contact type
	Zhou and Sun [79]	2008	Semi-active	Advanced semi-active vibration control systems	Water-based ferrofluid with porous particles
	Liu [102]	2009	Passive	Reduce the shock of small precision equipment	Porous elastic sheet
Ferrofluid inertia damper	Moskowitz et al. [46]	1978	Passive	Stepper motors and similar devices	Based on the second levitation principle of ferrofluids
	Bashtovoi et al. [51]	2002	Passive	Spacecraft	Sensitive to small external inertial forces
	Yao et al. [53]	2019	Passive	Low-frequency and small-amplitude vibration	Based on the first levitation principle of ferrofluids
TMFD	Abe et al. [116]	1998	Active	Control wind-induced vibrations in civil structures	Replaced normal liquids with MFs
	Ohno et al. [120]	2009	Active	Not reported	Inserted two iron cores into a coaxial cylindrical container
	Masuda et al. [122]	2013	Active	Suppress the vibrations in high-rise buildings caused by wind and earthquakes	U-tube container
	Oyamada et al. [123]	2014	Semi-active	Not reported	Installed two electromagnets on both sides of the U-tube
	Yang et al. [125]	2017	Active	Spacecraft structures with low-frequency vibration	Connected a cylindrical inertial mass to two non-magnetic springs

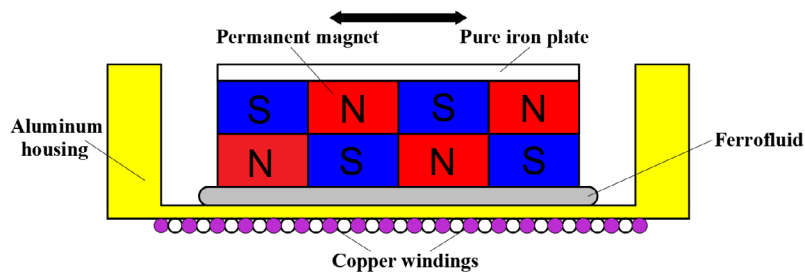


**Fig. 11** Electromagnetic ferrofluid-based energy harvester. Reproduced with permission from Ref. [133], © Elsevier B.V. 2012.

fields with different strengths and liquid columns with different heights affect the output voltages and

proved that the former factor affected the peak frequency and peak voltage of the harvester, whereas the latter factor had little influence on the amplitude of the output voltage. The output voltage of the harvester increased significantly with the surface area. In 2014, Alazemi and Daqaq [134] presented a TMFD as an energy harvester and showed that it could reduce structural vibrations while acting as an electromagnetic energy harvester. They also demonstrated that the optimal magnetic field for suppressing vibrations was different from that for the maximum output power.

In 2013, Chae et al. [135] invented an electromagnetic energy harvester that used an array of rectangular permanent magnets as linearly moving masses, with a ferrofluid as the lubricating material, as shown in Fig. 12. When external vibration acted on the device, the multipole magnets vibrated laterally as they were



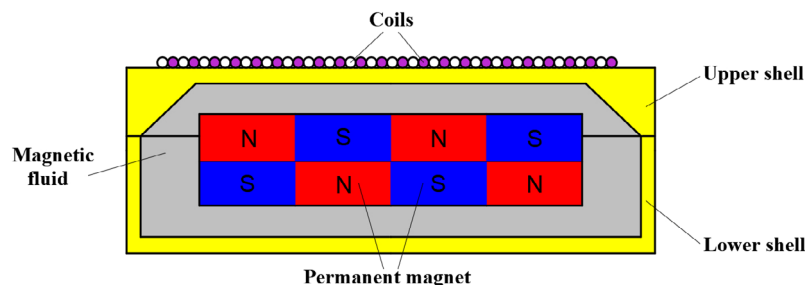
**Fig. 12** Electromagnetic vibration energy harvester using springless proof mass and ferrofluid as lubricant. Reproduced with permission from Ref. [135], © IOP Publishing Ltd. 2013.

lubricated by the ferrofluid. Thus, voltages were induced in copper windings connected in series. The pure iron plate on the upper surface of the magnet enhanced the magnetic flux density on the windings. This device with a ferrofluid generated a maximum open-circuit voltage of 0.47 V at a frequency of 12 Hz, which was 8% higher than that of a device without a ferrofluid. In 2015, a variety of vibration energy harvesters appeared one after another. Monroe et al. [136] used a peristaltic pump to cyclically drive the MF in solenoids to generate electric energy. As the frequency of the pulsating flow and the diameter of the ferro-nanoparticles increased, the induced voltage increased. The experimental data showed that a magnetic field with a stronger bias produced a larger voltage.

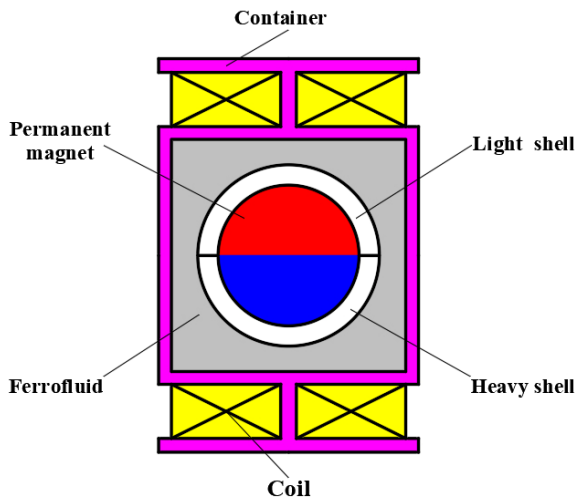
Figure 13 displays a novel vibration energy harvester based on an MF proposed by Wang et al. [137]. A magnet array formed by magnets with alternating north and south poles, which automatically align with a coil array, provides a large magnetic field gradient. At a fixed acceleration, the induced voltage depends on the vibration frequency and peaks at the resonant frequency. This performance can also be maintained at a higher input acceleration. Alazemi et al. [138] studied the performance of a cubic ferrofluid container as an energy harvester under

three conditions: the sloshing direction was parallel to the magnetic field lines, and the sloshing direction was perpendicular to the magnetic field lines in two different planes. The experimental results showed that when the direction of the windings was parallel to the sloshing direction, the output voltage was almost twice that of the other windings, regardless of the magnetic field direction.

Choi et al. [139] presented a low-frequency vibration energy harvester, as shown in Fig. 14. It has two hemispherical shells with a large difference in density that cover the spherical magnet, which results in a non-uniform mass distribution. When vibration causes the magnetic moment of the magnet to skew, gravity produces an opposite torque, which makes the magnet equivalent to a tumbler. The movement of the magnet causes a change in the magnetic field and generates an induced current in the coil installed outside the container to output electric energy. To evaluate the influence of the mass center position on the energy-harvesting performance, the experimental data were compared, and three center positions were analyzed. The maximum output power of the device at a load resistance of 80  $\Omega$  reached 9.03  $\mu\text{W}$ , which proved that changing the mass center position to improve the energy output was feasible. Kim et al. [140] designed an electrostatic energy harvester



**Fig. 13** Ferrofluid liquid spring for vibration energy harvesting. Reproduced with permission from Ref. [137], © IEEE 2015.

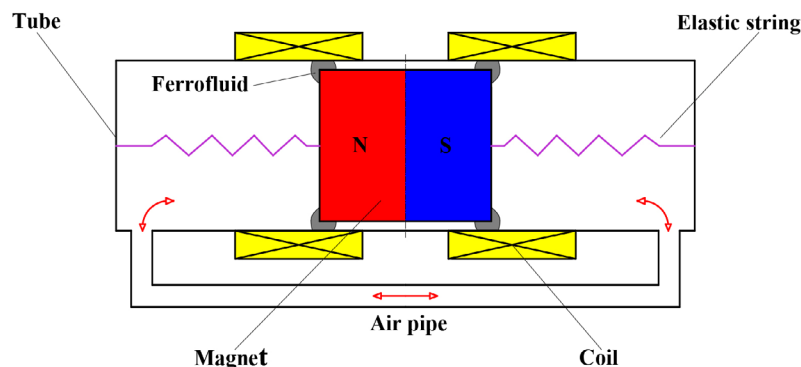


**Fig. 14** Low-frequency vibration energy harvester using spherical permanent magnet with controlled mass distribution. Reproduced with permission from Ref. [139], © IOP Publishing Ltd. 2015.

based on ferrofluid droplets. This device had top and bottom electrodes coated with a thin dielectric layer, a conducting liquid, and oil-based ferrofluid droplets. An external magnetic field was used to drive the MF droplets to rotate on hydrophilic and hydrophobic surfaces to cause a capacitance variation and thus generate electric energy. In 2017, Seol et al. [141] introduced a ferrofluid vibration energy harvester based on a triboelectric–electromagnetic hybrid mechanism. This device could be used to collect subtle and irregular vibrations and output electric signals, even at a vibration amplitude of 1 mm.

An independent power supply is a vital component of wearable devices. Therefore, the development of independent power supplies is crucial for the development of wearable devices. Vibration energy

harvesters based on MFs are regarded as independent power sources. In 2017, Wu et al. [142] invented a resonant human kinetic energy harvester. This harvester had a cylindrical permanent magnet connected to two end caps by two latex elastic strings and a carbon fiber tube with two wound coils on its surface, as shown in Fig. 15. Load resistance and energy storage tests were conducted with and without the MF. The experimental results indicated that the voltage generated by the harvester with the MF was 25% higher than that without the MF. This MF-based resonant human kinetic energy harvester has good prospects for broad applications. Subsequently, Wu et al. [143] introduced a cylindrical permanent magnet with three degrees of freedom. The simulation data indicated that the permanent magnet could still maintain a good self-levitation state even when subjected to 10 times the acceleration of gravity. A permanent magnet with three degrees of freedom significantly increased the energy conversion efficiency. In 2018, based on the concept of ferrofluid-based vibration energy harvesters [133, 138], Liu et al. [144] considered energy harvesters with eight diverse configurations to study the foundational mechanism for producing electromotive force. They found that in each sloshing cycle, the change in the magnetic flux in the coil was related to the magnetization of the ferrofluid. In 2019, Wang et al. [145] designed and studied a planar electromagnetic energy harvester comprising a container, ferrofluid, two permanent magnets, and two induction coils. It supplied energy to a wireless mobile communication module and a positioning module situated in an intelligent bicycle lock. Their results revealed that the performance of



**Fig. 15** Electromagnetic wearable resonance kinetic energy harvester with ferrofluid. Reproduced with permission from Ref. [142], © IEEE 2017.

the energy harvester was outstanding over a large range of operating frequencies (less than 5 Hz).

Vibration energy is the most ubiquitous energy in the environment and can be captured and converted into useful electrical energy. The energy conversion efficiency of existing vibration energy harvesters is low and cannot meet the actual demand. To solve this problem, it is necessary to study the energy conversion mechanism while optimizing the structure of the vibration energy harvester. Many studies on the energy conversion mechanism [146], including piezoelectricity [147, 148] and triboelectricity studies [149], have been carried out to improve the energy conversion efficiency of vibration energy harvesters. The development of vibration energy harvesters

would assist in the miniaturization of devices. Table 4 summarizes the typical vibration energy harvesters.

#### 4 Novel design for MFD

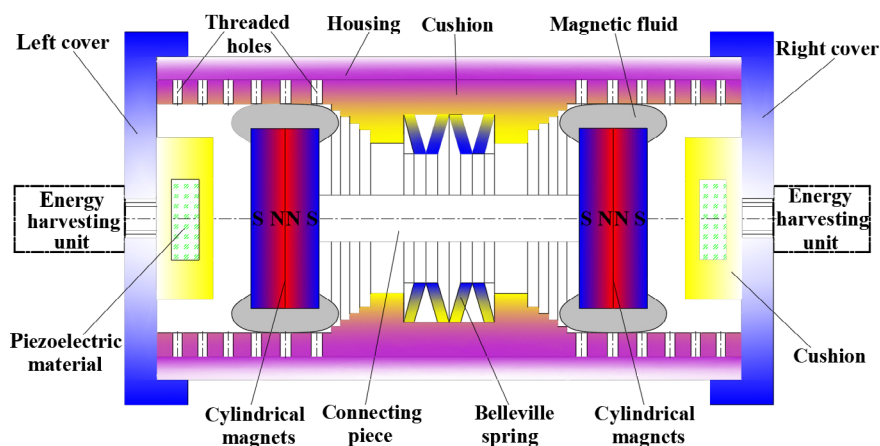
In this review, we present a novel MFD that can harvest vibration energy while suppressing vibration, as shown in Fig. 16. The multipole permanent magnet is composed of four ring-shaped permanent magnets placed so that adjacent poles are the same. It is used as a damping block to squeeze the piezoelectric material wrapped by cushion pads on the left and right sides. Through the piezoelectric effect [150–152], mechanical energy is converted into electric energy, which is stored in the energy-harvesting unit. The

**Table 4** Summary of the literature review of vibration energy harvesters.

Reference	Year	Material	Frequency (Hz)	Peak output voltage	Power	Load resistance ( $\Omega$ )
Bibo et al. [133]	2012	Hydrocarbon-based ferrofluid	9	18 mV	1 $\mu$ W	35
Alazemi and Daqaq [134]	2013	Hydrocarbon-based ferrofluid	2.04	7.5 mV	0.6 mW	190
Chae et al. [135]	2013	Ferrofluid	12	0.47 V	71.26 $\mu$ W	40.8
Wang et al. [137]	2015	Ferrofluid	320	0.58 mV	36 nW	2.3
Alazemi et al. [138]	2015	Ferrofluid	2.2	9 V	80 mW	254
Choi et al. [139]	2015	Ferrofluid	20	48.85 mV	9.03 $\mu$ W	80
Seol et al. [141]	2017	Water-based ferrofluid	7	TENG <sup>1</sup> 0.23 V EMG <sup>2</sup> 1.8 mV	TENG 0.621 nW EMG 4.5 nW	—
Wu et al. [143]	2017	Ferrofluid	1.1–3.8	0.3 V	2.28 mW	4
Wang et al. [145]	2019	Ferrofluid	5	0.6 V	5.047 mW	70

1 Triboelectric nanogenerator

2 Electromagnetic generator



**Fig. 16** Schematic of novel MFD.

magnetic field generated by the multipole permanent magnet is stronger than that generated by a single permanent magnet, which enhances the levitation stability of the damping block. The cushion attached to the inner surface of the housing has a tapered stepped structure, which increases the contact area between the MF and cushion, thus improving the energy consumption efficiency. It also provides the force required to restore the damping block. The cushion has threaded holes through which the MF can enter and exit during operation. These threaded holes also increase the energy consumption efficiency by increasing the contact area and flow resistance of the MF. In addition, the cushions can prevent any rigid impact between the components of the damper. A Belleville spring allows the damper to adapt to a wide range of vibration frequencies. This novel MFD not only enhances the damping performance but also harvests vibration energy, making it suitable for use in energy-deficient environments such as spacecraft. By changing the materials, further studies will explore the feasibility of using the MFD for reducing biological organ vibration.

In summary, compared to previous MFDs, the main innovation of this novel MFD is the addition of a cushion with a special structure. First, the cushion is machined with threaded holes and tapered stepped structures, which increases the contact area and flow resistance of the MF, thereby improving the damping performance of the MFD. Second, the cushion can absorb the impact of the MFD components. Third, cushions of different materials can be used to change the force of their interaction with the MF. This new device has been patented, and its application number is CN202011146231.5. Previous MFD designs did not consider the influence of the inner surface of the housing on the damping performance. We hope that this patent can assist scholars to consider the influence of the inner surface of an MFD on the damping efficiency.

## 5 Conclusions and perspective

This review introduced the main characteristics of MFs and described the development of the damping applications of MFs from the 1960s to the present.

Based on the different characteristics of MFs, their typical damping applications are divided into four categories: ferrofluid viscous dampers, ferrofluid inertia dampers, TMFDs, and vibration energy harvesters. Our review emphasized TMFDs and vibration energy harvesters, which have been the hottest research topics in the ferrofluid damping application field in recent years. We look forward to the future development of damping applications of MFs in relation to three main aspects: material, biology, and energy.

From a material point of view, some scholars have changed the main components of MFs, such as the carrier liquids, surfactants, and magnetic particles, in order to achieve better performance. Furthermore, it is also possible to develop composite MFs that combine MFs and other multifunctional materials such as graphene [153–156] and electro-rheological (ER) fluids [157]. Magnetic particles exhibit high damping performance at a low temperature of approximately  $\sim 80$  °C [158]. However, an MF has significantly reduced fluidity at low temperatures [159]. Therefore, compared to MFs, under low and ultralow temperatures, the damping application of magnetic powders has better development prospects. By changing the shell materials [160] or adding the inner surface textures [161], the damper can be miniaturized, lighter, and more flexible, which makes it more suitable for cutting-edge fields such as space and biology. Moreover, improving the methods for controlling the damper, such as passive control, semi-active control, and active control, as well as combining damping technology with other technologies such as lubrication [137, 142, 162, 163], could also significantly expand the range of damping applications of MFs.

In the field of biomedicine, MFs are now considered powerful and promising new multifunctional materials [164]. With the trend of developing miniaturized, flexible, and lightweight MFDs, they are expected to be used to reduce the vibration of biological organs, such as cardiac defibrillation. In addition, magnetic drug targeting [165], magnetic hyperthermia [166], magnetic thermoablation [167], and magnetically-assisted cell sorting [168] have demonstrated that MFs can play a pivotal role in the further development of biomedicine.

Energy harvesters have become a hot topic because

of their advantages. Vibration energy sources are freely available in the environment. However, the energy conversion efficiencies of vibration energy harvesters are much lower than the actual requirements. Because there is an urgent need to apply them in the fields with an energy shortage, such as aerospace, improving the damping performance and energy conversion efficiency of vibration energy harvesters are two meaningful and challenging research directions.

We hope that our work not only enlightens beginners and those who are ready to study in this field, but also provides a valuable reference for researchers and explorers in this field.

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## Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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